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A contribution towards the practical implementation of stress management concepts in underground mining

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AFFIDAVIT

I declare on oath that I wrote this thesis independently, did not use other than the specified sources and aids, and did not otherwise use any unauthorized aids.

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Date 21.12.2021

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Preface, Dedication, Acknowledgement

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Finally, my thanks and gratitude belong to my family, who supported me in the last years offside from writing my thesis and from conducting corresponding research and development and project work. Without their full support and commitment the finalization of this thesis would not have been possible.

For better legibility the masculine form has been chosen in this text. Nevertheless, the details provided refer to members of both sexes.

Abstract

The extraction of excavations disturbs the primary stress field and causes stress and energy changes in the rock mass. Highly stressed and de-stressed zones form and seismic energy is released. As mining progresses to greater depths, the primary stress magnitudes rise and hence the intensity of the stress and energy changes increases and rock pressure phenomena, such as stress driven fracture and failure or rock burst damage, start to occur. The severity of rock pressure phenomena increases with depth due to the rising primary stress magnitudes. If rock pressure phenomena become so severe that they endanger the objectives of mining, which are the safe, as complete as possible and economic mineral extraction, they are referred to as rock pressure problems. Rock pressure problems occur frequently in deep mining conditions. In these conditions the control of rock pressure is central for a successful operation. The present research work concentrates on rock pressure control in deep mining. The causes and consequences of rock pressure phenomena and rock pressure problems as well as applied strategies addressing them are reviewed and discussed. It is found that a passive strategy, which aims on alleviating the consequences of rock pressure problems, is dominating. In contrast, an active strategy, which tackles the sources of rock pressure problems to prevent their occurrence and which is therefore considered to be superior, is not widely utilized for different reasons. One reason is a shortage of applicable active strategies for many mining environments in particular for steeply dipping or massive deposits. This shortage of applicable active stress control strategies is addressed by proposing a stress management concept. The stress management concept relies on elements, which provide in isolation or in combination certain functions. Main elements are excavations, pillars, loading systems and time. The first three elements describe the mine layout and the fourth element describes the mining sequence. Hence, the proposed stress management concept is four-dimensional. The physical effects of the main elements and the element functions, which are based on these physical effects, are investigated. For the implementation of the concept the elements and their functions must be combined in a systematic way to control the rock pressure situation and to eliminate potential sources of rock pressure problems. Therefore, different mine layouts and mining sequences are proposed and analyzed as well as critical issues and open points for their application are highlighted. In the proposed layouts and sequences de-stressed zones are created in the deposit in the so-called de-stressing phase. The provided de-stressed zones are then utilized to protect infrastructure and stopes from rock pressure in the subsequent production phase, in which large-scale mineral extraction takes place. Furthermore, designated, specifically designed structures and mining sequences provide additional control of the rock pressure situation in both phases. Relevant aspects of the proposed layouts and sequences are first discussed on a conceptual basis. Then their application based on raise mining in steeply dipping or massive deposits is demonstrated. A case study in Kiruna mine, which highlights the application potential and advantages of the stress management concept, is conducted as well. In summary, the investigations show that the proposed stress management concept offers significant advantages and hence that its application facilitates or in certain situation even enables the safe, as complete as possible and economic mineral extraction at great depth.

Zusammenfassung

Das Auffahren von Hohlräumen verursacht Spannungsumlagerungen im Gebirge. Es kommt zur Ausbildung von hochbelasteten und druckentspannten Zonen sowie zur Freisetzung von seismischer Energie. Letztere Effekte werden aufgrund der steigenden Primärspannungen mit zunehmender Teufe ausgeprägter. Als Folge treten Gebirgsdruckerscheinungen, wie spannungsinduzierte Bruchzonen oder Gebirgsschläge, auf. Die Schwere der Gebirgsdruckerscheinungen nimmt dabei ebenso aufgrund der steigenden, primären Gebirgsspannungen mit der Teufe zu. Gefährden die auftretenden Gebirgsdruckerscheinungen den sicheren, möglichst vollständigen und wirtschaftlichen Abbau der Lagerstätte, werden diese üblicherweise als Gebirgsdruckprobleme bezeichnet. Derartige Gebirgsdruckprobleme treten häufig im tiefen Bergbau auf und deren Beherrschung ist entscheidend für einen erfolgreichen Abbau einer Lagerstätte. Die vorliegende Arbeit befasst sich mit der Beherrschung des Gebirgsdrucks im tiefen Bergbau. Zunächst werden die Ursachen und Konsequenzen von Gebirgsdruckproblemen sowie Strategien zu deren Bekämpfung untersucht. Dabei zeigt sich, dass eine passive Strategie, welche auf eine Abmilderung der Konsequenzen von Gebirgsdruckproblemen abzielt, dominiert. Eine aktive Strategie, welche potenzielle Quellen von Gebirgsdruckproblemen eliminiert und daher als überlegen angesehen wird, ist jedoch wegen verschiedener Gründe kaum verbreitet. Ein Grund davon ist der Mangel an anwendbaren aktiven Strategien in einer Vielzahl an Situationen und vor allem in steilstehenden und massiven Lagerstätten. Dieser Mangel wird adressiert und ein Konzept zur Gebirgsdruckbeherrschung vorschlagen. Dieses Konzept baut auf Elementen, welche entweder isoliert oder in Kombination gewisse Funktionen besitzen, auf. Die Hauptelemente sind Hohlräume, Festen, Belastungssysteme und Zeit. Die ersten drei Elemente beschreiben dabei den Abbauzuschnitt und das vierte Element die Abbausequenz. Das vorgeschlagene Konzept zur Gebirgsdruckbeherrschung kann daher als vierdimensional angesehen werden. Die physikalischen Effekte der Elemente sowie die Elementfunktionen, welche auf diesen physikalischen Effekten basieren, werden untersucht. Die Elemente und deren Funktionen müssen systematisch kombiniert werden, um das Konzept zur Gebirgsdruckbeherrschung zu implementieren. Dazu werden Zuschnitte und Sequenzen, welche eine entsprechende aktive Strategie zur Gebirgsdruckbeherrschung ermöglichen, aufgezeigt und analysiert. Des Weiteren werden kritische Aspekte sowie offene Punkte zur Implementierung des Konzepts diskutiert. Bei der Implementierung werden zunächst druckentspannte Zonen in der Lagerstätte in der sogenannten Entspannungsphase geschaffen. Die geschaffenen druckentspannten Zonen werden in der darauffolgenden sogenannten Produktionsphase, in welcher der großräumige Abbau stattfindet, genutzt, um Aus- und Vorrichtung sowie Abbauhohlräume vor Gebirgsdruckerscheinungen zu schützen. Die vorherrschende Gebirgsdrucksituation wird in beiden Phasen zudem durch speziell geplante Strukturen und Abbausequenzen positiv beeinflusst. Relevante Aspekte der aufgezeigten Zuschnitte und Sequenzen werden zunächst auf konzeptueller Basis behandelt. Danach wird die Anwendung des Konzepts zur Gebirgsdruckbeherrschung in steilstehenden oder massiven Lagerstätten demonstriert, wofür die Abbaumethode Raise Mining eingesetzt wird. Abschließend wird eine Fallstudie zur Implementierung des Konzepts im Bergwerk Kiruna durchgeführt. Diese Fallstudie zeigt deutlich das Potenzial und die Vorteile einer aktiven Strategie für die Gebirgsdruckbeherrschung. Insgesamt zeigen die Untersuchungen und Analysen der vorliegenden Arbeit, dass das vorgeschlagene Konzept zur Gebirgsdruckbeherrschung signifikante Vorteile bietet. Ein Einsatz des Konzepts wirkt sich daher positiv auf den sicheren, möglichst vollständigen und wirtschaftlichen Abbau von Lagerstätten aus oder macht diesen in manchen Fällen erst möglich.

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1 Introduction

Extraction of excavations disturbs the pre-mining stress field and thereby causes stress redistributions. Consequently, highly stressed zones and de-stressed zones are created. The spatial extent, the magnitude and the temporal extent of these stress changes depend on several parameters, which comprise amongst others the pre-mining stress field, the geological situation, the deposit size, shape and orientation, the prevailing rock mass formations and rock mass properties, the mine layout and the mining sequence. The presence of highly stressed zones can cause rock pressure phenomena and rock pressure problems. These phenomena and problems comprise for example rock fracturing in the vicinity of mining infrastructure, rock mass failure in extraction excavations, the failure of pillars or the occurrence of rock burst damage. The severity of rock pressure phenomena and problems depends amongst others on the resultant stress magnitudes, the strength of rock mass and the presence of large faults. Consequences can manifest themselves in stable, local and spatially confined fracture processes near excavations, in far-reaching rock mass failure and deformations in the surroundings of excavations or in sudden and violent failures causing the loss of excavations or in extreme cases the loss of whole extraction areas. Generally, the effects and consequences of rock pressure problems increase significantly, because primary stress magnitudes rise, whilst mining progresses to great depths. As rock mass strength is influencing rock pressure phenomena strongly, the term great depths must be seen in context with rock mass strength. In conclusion, a stress situation is prevailing at great depth, which can endanger the aim of mineral extraction, which is the safe, as complete as possible and economic extraction, if it is not handled properly. For this reason, the present research work focuses on the development of a stress management concept, which addresses high stress situations in a systematic and strategic manner. The proposed stress management concept relies on elements, which have a physical effect on the prevailing mining environment. The physical effects give elements or combination of elements, respectively, certain functions. These functions are then combined systematically for the implementation of the proposed stress management concept. Due to this combination mine layouts and mining sequences for an appropriate stress management are established. The combination of functions enables further to adapt the layouts and sequences to the prevailing conditions and requirements. Overall, a contribution is made, how rock mechanics principles for stress control can be implemented in underground mining to improve the safety, profitability and completeness of extraction in deep mines.

At the beginning of the research work the general implications of increasing mining depths and the need for an appropriate stress management are outlined in chapter **2 Increasing mining depths and stress control**. Based thereon the objectives of the present work are further specified. In the following chapter **3 Consequences and causes of rock pressure problems** rock pressure phenomena and rock pressure problems are discussed. Their consequences are highlighted and possible causes are demonstrated and examined. Key parameters, which can be actively influenced in and for the proposed stress management concept, and parameters, which cannot be influenced by the stress management concept, are outlined. Chapter **4 Rock pressure control approaches** introduces the general stress control approaches, which are the active approach and the passive approach. The suitability of these stress control approaches with respect to the proposed stress management concept is outlined and discussed. Thereafter, the stress management concept is introduced in chapter **5 Stress management concept**. The objectives of the concept, the individual elements of the concept and the element functions are outlined. The individual elements are investigated related to their physical effects on the mining environment in chapter **6 Elements of the stress management concept**. The physical effects of the elements are the basis for the element functions, which are described and examined in chapter **7 Element functions of the stress management concept**. In chapter **8 Implementation of the stress management concept** the implementation of the proposed stress management concept is outlined and investigated on a conceptual basis. Different layouts and sequences are therefore highlighted. The considered implementation relies on de-stressing the deposit with minimum amount of infrastructure and conducting large-scale stoping in the generated de-stressed zones. Thereby, the production activities can be protected from high stresses and mining-induced seismicity. Chapter **9 Application study** outlines then the application of the proposed stress management concept based on raise mining. A possible layout and sequence for the implementation are outlined and the individual steps for its implementation are discussed. Moreover, a case study in Kiruna mine, which highlights the advantages and potential of the proposed stress management concept, is provided. Chapter **10 Discussion and conclusion** summarizes the present work briefly, outlines open points, which require further considerations and investigations, and it concludes on the potential of the proposed stress management concept in deep mining.

2 Increasing mining depths and stress control

This chapter highlights the consequences and implications of increasing mining depths. Production and operational aspects are outlined and the demand for higher efficiency and productivity is recognized. The transition to deep mining conditions is defined in terms of rock mechanics aspects, which become increasingly important, once a certain depth is exceeded. Central rock mechanics aspects in deep mining are identified and discussed briefly. Critical points and questions resulting from increasing stresses and seismic energy release are thereby brought up. Moreover, it is shown that mainly due to rising primary stress magnitudes the importance of an appropriate stress control increases. Possible advantages of a proper stress control as well as possible consequences of an improper stress control are demonstrated. Afterwards, the current state of stress management practices is outlined. Deep South African gold mines can be considered as state of the art regarding the wide utilization of active stress control measures. However, there is a lack of stress management in many other mining environments, which can be seen by the implementation of existing mining methods at great depths without adapting them specifically to encountered deep mining conditions. Furthermore, reactions on rock pressure problems are in most instances of passive nature and aim for the alleviation and mitigation of the consequences of high stress and mining-induced seismicity. Contrary, the improvement of mining methods has mainly been made from a production perspective. For these reasons, the need for an improved stress management concept in a variety of mining environments is identified. Considerations in this chapter show further that besides providing effective stress control the proposed stress management concept must also enable an efficient and productive mineral extraction at great depths.

2.1 General implications of increasing mining depths

2.1.1 Aims of mineral extraction

The aim of mining and mineral extraction is to supply the society with raw materials for their sustainable growth and development. Minerals are mined from mineral deposits, which were formed by different geological processes. Deposits are natural accumulations of certain minerals (or elements) and of confined spatial extent. Thus, deposits can also be considered as anomalies in the earth crust. Overall, deposits are finite and non-renewable within human timescale. New deposits are actually formed within geological timescales. For this reason, a central objective of mining is to extract these deposits as complete as possible so that the society can use most of the valuable minerals (or elements). Another main objective of mining is that the extraction process and associated side processes are conducted in a safe manner. Finally, economics is important in mining as well, as mines are usually profit-oriented nowadays. An exception of the latter circumstance may be mining of strategic commodities, which are subsidized by governmental funds due to development and growth aspects or other considerations. Overall, the objectives of mining can be summarized as the safe, as complete as possible and economic extraction of mineral deposits. These objectives are important aspects and they are valid for all kind of mining, irrespective of the applied method and extraction depth. Therefore, the aims of mining are the motivation for the development of the stress management concept in this research work.

2.1.2 Advancing to greater depths

Deposits are finite and thus become depleted, after they were mined a certain period. In comparison, a deposit, which is located at shallower depth, is normally easier and less costly to mine than a deposit, which is located at greater depths. In the given example, it is presumed that both deposits have or are associated, respectively, with the same shape, size, grade, rock and rock mass properties, surface topography, geographical location etc. Furthermore, shallow deposits are in general easier to find. For these reasons, shallow deposits are usually mined first. Accordingly, there has been a (continuing) trend towards greater mining depths. Illustrative examples are:

- Transition of open pits to underground mines (e.g. Brown (2007), Flores and Catalan (2019), Casten et al. (2020))
- Increasing depths of existing operations or increasing extraction depths in active mining areas (e.g. Mercier-Langevin (2010), Quinteiro (2018), Araneda (2020), Paetzold et al. (2020))
- Increasing depth of discovered deposits (Schodde (2017))

Increasing mining depths are associated with a number of aspects, which add additional costs, constraints or other difficulties to the operation. These aspects comprise:

- Rock mechanics
- Ventilation
- Transportation
- Development times
- Exploration

The above-mentioned points are outlined and their implications are discussed briefly. Therein, it assumed that important parameters of the mining environment, such as the deposit size and shape, the rock mass properties and the deposit grade, are constant. These assumptions simplify the discussion. Indeed, at least some parameters change normally, as mining moves on to other (deeper) portions of the deposit. However, the outlined overall trends and consequences of increasing mining depth remain generally valid.

2.1.2.1 Implications on rock mechanics

Increasing mining depth is associated with several circumstances, which may affect the objectives of mineral extraction significantly. Brady and Brown (2006) present results of primary stress measurements (Figure 1) and conclude that vertical stresses increase approximatively linearly with depths according to Equation 1, where σ_{vp} is the primary vertical stress, γ is the unit weight and d is the depth below surface. They determine

27 kN/m³ as average unit weight for the primary vertical stress increase with depth. According to Brady and Brown (2006) the primary horizontal stresses (σ_{hp}) are more variable with depth than the primary vertical stresses. They use a factor k, which describes the ratio between primary horizontal and primary vertical stresses (Equation 2). At shallower depths less than 500 m below surface k varies largely and ranges between 0.3 and 3.5. As depth increases below 1000 m below surface the maximum k values decrease and k varies between 0.3 and 1.5. However, even though the maximum k values decrease towards greater depths, the absolute magnitude of primary horizontal stresses is larger than at shallower depths due to the constantly rising primary vertical stresses. Table 1 provides expected primary vertical and primary horizontal stress magnitudes at different depths.

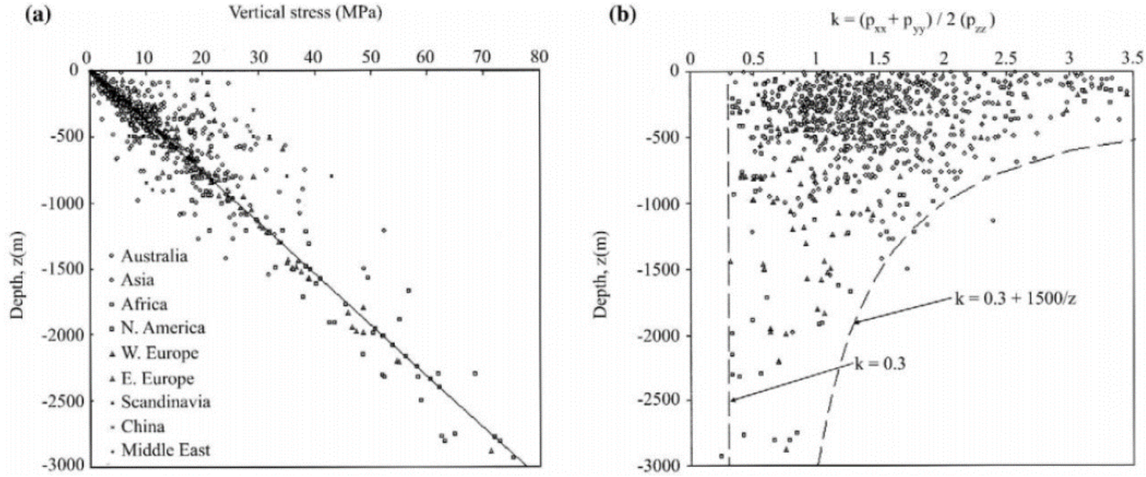


Figure 1: (a) measured primary vertical stresses and (b) ratio between average measured primary horizontal to primary vertical stresses as function of depth (Brady and Brown, 2006)

$$\sigma_{vp} = \gamma * d$$

Equation 1

$$\sigma_{hp} = k * \sigma_{vp}$$

Equation 2

d [m]	σ_{vp} [MPa]	min. σ_{hp} [MPa]	max. σ_{hp} [MPa]
250	6.75	2	23.6
500	13.5	4.1	44.6
1000	27	8.1	48.6
1500	40.5	12.2	52.7
2000	54	16.2	56.7
3000	81	24.3	64.8
4000	108	32.4	72.9

Table 1: Primary vertical and minimum and maximum primary horizontal stress magnitudes at different depths. Primary stresses are calculated after Brady and Brown (2006)

The uniaxial compressive strength of rocks ranges typically between 30 MPa and 300 MPa. The rock mass strength is normally lower than the strength of intact rock. Thus, it can be concluded that stress magnitudes start to reach and exceed rock mass strength, as depth increases. The redistribution of stresses due excavation establishment increases stress magnitudes further and exceeding the rock mass strength becomes more likely. Additionally, ongoing mining activities alter the stress field significantly, which circumstance leads to the formation of highly stressed zones. Concluding, the above made simple and straightforward considerations point already out that rock mechanics aspects become increasingly important with increasing mining depth.

The implications of rock mechanics with increasing mining depth are discussed further in section 2.2. The rock mechanics implications are therein used to define deep mining conditions. There are different approaches and strategies addressing increasing rock pressure at great depths, which are subject of this thesis.

2.1.2.2 Implications on ventilation

Rock temperature increases with depths. The geothermal gradient depends on various parameters and ranges typically between 7.7 °C/100m and 0.8 °C/100m. (McPherson, 1993) In order to meet work place requirements, certain air temperatures must not be exceeded in active working areas. These requirements may cause additional demands on the ventilation system such as for example a larger airflow or cooling of air. Additionally, changes to the mine layout and mining sequence could be introduced to limit heat inflow, such as sealing of old mined-out areas or backfilling of excavations to reduce the exposed surface. The additional cooling demands at great depths and possible concepts addressing the heat problem have been subject of various studies (Wagner (1986), Mackay et al. (2010), Kamyar et al. (2016), Greth et al. (2017), Jones (2018)).

2.1.2.3 Implications on transportation

Going deeper also affects the transportation of ore, waste, water, machinery, workforce and other materials. Transportation distances increase and larger elevations must be overcome. These circumstances manifest themselves in a lower capacity and efficiency of certain transportation systems. Moreover, the energy demand for the transportation increases. Improving or changing the transportation system can counteract to some extent, but will not stop the general trend.

Besides distances and elevations the transportation time rises. Increased transportation times are critical for equipment and particularly workforce, which have to be moved from surface to a workplace on a regular basis or daily basis, respectively. Consequently, the effective work time decreases and productivity is affected directly.

2.1.2.4 Implications on development time

Increasing mining depth affects planning and construction of the operation as well. The amount of and the time for infrastructure development increases. Consequently, investment cost rise and payback is delayed. These effects may have a considerable impact on the economics and profitability of the operation.

2.1.2.5 Implications on exploration

Another issue of increasing mining depth may be that less exploration is conducted in order to save cost. Thereby the available information for mine planning in terms of quantity and certainty is reduced resulting in higher risks. Furthermore, exploration campaigns tend to concentrate on geology, ore body definition and reserve estimation, thus relevant data for the rock engineering design of the mine, such as rock mass properties, primary stress situation or position and orientation of large faults, are often sparse. (Potvin (2011), van As (2020)) Brown (2012) highlights significant geomechanics risks in deep mining, which arise from this limited exploration and knowledge. In light of the importance of rock mechanics in deep mining and against the background that the overall mine design is to a large extent fixed at an early stage, this limited geotechnical knowledge and the associated risks are critical. Finally, the mine design has a considerable impact on the safe, as complete as possible and economic extraction.

Regarding geological and geotechnical knowledge, it is further reasonable to distinguish between greenfield and brownfield projects. A gradual increase of depth over time in a mine or mining area, where geological and geotechnical conditions are relatively consistent, may alleviate some drawbacks resulting from the limited geotechnical exploration. First, infrastructure is constructed in stages and already existing infrastructure may be utilized for depth explorations as well, whereby (drilling) distances to greater depths and correspondingly exploration costs can be reduced. Second, mining experience can provide valuable geological and especially geotechnical data and knowledge. Indeed, a prerequisite for this is a proper monitoring and data collection program as well as an adequate back analysis of gathered data. Mines progressing stepwise to greater depths make commonly use of this approach and incorporate mining experience in design improvements or design changes. Examples therefore are:

- Adjusting the mine layout, mining sequence and support systems for a depth extension at LaRonde mine (Mercier-Langevin, 2010)
- Adjusting the mine layout, mining sequence and support systems at Kanowna Belle for subsequent depth extensions (Varden and Esterhuizen, 2012)
- Adjusting the mine layout, mining sequence and support systems at Kidd mine for subsequent depth extensions (Counter, 2014)
- Developing and improving the de-stressing layout applied in South Deeps mine from a tabular slot to a yield pillar system (Andrews et al., 2019)

Consequently, uncertainties in mine planning can be decreased at lower cost in such brownfield operations compared to greenfield projects.

2.1.3 Overall consequences of mining at greater depths

The considerations above outline that mineral extraction becomes more complex and difficult, as mining depth increases. Consequently, there is a decrease in productivity. On top investment and operational cost tend to rise due to various reasons significantly. Regarding costs, it is reasonable to distinguish between costs, which are directly and indirectly related to depth. A direct relation implies that costs increase constantly, as mining advances to greater depths. Accordingly, the direct relation marks a steady increase in costs, which could be linear, exponential or stepwise. In contrast, an indirect relation implies that the costs do not increase significantly for certain depths ranges, but as a certain depth is exceeded, these costs become relevant. Indirect costs could thereby show a stepwise increase with depth, a large exponential increase starting a certain depth or a combination of them. Typical examples for indirect costs are changing from room and pillar mining to longwall mining at depth, if support pillars have to be made so large that the extraction ratio of the deposit becomes unacceptably low, or introducing of mine cooling systems to maintain acceptable climatic conditions in the working areas. Table 2 groups the costs of afore mentioned aspects into directly and indirectly related to increasing depth for a specific mine site. It must be noted that this grouping is rather coarse. Generally, it will depend on a number of site-specific conditions and the history of the operation. Costs could also be somewhere between the outlined two extremes. Furthermore, other costs, such as costs related to ongoing stoping, are not considered and assumed to be independent from depth. This simplification is adequate for the discussion of some principal depth related effects and their consequences on the operation.

Cost increase due to	Directly related	Indirectly related
Rock mechanics		X
Ventilation		X
Transportation	X	
Development time	X	
Exploration	X	

Table 2: Broad classification of cost increases into directly and indirectly depth related arising from considered aspects of increasing mining depths

Transportation, development time and exploration are obviously directly related with increasing depth. The main driver for this is the increasing elevation, which must be overcome. The consequence on transportation is a longer transportation time, a larger energy input and potentially additional transfers between individual transportation systems, such as hoist shafts or conveyer belts. Meters of required infrastructure increase resulting in higher development cost and a longer development time, which delays the start of the production further and thereby causes additional cost. Exploration requires more drill meters as well.

Ventilation and rock mechanics are indirectly related with depths. The reason therefore is that at a certain, site-specific depth the ventilation demand and rock mechanics requirements start to become considerable or start to increase rapidly. For ventilation the depth and the rapid cost increase are related to the required cooling efforts. (e.g. Wagner (1986), Mackay et al. (2010)) For rock mechanics the depth and rapid cost increase are related to the requirement of controlling rock pressure. Possible measures therefore are adapting the mine layout and mining sequence (e.g. Yao and Moreau-Verlaan (2010), Jalbout and Simser (2014), Esterhuizen (2018)), increasing the support capacity (e.g. Jacobsson et al. (2013), Morissette et al. (2014b), Turcotte (2014), Morissette et al. (2017b), Woods et al. (2018)) or applying special stress control measures such as pre-conditioning or de-stress blasting (e.g. Kempin et al. (2007), Andrieux et al. (2010), Catalan et al. (2012), Townend and Sampson-Forsythe (2014), Simanjuntak et al. (2020)). All of these rock mechanics measures have in common that they either add costs directly due to increased support cost, rehabilitation or application of special measures or indirectly due to a lower productivity resulting from for example smaller stope sizes, sequencing constraints or longer transportation distances, as main infrastructure may no longer be situated close to the deposit.

From an overall perspective the indirectly related costs of rock mechanics and ventilation start to cause over proportionally large cost increases at a certain depth. Besides the technical difficulties associated with the increased ventilation and geotechnical requirements the increasing costs impose a major operational challenge for mines and their profitability. For this reason, the depth, at which ventilation or rock mechanics issues start to become important, can be used for the definition of a “deep mining environment”. (Wagner, 2019) For the present thesis the definition of “deep mining” is also based on rock mechanics and latter depth; compare section 2.2.1. The strongly increasing costs in combination with the limited geological and geotechnical knowledge are responsible for the comparatively larger risks of deep mining.

Prices are normally fixed at the (world) market and thus they cannot be influenced by a mining operation itself. Consequently, the reduction of the additional extraction costs emerging from increasing mining depths is essential. First, the productivity and efficiency of the operation must be improved. (Wagner (1986), Flores (2014), Morrison (2017)) Second, the escalating costs associated with ventilation and rock mechanics in deep mining must be addressed. Despite the significance of additional costs caused by rock mechanics issues these costs and the driving mechanisms behind are often accepted; compare section 2.4. A number of possible options for improving the efficiency and productivity are listed below:

- Increasing the size of extraction excavations (extraction units) to reduce the amount of infrastructure development and to reduce the amount of extraction preparation
- Increasing the production rate
- Situating infrastructure closer to the extraction area to reduce transportation distances and amount of infrastructure development
- Increasing the speed of mine and infrastructure development and developing infrastructure just-in-time
- Avoiding complex and complicated mining sequences and extraction procedures
- Increasing the degree of mechanization and automation

At least some of these possibilities, such as increasing the stope size or situating the infrastructure closer to extraction areas, call for higher demands from a rock mechanics and rock engineering point of view. Thus, it can be concluded that rock mechanics considerations are important from two perspectives for the cost reduction in deep mining. Namely the reduction of considerable cost increases, which result from rock mechanics demands in deep mining, and the facilitation or enabling of measures increasing the productivity.

An aspect, which has not been considered so far, is ore grade. There is a general trend towards the extraction of lower grade deposits. (Mudd (2010), Müller and Frimmel (2010), Calvo et al. (2016)) Declining ore grades aggravate the overall situation, because they lower the value of the ton of ore mined, whereas the mining costs per ton remain constant. Accordingly, further improvements in efficiency and productivity are necessary. Furthermore, the global demand of minerals is increasing strongly in the near future. (OECD, 2019) Therefore and due to declining ore grades the production of mines must increase.

Concluding, mining becomes principally more challenging in future. The mineral demand is increasing, the ore grades are decreasing and mining must advance to greater depths, because shallow and high-grade deposits were already extracted. Despite the rising operational and technical difficulties, which are particularly prominent in deep mining, the aims of mining, namely the supply of the society with minerals and the associated safe, as complete as possible and profitable extraction of deposits, must still be met. Overcoming the currently encountered rock mechanics related issues will therefore be decisive.

2.2 Rock mechanics issues encountered at great depths

The last section and Table 1 outline that stress magnitudes rise constantly with increasing mining depth. Correspondingly, stress and energy related rock mechanics issues become more pronounced. Moreover, it was highlighted that additional costs and difficulties of rock mechanics origin arise, once mining exceeds a certain depth, which marks the transition to deep mining conditions. The importance of thorough integration of rock mechanics aspects in mine design becomes vitally essential in such conditions. In the following, the transition to deep mining conditions, central rock mechanics issues in deep mining and the effect of increasing mining depths are discussed briefly.

2.2.1 Deep mining conditions

According to Wagner (2019), deep mining conditions can either be defined by the increasing ventilation and cooling demand or by the increasing relevance of rock pressure related effects, which both start to become important at a certain depth, which is referred to as transition depth. Once this transition depth is exceeded, deep mining conditions are prevailing. The transition depth depends on the local, site-specific mining conditions. For the present thesis, deep mining is defined in terms of rock mechanics. Accordingly, the terms “deep mining”, “great depths” or similar terms refer to a situation or conditions, where rock pressure is relevant and where rock pressure has significant effects on mining activities. Deep mining in relation to the rising ventilation and cooling is not further considered.

Rock pressure becomes important, once prevailing stresses start to cause stress driven fracturing of rock mass. Fracturing can cause the subsequent failure of excavations or structural elements, such as pillars, and it must therefore be addressed by additional measures, for example with additional support or changes in the mine layout, to enable a safe extraction. The occurrence of stress driven rock mass failure is governed by the prevailing stress magnitudes and strength of rock mass. For this reason, the ratio between stress and strength can be utilized for the definition of deep mining. (Wagner, 2019) The actual stress state in the vicinity of excavations and in structural elements depend on a number of variables, which comprise the far-field stresses, the shape, position and orientation of excavations, the extent of extraction areas, the mine layout etc. Short, the actual stress state is a quite complex function of many parameters. These parameters and their impact on the stress situation are discussed in subsequent chapters and sections. In order to define deep mining conditions appropriately, the influence of these parameters must be as far as possible eliminated. An isolated tunnel or shaft is therefore best suited. First, there is no influence of any nearby excavations or extraction areas on the stress field. Second, tunnels and shafts are used in basically every mine and their geometries are comparable regarding their cross-section shape and dimensions. Therefore, the stress changes near tunnels and shafts are quite similar as well and they can be approximated by Kirsch equations (Kirsch, 1898). The maximum tangential stress (σ_{tmax}) at the wall of an infinitely long excavation with a circular cross-section can be calculated after Equation 3. σ_1 and σ_3 are the maximum and minimum far-field principal stresses, respectively, oriented perpendicular to the excavation axis.

$$\sigma_{tmax} = 3 * \sigma_1 - \sigma_3$$

Equation 3

For the definition of a deep mining situation a horizontal tunnel is considered, because tunnels are utilized in most mining methods on a regular and extensive basis. For the definition of deep mining, it is further assumed that the maximum and minimum far-field principal stresses correspond to the primary vertical and primary horizontal stresses. Therefore, the only variables being left are the far-field stresses and the orientation of the tunnel in relation to the far-field stresses. The ratio of primary horizontal to primary vertical stresses is important. As mining tunnels are typically developed in different directions, it can be assumed for the definition of deep mining conditions that tunnels are oriented such that the ratio of primary horizontal to primary vertical stresses causes most unfavorable stress changes, namely the highest stress magnitudes near the tunnel boundaries. Another advantage of considering an isolated mining tunnel is that the rock mass was not disturbed by other mining activities, which may result in a degradation of rock mass strength.

The ratio (R_{StSt}) between the maximum tangential stress and the rock mass strength (σ_{RM}) is then used to define the presence of a deep mining situation (Equation 4). The magnitude of R_{StSt}, above which a deep mining situation is present, is based on deep mining experience in South Africa. Therefore, Wagner (2019) uses the critical field stress concept of Wagner and Salamon (1973). A ratio of 0.4 between the maximum principal stress to the uniaxial compressive strength of rock represents the transition to deep mining. The critical field stress criterion neglects though the influence of the ratio of primary horizontal to primary vertical stresses and it considers only the strength of intact rock. An extension of the critical field stress criterion is the rockwall condition factor (RCF) criterion developed by Wiseman (1979). The RCF criterion was developed by back analyzing several kilometers of tunnels in deep South African gold mines. RCF considers the influence of stress state, rock mass strength and support on tunnel conditions. RCF is calculated after Equation 5, wherein the dividend corresponds to the maximum tangential stress at the wall of a circular tunnel and wherein the divisor corresponds to the rock mass strength. The rock mass strength is derived from the uniaxial compressive strength of rock (σ_{UCS}) and a degradation factor F. F ranges typically between 0.5 and 1 and resembles the influence of rock mass characteristics and size of excavations on rock mass strength. (Jager and Ryder, 1999) Equation 5 and Equation 4 are thus equal.

$$R_{StSt} = \frac{\sigma_{tmax}}{\sigma_{RM}}$$

Equation 4

$$RCF = \frac{3 * \sigma_1 - \sigma_3}{F * \sigma_{UCS}}$$

Equation 5

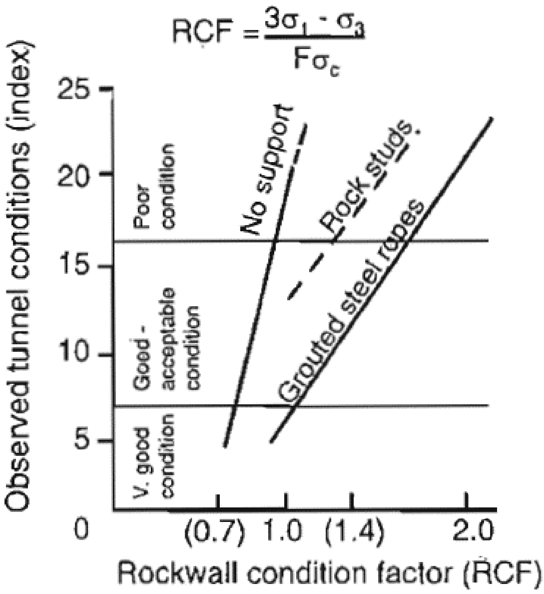


Figure 2: Correlation of tunnel conditions, installed support and RCF (Jager and Ryder, 1999)

Figure 2 correlates RCF values for certain support types with observed tunnel conditions in South African gold mines. It can be seen that the tunnel conditions in an unsupported tunnel become poor for RCF values larger than approximatively 0.9. If the critical field stress concept is converted to RCF values for typical ratios of primary horizontal to primary vertical stresses in deep South African gold mines, which are in the range of 0.5 to 1, the critical field stress criterion yields RCF values in the range of 0.8 to 1, which correspond well with outlined RCF value above. For these reasons, an RCF value (and ratio R_{StSt}) larger than 0.9 is used to define the presence of a deep mining situation.

The transition depths to deep mining conditions have been derived for typical primary stress situations and rock mass conditions and are shown Figure 3. Therein uniaxial compressive strength values of 70 MPa, 150 MPa and 230 MPa are considered. These strength values represent typical strengths of low, intermediate and high strength rock types. To show the effect of rock mass strength on the transition depth the degradation factor is set to 0.5, 0.75 and 1. The primary vertical stresses are assumed to increase with 27 MPa/1000m; compare Figure 1.

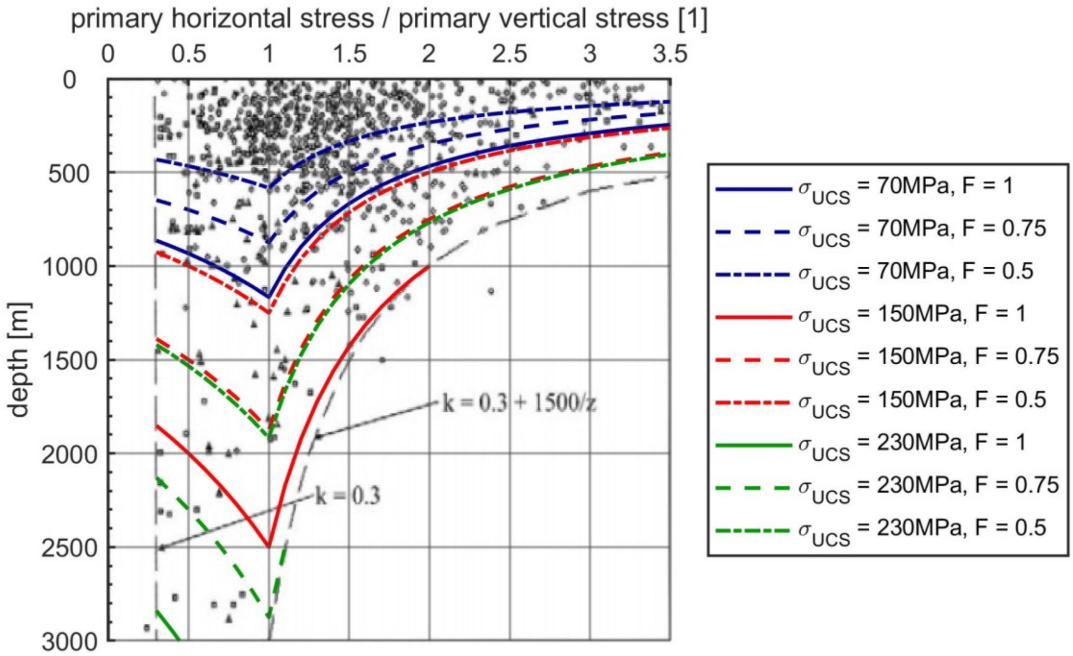


Figure 3: Transition depths to deep mining conditions for different rock and rock mass strengths and typical primary stress states. The figure with the range of primary horizontal to primary vertical stresses is taken from Brady and Brown (2006)

From Figure 3 it can be concluded that the occurrence of deep mining conditions depends strongly on the rock mass conditions and the primary stress state. Following main observations are made:

- The rock mass strength has a dominant influence on the transition depth. In weak rock mass conditions deep mining conditions can already be present at a depth of several hundred to 1000 m, whereas for high strength rock masses deep mining aspects may only be relevant at depths beyond 2000 m to 2500 m.
- The influence of the ratio of primary horizontal to primary vertical stresses is significant. For a hydrostatic stress state, the transition to deep mining conditions occurs on largest depths, because the tangential stresses at the tunnel wall are lowest in this case. In contrast, the transition depth decreases rapidly for primary stress states departing from the hydrostatic one. This decrease is more pronounced for primary horizontal stresses, which are larger than primary vertical stresses. This

aspect outlines the importance of considering the primary stress state in particular high primary horizontal stresses appropriately.

- If the rock mass strength is higher, the transition depth is more sensitive to changes in terms of primary stress state and rock mass strength. The reason for this is related to the higher stress magnitudes, which are present at the transition depth. A small change of the ratio of primary stresses causes a comparatively larger change of the absolute tangential stress magnitudes. As the rock mass strength is constant, this larger change in absolute stress magnitudes results in the observed, more pronounced effect on the transition depth. Another reason is that high strength rocks and rock masses react more noticeable on the strength decreasing effect of discontinuities, which is represented by the factor F in the applied model.

Because of the considerable influence of rock mass strength and primary stress state, a unique transition depth to deep mining conditions cannot be defined. However, the considerations show that the occurrence of a deep mining situation would mostly commence at depths between 500 m to 2000 m. This depth range is relatively large and thus relatively unprecise. Nonetheless, it is a depth range, where many underground mines either are operating today or are planned in future.

If a deep mining situation is present, a number of important rock mechanics issues arise, which are outlined in the following sections. These issues are not relevant for shallow mining situations or they can be managed in shallow mining conditions without undue difficulties. However, in deep mining conditions these issues become of paramount importance and dictate mine design. An insufficient consideration could cause major rock pressure problems. A characteristic of rock mechanics issues is that they often start to occur quite rapidly, once a deep mining situation is entered. The severity of these issues increases then further with depth. This circumstance is delicate, because mines could run into unforeseen problems. It highlights further that a careful examination, whether a deep mining situation is expected, is essential.

2.2.2 Stress changes and rock mass fracturing

Excavations disturb the pre-mining stress field and therefore cause stress redistributions. Consequently, zones of high stress, where prevailing stress magnitudes exceed pre-mining stress magnitudes, and zones of low stress, where prevailing stress magnitudes drop below pre-mining stress magnitudes, develop. Moreover, changed stress magnitudes may cause the formation of zones of fractured rock mass in the immediate vicinity of the excavation, which ultimately could result in excavation failure. The magnitude and spatial and temporal extent of the stress redistributions depend on several parameters, where the most relevant ones are the magnitude and orientation of the pre-mining stresses, the size and shape of the excavations, the strength and deformation characteristics of rock mass, the relative excavation locations and the excavation development sequence. Because of these numerous parameters, the analysis of the stress changes resulting from all excavations is a rather complex and comprehensive task. The difficult determination of and knowledge about the pre-mining stress field (Fairhurst, 2003), the rock mass strength and behavior (Brown, 2012) and the associated uncertainties make it even more challenging. For this reason, it is necessary to obtain an understanding of the complex interaction of the various parameters. This can be best done using simplified and idealized situations and models.

The Kirsch equations (Kirsch, 1898) describe such an idealized situation, namely they can be used to calculate the stress changes in the vicinity of an isolated, infinitely long, circular excavation, such as a mine tunnel or shaft, which is situated in linear elastic rock mass. Figure 4 shows the resultant tangential (σ_{tan}) and radial stresses (σ_{rad}) along a horizontal line in the sidewall and along a vertical line in the roof of a horizontal, circular tunnel according to Kirsch equations, respectively. The tunnel diameter is 4 m and primary stress magnitudes are taken from Table 1 at depths of 1000 m, 2000 m and 3000 m. For primary horizontal stresses mean values from outlined minimum and maximum values in Table 1 are considered. Tangential stresses rise markedly, whilst radial stresses drop to zero at the excavation wall. Stresses approach primary stress magnitudes with distance from the wall. The influence of the ratio of primary stress magnitudes causes the considerable increase of tangential stresses in the sidewall, as depth increases. In contrast, the tangential stresses in the roof do not increase as strongly as in the sidewall. The reason for this is that the considered ratio of primary horizontal to primary vertical stresses changes with increasing depth, namely the ratio drops and as a result the tangential stresses in the roof do not increase considerably despite the larger absolute far-field stress magnitudes.

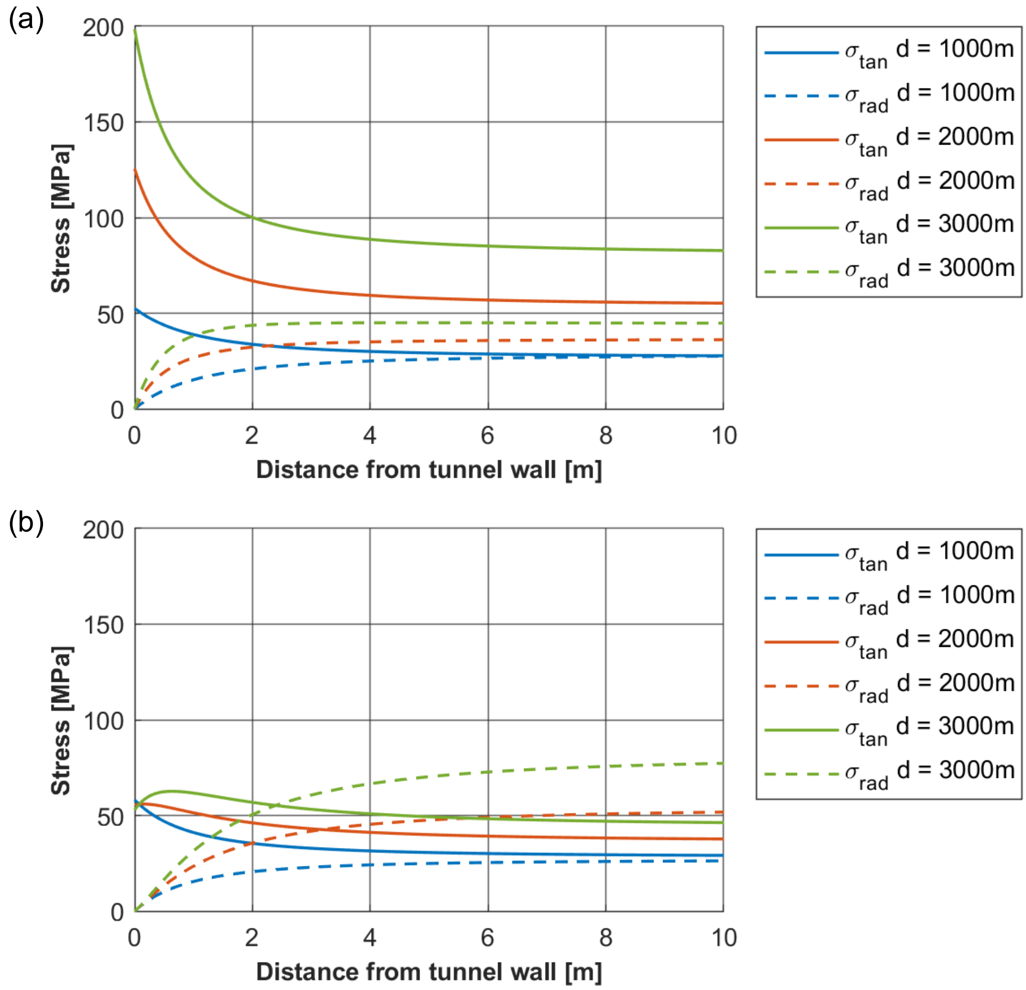


Figure 4: Resultant tangential and radial stresses (a) along a horizontal line in tunnel sidewall and (b) along a vertical line in tunnel roof (b)

The resultant stresses have to be seen in context with rock mass strength. If the stresses exceed the strength, a fractured of rock mass forms. The spatial extent of this fractured zone increases in general with increasing far-field stress magnitudes for the same excavation and same rock mass properties. Figure 5 provides a simplified example and shows the fracture zone depth in the sidewall and roof of a circular tunnel. The same tunnel dimension and primary stress states as in the last example are used. The resultant stresses in the vicinity of the tunnel are calculated after Kirsch equations; compare Figure 4. The strength of the rock mass is derived after Hoek et al. (2002), whereby the uniaxial compressive strength of rock is set to 150 MPa, the rock material constant m_i is set to 20, the disturbance factor D is set to 0 and GSI values of 100, 60 and 40 are used. The GSI of 100 represents intact rock, whilst the GSI of 40 describes a relatively disturbed and hence weak rock mass. The fracture zone depth is estimated by comparing the resultant stress state with the rock mass strength. This comparison does not consider the actual, complex fracture processes in detail. Further stress changes resulting from rock mass fracturing as well as associated alteration of rock mass properties are neglected. Moreover, possible differences of the fracture mode of the intact rock and of the rock mass with GSI 60 and 40 are not considered. Despite these simplifications this model is suitable to outline the central aspect, namely that rock mass fracturing becomes more prominent due to increasing far-field stresses at greater depths; compare Figure 5. Again, the ratio of primary stresses affects fracture zone depth in the roof and sidewalls.

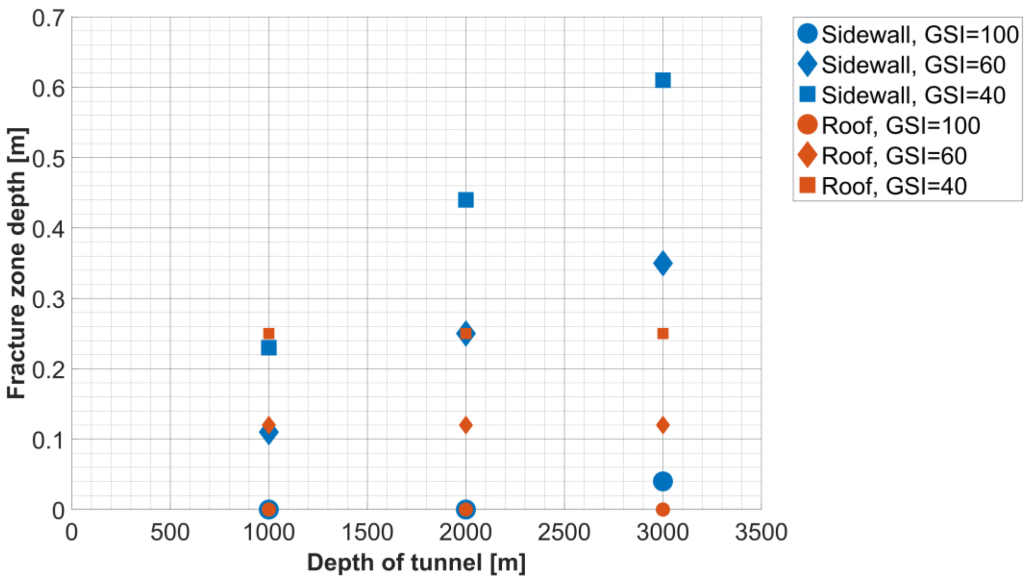


Figure 5: Fracture zone depths near a circular tunnel for varying depths and rock mass properties

The example of fracturing in the vicinity of an isolated tunnel (Figure 5) is simple, but it shows the increasing relevance of rock pressure with depth. The fracture zones need to be supported to maintain safe working conditions.

On a general perspective fracturing near small infrastructure excavations is mostly of rather local extent. Contrary, fracture zones in the surroundings of larger excavations, such as stopes, or extraction areas can be of larger and sometimes even regional extent. Again, the intensity and extent of fracturing increase with depth. Obviously, stress magnitudes rise in structural elements, for example pillars, with increasing depth as well. Thus, fracturing and the likelihood of failure of these structural elements increase.

In summary, rock stresses and stress related rock mass fracture start to occur at certain depths. The severity of fracturing increases with depth. The shape and size of the excavation, the type and size of the structural element or the size and extent of extraction areas as well as the magnitude and orientation of primary stresses and prevailing rock and rock mass conditions are important parameters for fracture processes. From a mine design point of view a central aspect is:

- How to control the increasing stress magnitudes, occurring fracture zones and the increasing extent of fracture zones?

2.2.3 Energy changes and energy release

Rock mass stores elastic strain energy. The creation of excavation causes changes in the stored elastic strain energy. Salamon (1984) provides a detailed, generalized description of these energy changes for an elastic rock mass. Salamon shows as well that as a result of these energy changes excess energy is present and released, which he refers to as released energy. The released energy is then either transformed to kinetic energy in form of seismic waves or consumed in rock mass fracturing, sliding along discontinuities or other non-elastic processes. The amount of released energy depends on several parameters, which comprise the prevailing geological conditions, the stored strain energy in the rock mass, the stress and deformation changes resulting from creating the excavation or from increasing the size of an existing excavation and the utilized regional support systems. (Salamon, 1983a) The amount of released energy resulting from creating or enlarging an excavation can be related to the volume of rock mass, which is thereby extracted. The resulting quantity is then referred to as energy release rate.

Energy changes and energy release rates resulting from creating or enlarging excavations have been studied in detail for deep tabular excavations. Correlations between energy release rates and conditions in stopes, mining-induced seismicity and rock bursts were developed and utilized in the design of deep tabular stopes. (e.g. Cook et al. (1966), COMRO (1977), Heunis (1980), Dempster et al. (1983)) These correlations show in general that the conditions in stopes, the experienced mining-induced seismicity and the number and severity of rock bursts increase with increasing energy release rate. The energy release rate (ERR) for a deep horizontal tabular stope with width (W_{ts}) and an infinitely long span, which is enlarged in incremental steps, can be calculated after Equation 6 (Wagner, 1975). An infinitely long span implies that total closure was achieved and that primary stress magnitudes are transferred through the totally closed areas again. Equation 6 shows that the energy release rate depends in this case solely on the stope width and the primary vertical stress (σ_{vp}). For the constant stope width of 1 m and a primary vertical stress gradient of 27 MPa/1000m the energy release rate at depths of 1000 m, 2000 m, 3000 m and 4000 m is 27 MJ/m², 54 MJ/m², 71 MJ/m² and 108 MJ/m², respectively. Accordingly, the energy release rate increases with increasing depth. Hence, the stope conditions become poorer and the number and severity of rock bursts increase with depths. The control of energy release rates is therefore critical for a successful mineral extraction at great depth.

$$ERR = W_{ts} * \sigma_{vp}$$

Equation 6

The energy release rate is associated with some disadvantages, namely it does not consider inelastic processes, which could reduce the energy release rate significantly, (Napier (1991), Malan and Jooste (2019)) and it cannot describe the energy release, which results from unstable failure mechanisms in the rock mass or along distinct structures. Moreover, relations between the energy release rate and stope conditions or the number and severity of rock bursts, which have proven to be a powerful design tool in deep South African gold mines, are not available for other mining situations. Accordingly, such relations should be developed in future.

Besides the creation and enlargement of excavations energy can also be released by unstable failure mechanisms, such as slip along faults or pillar bursting. Mining experience shows that shear rupture of rock mass, slip along structures as well as violent pillar failures can release considerable amounts of energy and cause associated large seismic events and rock bursts. (Gay et al. (1984), McGarr et al. (1989), Lenhardt (1992), Malovichko et al. (2012), Morissette et al. (2017a)) These types of seismic events are generally triggered by unstable failures and they impose a considerable damage potential. The occurrence of such an unstable failure depends on the local, site-specific conditions as well as on the mine layout and mining sequence. However, such an unstable failure becomes principally more likely with increasing depth due to the higher primary stress magnitudes.

In summary, energy changes and the associated occurrence of mining-induced seismicity become increasingly relevant in deep mining conditions. The actual amount of released seismic energy and the severity of rock bursting depend strongly on the local, site-specific mining environment as well as on the mine layout and mining sequence. However, the amount of released seismic energy and the severity of rock bursting increase principally with increasing mining depths. Thus, from a mine design point of view a central aspect is:

- How to control energy changes, energy release and corresponding mining-induced seismicity and rock bursting?

2.2.4 Influence of excavation size and spatial extent of mining

In the previous sections, stress and energy changes resulting from mining activities were highlighted briefly. Zones of high stress and low stress are formed near excavations and energy changes result in the release of energy and associated mining-induced seismicity and rock bursting. A critical aspect therein is the spatial extent of these changes. Localized and restricted changes and effects are less important than regional, mine-wide ones. For this, a central point is the size of excavations and the spatial extent of mining, which point is demonstrated on basis of simple examples in the following. In every example, only the excavation size and extent of mining are varied, other parameters are constant.

The spatial extent of stress changes around an excavation can be illustrated with an infinitely long, horizontal circular excavation of varying diameter. Resultant stresses are determined with Kirsch equations. Tunnel diameters (d_{tunnel}) of 4 m, 10 m, 30 m and 60 m are considered. The tunnel with 4 m diameter represents a typical mine tunnel, the tunnel with 10 m diameter represents a larger infrastructure excavation or a single, small stope and the tunnels with 30 m and 60 m diameter, respectively, represent the (total) extraction of larger stopes, mining panels or even sections of an ore body. Describing stopes, panels or sections of an ore body with an infinitely long circular tunnel is in most instances a broad simplification, because the ore bodies have rarely a circular shape and particularly rarely a large extension in direction of their long axis. However, for the present purpose of showing the influence of the consequences of the spatial extent of mining this simplification is reasonable, because it eliminates most variables and thus allows to focus on the size of excavations, stopes or mining panels. Figure 6 shows the resultant tangential (σ_{tan}) and radial stress (σ_{rad}) distribution according to Kirsch equations along a horizontal line in the tunnel sidewall for considered tunnel diameters at a depth of 2000 m. Primary stresses are taken from Table 1, whereas the considered primary horizontal stress magnitudes are again the mean of the outlined minimum and maximum primary horizontal stress magnitudes. Whilst the absolute resultant stress magnitudes remain the same for all tunnel dimensions, the spatial extent of stress changes increases drastically with increasing excavation size. Following conclusions can be drawn from this observation:

- The size of a potential rock mass fracture zone increases with excavation size. This has first an impact on the stability of the excavation itself. Ground support capacity must increase. For larger excavations such as mining panels, ground support is most likely not effective and regional support systems, such as pillars or backfill, must be used or the excavations is allowed to cave. Second, rock mass properties are altered over larger areas due to fracture processes. This could have an impact on other excavations or structural elements, such as pillars, which are created within this zone.
- The stress situation at the position of excavations or structural elements, which are situated in the surroundings, is influenced stronger with increasing excavation size. The reason therefore is that the stress gradients are lower and thus that primary stress magnitudes are reached at larger distances from the excavation. This influence could be either positive, if a stress state promoting stability is generated, or negative, if a stress state promoting instability is generated. Moreover, the influence of large excavations could be felt quite far away. Accordingly, extraction areas are decisive for the regional, mine-wide stress changes, whilst the influence of infrastructure excavations is principally of local nature.

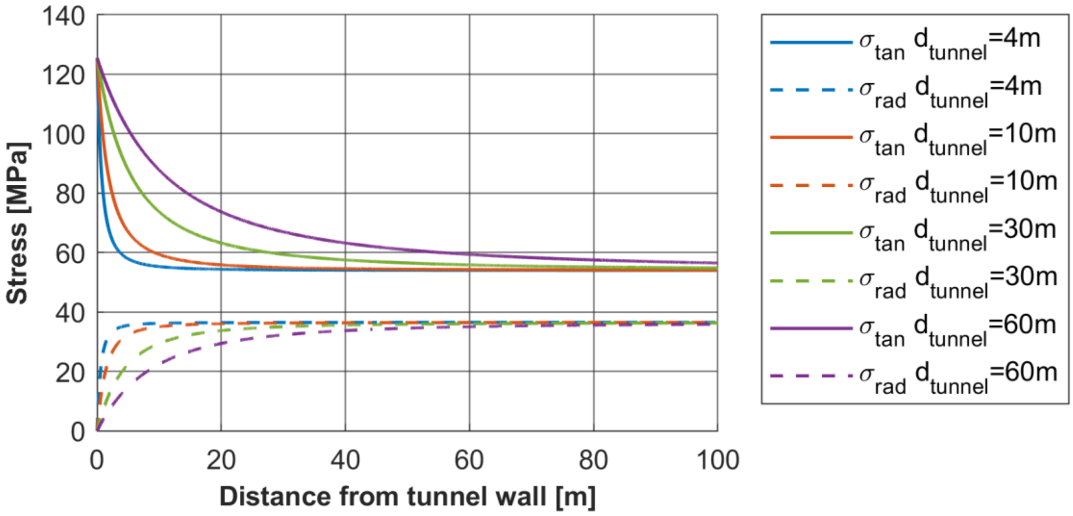


Figure 6: Resultant tangential and radial stress distributions along a horizontal line in the sidewall of an infinitely long circular tunnel of varying diameter

The size of excavations and the spatial extent of mining influence the energy release and associated mining-induced seismicity as well. The energy changes in the rock mass as a result of mining activities increase with increasing disturbances to the rock mass and primary stress field. The larger the size of excavations and the larger the spatial extent of mine workings, the larger are these disturbances. The energy release increases as well with increasing disturbances and hence increasing excavation sizes and spatial extent of mining. However, the increase of the energy release may differ from the overall increasing energy changes. The reason for this is that fracture zones near excavations, which absorb energy due to creation of fractures, increases with increasing size and spatial extent of mining. Besides the amount of energy release the excavation size and spatial extent of mining have an impact on mining-induced seismicity resulting from unstable failure along large geological structures or unstable pillar failure. Larger excavations, cause larger spatial disturbances to the stress field. Accordingly, a larger volume of rock mass, where unstable failure along structures or unstable failure of pillars could be triggered, is present. Moreover, geological structures could further be activated over larger areas.

The regional degree of extraction is another important aspect to consider regarding the spatial extent of mining. As mining progresses, the unmined portions of an ore body become smaller and stress magnitudes start to significantly increase in unmined portions, which are considerably stiffer than the mined-out areas. At a late stage of mining the only ore left is usually situated in remnants, which are usually highly stressed. Mining experience highlights that extraction normally becomes more difficult from a rock mechanics perspective in maturing mines or maturing panels of a mine. The extraction of remnants, such as shaft pillars or crown pillars, is often rather challenging and problematic and accompanied with high stresses and significant seismic energy release. (Simser (2005), Kempin et al. (2007), Murphy (2012), Townend and Sampson-Forsythe (2014), Masethe et al. (2019))

In summary, the size of excavations and the spatial extent of mining have a considerable impact. Based on simple examples focusing on most relevant, general effects, it can further be concluded that these effects become increasingly important with depth, because stress and energy changes become more relevant with depth. However, it is mentioned that the actual effects depend strongly on site-specific conditions and the mine layout and mining sequence. Not all regional effects were shown here, but they will be examined and discussed in subsequent chapters. Concluding, the regional effects of mining on the stress situation and on the energy release are critical. Thus, from a mine design point of view a central aspect is:

- How to control regional stress and energy changes and their associated effects?

2.2.5 Regional stability, stress transfer and energy release control

Underground mines are complex structures. Different types of infrastructure excavations, extraction excavations and structural elements are required for extraction. Infrastructure comprises tunnels, drifts, drives, shafts, raises, cross-cuts or caverns, extraction excavations are voids of varying shape and size and they are for example cut-and-fill stopes, open stopes or caving stopes and structural elements are required for maintaining the stability of the mine and include amongst others different kind of pillars (e.g. crush pillars, stabilizing pillars or bracket pillars), the immediate roof and floor strata, loading systems, abutments, pillar foundations, backfilled areas or caved areas. By nature, mining is a dynamic process and thus mine workings are constantly extended and the size of areas under extraction and extracted areas increases. From a rock mechanics point of view these dynamic aspects provoke on the one hand that the stress situation is continuously modified and on the other hand that structural elements are created, changed, altered or removed or that these elements deteriorate and eventually may fail and lose their considered function. Moreover, the extent and magnitudes of stress changes become usually more pronounced in an advanced stage of extraction in a particular area. The mining sequence governs these aspects related to the continuous change of the stress situation. Accordingly, an appropriate sequence is decisive for success.

The ongoing regional stress and energy changes during extraction must be controlled and the overall structural integrity and stability of the mine ensured. Key issues are:

1. the distribution and transfer of far-field stresses through the mine structure,
2. the structural elements undertaking this regional stress transfer,
3. the stabilization of individual active extraction areas (mining panels),
4. the structural elements ensuring the stability of active extraction areas,
5. the amount and spatial and temporal position of energy release and
6. the regional mining sequence.

Figure 7 provides an illustrative sketch of outlined key issues. The first two points aim on the overall stability of the mine and must be considered throughout the lifetime of a mine. A faulty or failing overall stress transfer and stability concept would put the (further) extraction in the affected parts of the mine or the complete mine at considerable risk. The third and fourth points focus on the stability of individual active extraction areas, which must be ensured as long as extraction is ongoing in these areas. An inappropriate design of extraction areas may cause instability or failure of individual areas. However, the overall structural integrity and stability of the mine shall be designed such that it is not affected by unstable or failing extraction areas. An illustrative example for the latter circumstance are room and pillar mining operations. Individual mining panels are supported by panel pillars. These panel pillars in combination with the (immediate) roof and floor strata are the critical structural elements for providing the stability of individual panels. Neighboring mining panels are usually separated by larger interpanel or barrier pillars. In contrast to panel pillars are these interpanel or barrier pillars considerably stronger. Their main task is to constrain panel pillar failures and associated instabilities to individual panels. Thereby the collapse of large areas of the mine is prevented. Accordingly, interpanel and barrier pillar are central structural elements for the overall integrity of the mine. An infamous example for the lack of such structural elements ensuring the overall stability of the mine is the Coalbrook accident. Panel pillars started to fail in an experimental section of the mine, which caused the subsequent failure of thousands of pillars within less than one hour resulting in more than 400 fatalities. (van der Merwe, 2006) Barrier pillars were not used and thus the panel pillar failure and collapse could spread rapidly. As a consequence of the Coalbrook accident barrier pillars were introduced on a general basis to provide regional support. (Wagner, 1980) The fifth point becomes especially important in rock burst prone mining conditions. Rock bursts are defined as that subset of seismic events that could cause significant damage to infrastructure, extraction areas and structural elements being relevant for the overall integrity of the mine. Approaches against rock bursts are to reduce the number of seismic events, to decrease the kinetic energy content of events, to reduce the number of seismic events becoming rock bursts and to minimize the damage resulting from rock bursts. (Salamon, 1983a) Finally, the sixth point, the regional mining sequence, has a strong influence on the regional stress distribution and the released seismic energy over time, on the formation and performance of critical structural elements as well as on the creation of remnants. The infrastructure itself is not considered a key issue for controlling regional stress and energy changes. The reason is that infrastructure has in general only a rather localized effect compared to extraction areas. However, infrastructure may be severely affected by regional stress and energy changes resulting from extraction areas.

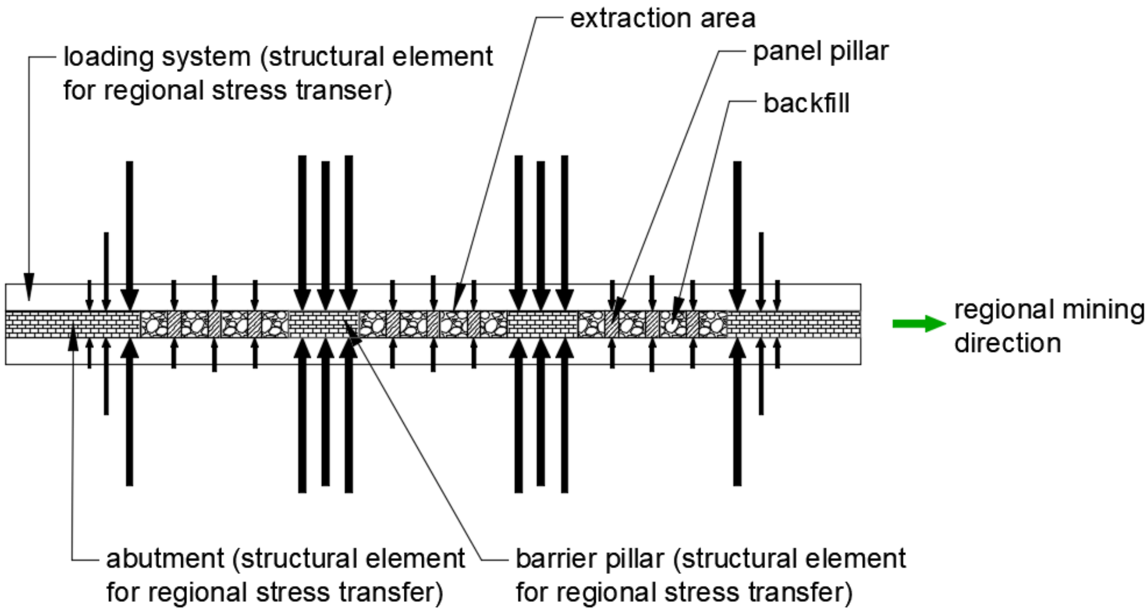


Figure 7: Schematic representation of extraction areas with panel pillars and backfill, barrier pillars and regional stress flow. Bolt black arrows indicate the loads on pillars and abutments and thereby indicate the regional stress flow through the mine. Thin arrows indicate that pillars inside extraction areas transfer only rather small loads. The filled green arrow to the right outlines the regional mining direction.

From a rock mechanics mine design point of view three general approaches for providing overall stability of the mine and stability of individual extraction areas can be distinguished, namely naturally supported, artificially supported and caving. Underground mining methods are also commonly grouped according to latter approaches. (Hartman and Mutmansky, 2002) In the first approach pillars take over the central role in transferring stresses and maintaining stability. In the second approach, backfill is central for providing stability, especially inside extraction areas. Within extraction areas backfill is often combined at least temporarily with pillars. Moreover, depending on the mining method and mine layout backfill may also take part to some extent in stress transfer, after backfill was compressed sufficiently. However, due to the soft properties of backfill regional stress transfer in the mine is usually carried out by stiffer elements, namely abutments and intact pillars; compare for example Varden and Esterhuizen (2012) or Jalbout and Simser (2014). A regional stress transfer to abutments implies that stresses are diverted around extracted areas. In the third approach, large volumes of rock mass are allowed to cave in a controlled manner. The objective of caving is to fill and close mined-out areas and in certain mining methods also to fragment the in-situ rock mass for subsequent extraction. In general, caving assists in ensuring the regional mine stability, which is similar to the backfill approach realized by intact pillars and abutments. Caving removes at least some of the stresses from abutments and pillars in certain situations; see for example Butcher (1999) or Trueman et al. (2002). The weight of the caved masses is transferred through the caved area and induces stresses in the rock mass below the caved area. Thereby the load on abutments and pillars providing regional stability is reduced. This load reduction from caving is most pronounced in vertical direction and after caving progressed to considerable heights compared to the depth of the extraction area. In horizontal direction the load reduction resulting from caving in abutments of caved areas is usually of considerably smaller extent, because caving does in general not affect the far-field horizontal stress state. Hence, the horizontal stress magnitudes in the abutments, in particular the lower abutment, of the cave can be considerably high. Besides removing some of the weight caved areas could also participate comparable to backfill in the regional stress transfer, after they were sufficiently compressed.

The composition of the hangingwall is further important for the overall stability in all three approaches (naturally supported, artificially supported, caving). The hangingwall takes over an integral role in the regional stress transfer and stress distribution. Weak, friable hangingwall can usually not bridge large distances, which limits stress transfer to abutments. Hence, higher stress magnitudes must be transferred through extraction areas. Moreover, weak hangingwall promotes caving and thus the caving approach. In contrast, strong competent hangingwall can bridge large distances. Stresses are transferred to abutments and extraction areas experience lower stresses. Another circumstance is that strong hangingwall does usually not cave easily. From a regional stability perspective strong competent hangingwall requires particular attention, namely the loss of the bridging capability can result in a significant (often unexpected) load increase in extraction areas, and the poor caveability of strong hangingwall requires large areas to be undercut, before caving can commence. Furthermore, it can cause a stall of or restrict cave progression, which can be associated with considerable operational and safety hazards. Unfortunately, there were some accidents caused due to latter aspects related to strong, competent hangingwall in the past, for example Coalbrook (van der Merwe, 2006) or Northparkes (Hebblewhite, 2003).

The foregoing discussion highlights that pillars and abutments surrounding extracted areas are critical structural elements in all of the outlined approaches for providing overall stability of the mine and for regional stress transfer through the mine. This circumstance has some particular implications, as mining depth increases. Rising primary stresses cause increasing loads on pillars and abutments. Consequently, the size of these regional pillars has to be increased that pillars can withstand rising stress levels. The extraction ratio drops accordingly. Furthermore, potentially higher abutment and pillar stress magnitudes result in more difficult mining conditions and larger amounts of mining-induced seismicity, if extraction advances in these areas. In conclusion, considerations made in this section highlight the central aspect:

- How to ensure regional stability and stress transfer and how to control energy release whilst enabling an acceptable extraction ratio and whilst providing acceptable mining conditions?

2.3 Necessity for stress management

The last sections showed that rock mechanics issues become increasingly important at great depths. Larger fracture zones and higher energy release and associated mining-induced seismicity have to be expected. Providing regional stability and controlling the flow of stresses through the mine are further relevant points. The occurrence and severity of rock pressure phenomena or rock pressure problems could therefore rise significantly. Rock pressure phenomena or rock pressure problems could manifest themselves for example in localized, manageable fracture zones and instabilities near extraction drifts, in severe instabilities and loss of mining sections or in damage and loss of critical, vital infrastructure. Chapter 3 outlines rock pressure phenomena and rock pressure problems related to the objectives of the present work further. Rock mechanics issues at great depths necessitate an appropriate stress management to mitigate consequences of or better to prevent rock pressure problems.

2.3.1 Objectives of stress management

Stress management has to address rock pressure in a systematic and strategic way. Objectives are:

1. to control the prevailing stress and energy situation and thereby to eliminate the source of rock pressure problems,
2. to provide as far possible a favorable stress situation for infrastructure or extraction excavations and
3. to manage the consequences of high stresses and energy release.

The first point aims on preventing situations, which could result in considerable rock pressure problems. Examples are highly stressed zones near active extraction areas or active infrastructure or the release of considerable amount of seismic energy. The second point aims on generating a stress situation, which facilitates and improves the stability. Examples are the creation of de-stressed zones or the limitation of abutment stress magnitudes. Accordingly, the safety is improved and a better productivity should be achieved. The third point aims on handling possible consequences of high stresses and mining-induced seismicity. Indeed, a proper stress management concept aims on constraining and concentrating high stress zones to mined-out and abandoned areas or on releasing seismic energy distant from active mining areas and active infrastructure.

The implementation of stress management in practice is a challenging and demanding task, which must be an integral part of the mine design and of the ongoing operation. In order to assist mines in the implementation of an appropriate stress management the South African Department of Minerals and Energy published a guideline for the implementation of a mandatory code of practice against rock falls and rock bursts. (DME, 2002) Part of this guideline is the establishment of a Rock Engineering Support Service (RESS). The RESS is a person, which is competent in the field of rock engineering. The role of the RESS is *"to assist the employer in ensuring that rock mechanics and strata control principles for the safe and economic design of mine workings are applied"*. (DME, 2002) Further, the RESS should assist in the identification of rock-related risks and provide advice on appropriate measures addressing them. Therefore, the RESS must provide following basic supportive roles, functions and contributions (DME, 2002):

- *"Participate in planning activities in order to identify and evaluate all layouts and face positions to determine any potentially dangerous or damaging situations created by, or likely to be created by, mining operations."*

- *“Review, identify and make recommendations to management with regard to systems, procedures and techniques employed by the mine to reduce or eliminate rock fall and rock burst hazards.”*
- *“Establish an efficacious monitoring, recording and reporting systems, which will ensure that relevant information is timeously provided to the correct people in planning and operating functions.”*

Due to the dominant role of rock mechanics for a successful stress management, specific and advanced skills and knowledge in rock mechanics and rock engineering are required. Skills and knowledge must be present at different levels, namely:

- <u>Operation level:</u> This level concerns the mines directly. Mines are responsible that the stress management is implemented in practice appropriately. Therefore, they must provide the relevant mine design capabilities as well as suitable structures that the mining personnel follows and adheres to the design and that mining experience is fed back into the design. Mines may be assisted by specialized consultants or experts in this task.
- <u>Authority level:</u> The role of authorities is to review and approve the mine design before its implementation and to survey ongoing mining activities particularly in respect to safety. For this reason, authorities take over a very important and responsible task. Authorities examine, whether stress management is appropriate in the design or in the ongoing operation, and they can call for adaptations and changes, where stress management is insufficient. Similar to mines, authorities can also call for assistance of specialized consultants or experts.
- <u>Research and development level:</u> Deep mining conditions and the associated stress management is often entering novel ground or areas, where limited experience and knowledge are available. Therefore, there is a constant demand of generating and enhancing knowledge and of developing and improving tools, practices, methods, machineries etc. These aspects must be addressed by research and development groups. It is of paramount importance that these groups work closely together with mines and authorities. A close collaboration ensures that critical areas are identified properly, which enables a targeted, focused approach, and that knowledge, developments and experience are shared and discussed directly. Moreover, it facilitates the implementation of new developments and improvements as well as the evaluation and review of their effectiveness. Overall, all parties benefit from a close collaboration considerably. Research and development is usually taken over by specialized institutions, such as universities or research centers, or by internal groups in mining companies. For a successful research and development a long-term strategy is highly recommended, as it enables to build up and keep the required, high-level research and development structures in terms of personnel, expertise, equipment and facilities.
- <u>Education level:</u> Finally, a high-level education is crucial for all of the above outlined levels, roles and responsibilities. The education addresses both the initial training before entering a specific role as well as the ongoing training of personnel already working in a specific role. Moreover, it is important that personnel working at different levels and positions is trained properly and equipped with the necessary skills, which

vary from position to position, in the field of rock mechanics and rock engineering. Education is often provided by universities or other specialized institutions. However, the role of mines for training, particularly for operational personnel working underground, should not be underestimated. Similar to research and development, a sufficient expertise and experience must be present and maintained at the education level to guarantee an appropriate education and training.

Despite the importance of rock mechanics and rock engineering in deep mining there has been a constant decline of expertise, capabilities and output at the research and development and education level for several years or even decades. Reasons therefore are manifold and comprise a decline of research, development and education institutions and departments, a reduced attractiveness to work in research, development and education, a reduced governmental funding and a reduced willingness of the mining industry to invest in long-term strategic research, development and education. These circumstances aggravate encountered problems and challenges in deep mining particularly on a long run. They have been widely recognized. (Stacey et al. (2008), Hebblewhite and Knights (2011), Riemer and Durrheim (2012), Durrheim (2014), McKinnon and Ferguson (2018), Stacey (2019b), Wagner (2019)) In order to address decreasing knowledge and skills in the field of rock mechanics and rock engineering the EIT RawMaterials supported the establishment of a rock engineering training program specialized on deep mining. The program is called "SafeDeepMining" and addresses personnel working in the deep European mining industry. (Wagner (2019), Sifferlinger et al. (2021))

2.3.2 Consequences of an improper stress management

Improper stress management can result in difficult mining and ground conditions or it can cause serious rock pressure problems, such as excessive damage to mining infrastructure or frequent occurrence of rock bursts. All are issues, which typically occur in a deep mining situation and which increase in intensity with mining depth. For this reason, the consequences of an improper stress management can be highlighted on basis of the transition depth from shallow to deep mining conditions.

The transition depth to deep mining conditions for primary stress conditions was discussed in section 2.2.1. Figure 3 outlines the transition depths for typical rock mass strengths and primary stress situations. Three typical mining situations are outlined to highlight the consequences of an improper stress management on the transition depth. Following situations are considered:

- A sublevel stoping situation, where mining takes place adjacent to a sill pillar separating two stoping panels at an advanced stage of extraction
- A block caving situation during undercutting
- A sublevel caving situation with ongoing extraction towards greater depths

All of these situations are known to be problematic from a rock pressure point of view. Encountered rock mechanical difficulties are reported for example by Hudyma et al. (1994), Yao et al. (2009), Varden and Esterhuizen (2012), Jalbout and Simser (2014) and Turcotte (2014) for sill pillars in sublevel stoping, by Araneda and Sougarret (2008), Gomes et al.

(2016), Campbell et al. (2020) and Holder et al. (2020) for undercutting in block caving and by Dahnér et al. (2012), Esterhuizen (2018), Hopkins et al. (2018) and Woods et al. (2018) for ongoing extraction in sublevel caving.

The transition depth to deep mining conditions is again determined by means of the RCF criterion, wherein an RCF larger than 0.9 marks deep mining conditions; compare section 2.2.1. For rock mass strengths uniaxial compressive strengths of rock (σ_{UCS}) of 70 MPa, 150 MPa and 230 MPa and a degradation factor F of 0.75 are considered. These rock mass strengths represent a weak, a medium and a high strength rock mass, respectively. The stress situation near mined-out areas is determined by two-dimensional, linear elastic numerical simulations with FLAC (Itasca, 2016). The Young's modulus of the rock mass is 40 GPa and the Poisson ratio is 0.2. The elastic properties are the same in all models. Stress gradients are not considered in the sublevel stoping and block caving model and thus the primary stress state is constant. In contrast, stress gradients are considered in the sublevel caving model and hence the vertical and horizontal primary stresses increase with depth. In all models the excavations are removed at once. The mining geometries are shown in Figure 8.

- Sublevel stoping is represented by a vertical cross-section perpendicular to the strike extension (out-of-plane extension) of the mining panels. Two vertical mining panels, 210 m and 180 m, respectively, high and 30 m wide were mined. A 30 m by 30 m sill pillar is left between the panels. The lower panel was mined in a bottom-up sequence and the sill pillar is going to be extracted. The stress situation at a drift in striking direction, which is situated 15 m into the footwall and at the elevation of the current top of the lower panel, is taken for the determination of the transition depth. The position and orientation of this drift represent a commonly used access drift for stopes in sublevel stoping.
- Undercutting in block caving is represented by a horizontal undercut, which has a horizontal extension of 100 m and a vertical extension of 10 m. The stress condition at the position of a drift, which is 15 m ahead and 20 m below the undercut, is used for the determination of the transition depth. This drift location represents a typical drift at the production level in an advance- or post-undercutting strategy. It must though be considered that the isolated drift underestimates the stress situation, because the production level comprises several, closely spaced drifts, for what the stresses increase further. The rather small pillars between adjacent drifts are moreover often subjected to significant damage.
- Sublevel caving is represented in a rather simplified way by a vertical tabular slot. The vertical tabular slot begins on top of the model so that all horizontal stresses must pass below the slot. Up to a depth of 400 m the slot height is extended in the model and corresponds to the depth below surface. Below 400 m depth the slot height is fixed at 400 m to maintain a reasonable model size. Instead a vertical load is applied on top of the model to account for the actual mining depth. The actual mining depth is considered in the horizontal stress gradient as well. Limiting the slot height in the sublevel caving models with 400 m underestimates the stress situation at the drift position below 400 m. The drift is positioned 25 m below the mined-out area and 10 m into the footwall. This drift represents a typical access drift in striking direction in sublevel caving.

The used models are associated with some simplifications. All models are two-dimensional, and the excavations are considered to be infinitely long. Thus, the influence of the third dimension on the stress situation, which improves the stress situation for comparatively small out-of-plane extensions of the considered excavations, is not accounted for. The sublevel caving geometry is simplified strongly. Caving of the hangingwall would change the geometry significantly. However, the used geometry maintains the important characteristic of sublevel caving, namely that all far-field horizontal stresses must pass below the mined-out area. Furthermore, rock mass fracturing and yielding, which could change the stress distribution significantly at the considered drift positions, is not taken into account in all three situations. However, rock mass fracturing could also have a negative effect on the drift stability, if it occurs near the considered drift position. Finally, a possible effect of backfill or caved rock mass is not considered in all models.

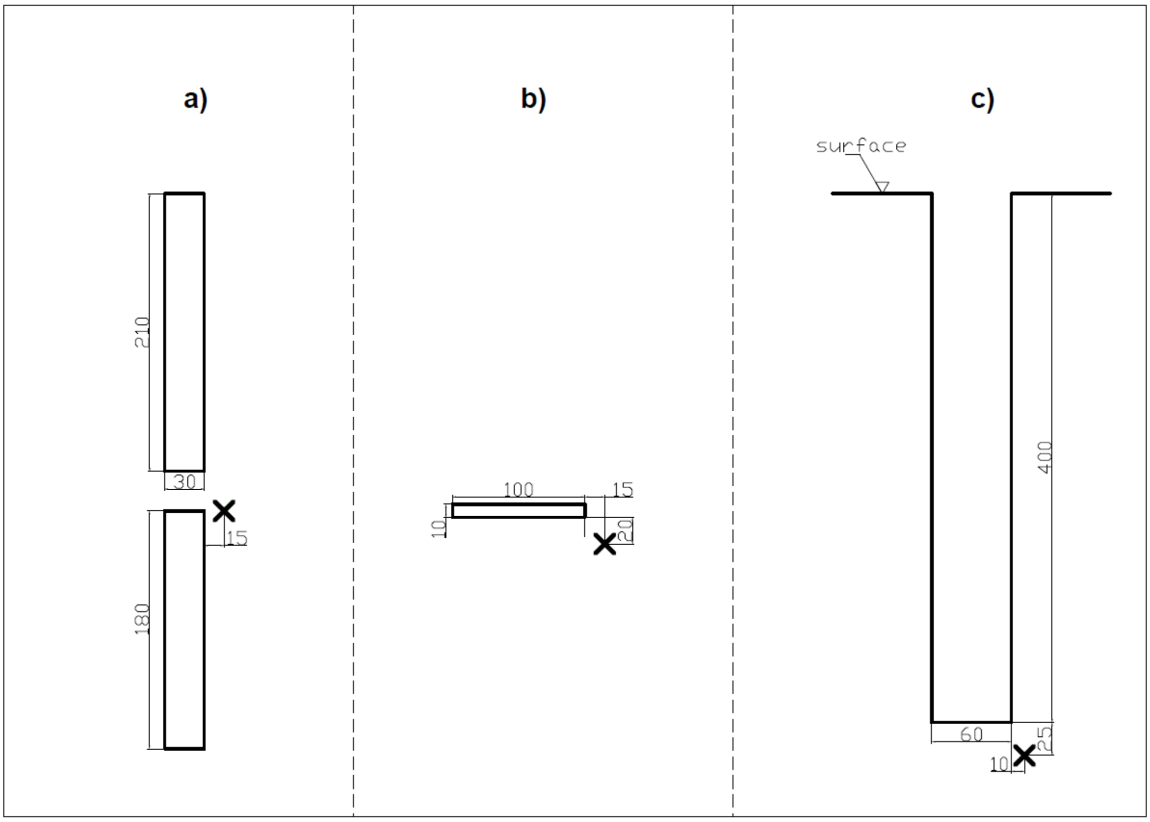


Figure 8: Considered mining geometries for (a) sublevel stoping, (b) block caving and (c) sublevel caving. The position of the considered drift is shown as “x”. All dimensions are in meter.

Despite the mentioned simplifications these simple, basic models highlight the consequences of improper stress management on the transition depth to deep mining conditions. For the determination of the transition depth, the model depth and thus the primary vertical stresses are increased in steps of 200 m and the primary stress gradient is 27 MPa/1000m. The typical range of primary horizontal stresses is considered in each model; compare Figure 1. The ratio of the primary horizontal stresses to primary vertical stresses is taken as 0.3, 0.5 and then in successive steps of 0.5. The maximum and minimum in-plane principal stresses at the considered drift positions are then derived in the numerical simulation. The RCF ate each drift position is calculated for each model run.

Afterwards the depth corresponding to an RCF of 0.9, which marks the transition to deep mining conditions, is determined by interpolation.

Figure 9 to Figure 11 show the transition depths to deep mining conditions for considered mining situations and rock mass strengths. The transition depth to deep mining conditions without the influence of mined-out areas is shown as well. Following conclusions can be drawn:

- The considered mining situations have a considerable impact on the transition depth.
- For the sublevel stoping and sublevel caving situation the transition depth decreases drastically with increasing ratios of primary horizontal to primary vertical stresses. The decrease is more pronounced for the sublevel caving situation, because all far-field horizontal stresses must pass below the mined-out area, where the drift is situated. For a ratio of primary horizontal to primary vertical stresses larger than 1.5 the transition depth is below 500 m even for a high strength rock mass. The reason for the strong effect of primary horizontal stresses is that the stress state at the considered drift position in sublevel stoping and sublevel caving is dominated by the primary horizontal stress.
- For block caving the transition depth decreases for ratios of primary horizontal to primary vertical stresses below 1 to 1.5 significantly. For stress ratios larger than 1 to 1.5, the transition depth even increases and is slightly deeper than the transition depth resulting from primary stresses. The reason therefore is that the larger primary horizontal stresses counteract the increased vertical stresses from undercutting and that they generate a more favorable stress state for drift stability. However, related to block caving it must be noted that although the transition depth is not affected that strongly or even slightly increased, there are some further aspects, which (could) reduce the transition depth. The production level is usually made of several closely spaced drifts and rather small pillars between drifts. These pillars are first more vulnerable to vertical stresses and second they can divert horizontal stresses away from drifts, whereby their stabilizing effect is lost. Furthermore, the undercut level drifts are subjected to even higher stress magnitudes and more unfavorable stress states than the considered production level drift.
- It is also noted that the outlined, difficult conditions are encountered in block caving and sublevel stoping mostly temporarily, either during undercutting or during mining near a sill pillar. Whereas the high stress situation in sublevel caving is permanent, because extraction takes always place below the totally mined-out area. However, also the temporal occurrence in block caving or sublevel stoping could be of major concern and could jeopardize the safe, as complete as possible and economic extraction.
- Finally, it is remarked that the outlined transition depths are strongly influenced amongst others by the chosen mine layout, the drift position and the rock mass properties. Changes of these parameters could have a strong influence on the transition depth. For this reason, transition depth studies should be individually conducted for mining sites with the prevailing conditions.

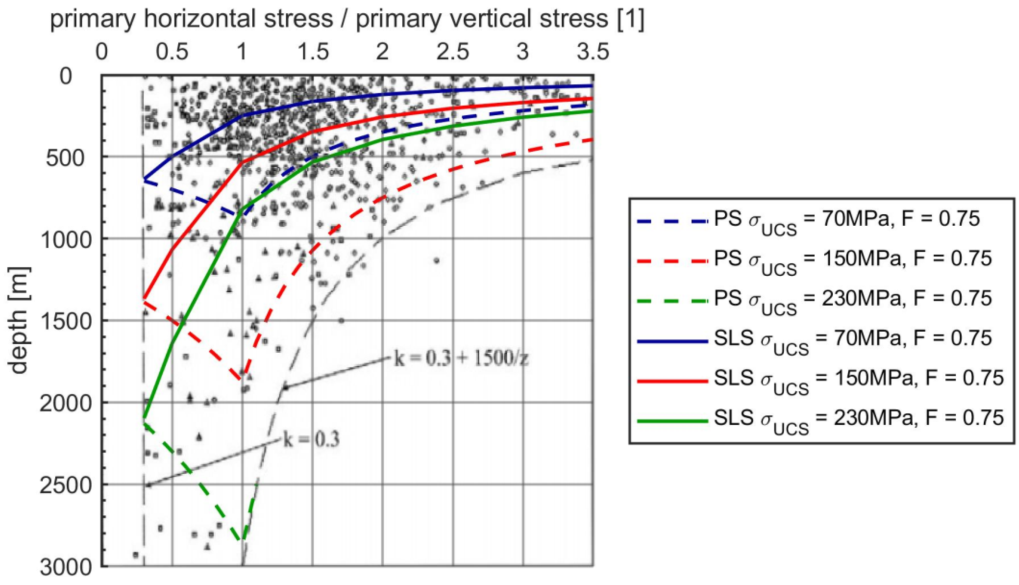


Figure 9: **Transition depths to deep mining conditions for sublevel stoping (SLS), where a sill pillar is created in a bottom-up sequence, shown as full lines. Typical rock mass strength and primary stress situations are considered. The transition depths for the primary stress state (PS) are shown as dashed lines. The figure with the range of primary horizontal to primary vertical stresses is taken from Brady and Brown (2006).**

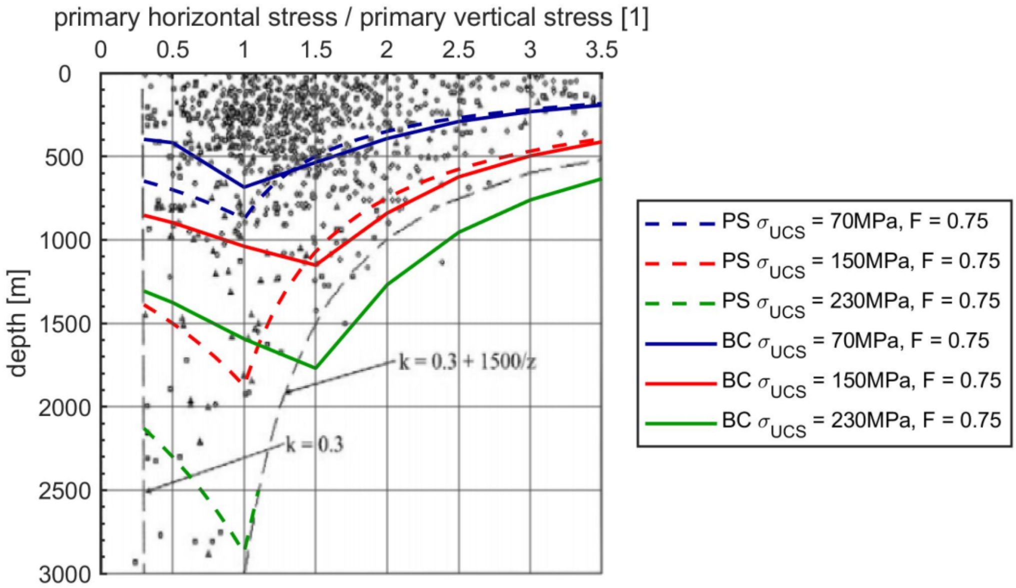


Figure 10: **Transition depths to deep mining conditions for block caving (BC) during undercutting shown as full lines. Typical rock mass strength and primary stress situations are considered. The transition depths for the primary stress state (PS) are shown as dashed lines. The figure with the range of primary horizontal to primary vertical stresses is taken from Brady and Brown (2006).**

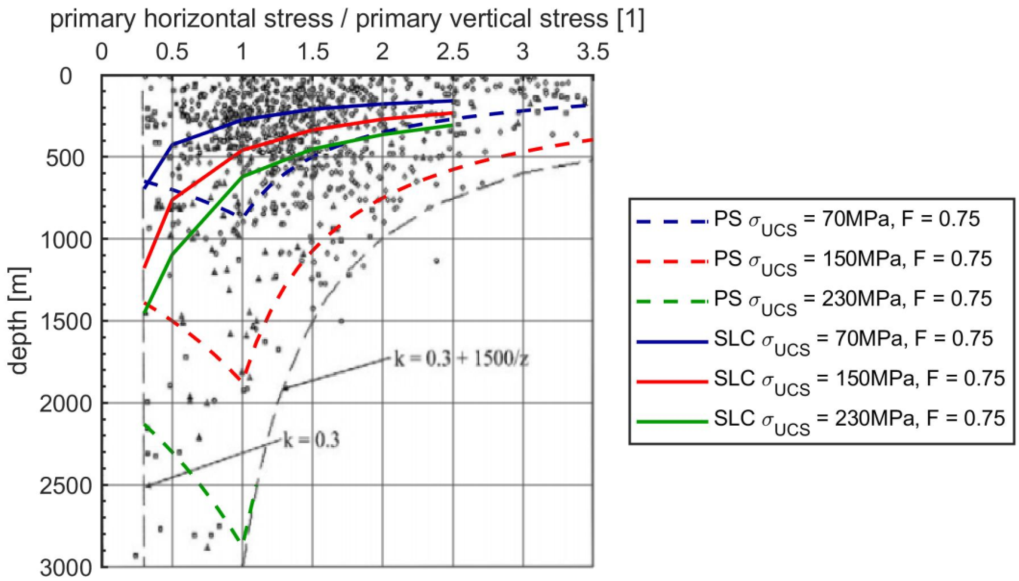


Figure 11: Transition depths to deep mining conditions for sublevel caving (SLC) for ongoing extraction shown as full lines. Typical rock mass strength and primary stress situations are considered. The transition depths for ratios of primary horizontal to primary vertical stresses larger than 2.5 are not outlined, because they are that shallow that they cannot be calculated with the studied models. The transition depths for the primary stress state (PS) are shown as dashed lines. The figure with the range of primary horizontal to primary vertical stresses is taken from Brady and Brown (2006).

The consequences that result from the investigated mining situations on the stability of the considered drifts can also be highlighted by means of the "effective mining depth". The effective mining depth is the depth, at which a drift would have to be positioned in the primary stress field, so that the condition of the drift in the considered mining situation and in the primary stress field are the same. The condition of the drift is expressed with the RCF concept. This means that the RCF of the drift in the considered mining situation is equal to the RCF of a drift in the primary stress field at the effective mining depth. Figure 12 outlines the effective mining depth for the considered drifts in the investigated sublevel stoping, block caving and sublevel caving situation at a depth of 1000 m. The conclusions are:

- The effective mining depth is in most instances larger than the actual mining depth of 1000 m. The ratio of primary horizontal to primary vertical stresses has a strong influence.
- For sublevel stoping and sublevel caving the effective mining depth increases dramatically with an increasing ratio of primary horizontal to primary vertical stresses. The effective mining depth can be up to many times larger than the actual mining depth. The reason therefore is the significant influence of horizontal stresses in these methods.
- For block caving the effective mining depth is a couple of hundred meters larger than the actual mining depth of 1000 m for ratios of primary horizontal to primary vertical stresses smaller or equal than one. At larger ratios the effective mining depth decreases and becomes eventually smaller than the actual mining depth.
- A ratio of primary horizontal stresses to primary vertical stresses larger than one decreases the effective mining depth in all situations. This influence seems to be

positive, however, the observed effect is largely related to the aspect that the drift conditions at ratios larger than one are generally poorer. Regarding block caving it is further noted that the larger ratio of primary horizontal to primary vertical stresses leads to a more favorable stress situation, because the larger primary horizontal stresses counteract the increasing vertical stresses from undercutting. However, the same considerations regarding drift stability and the influence of the ratio of primary stresses as made before apply to the block caving situation.

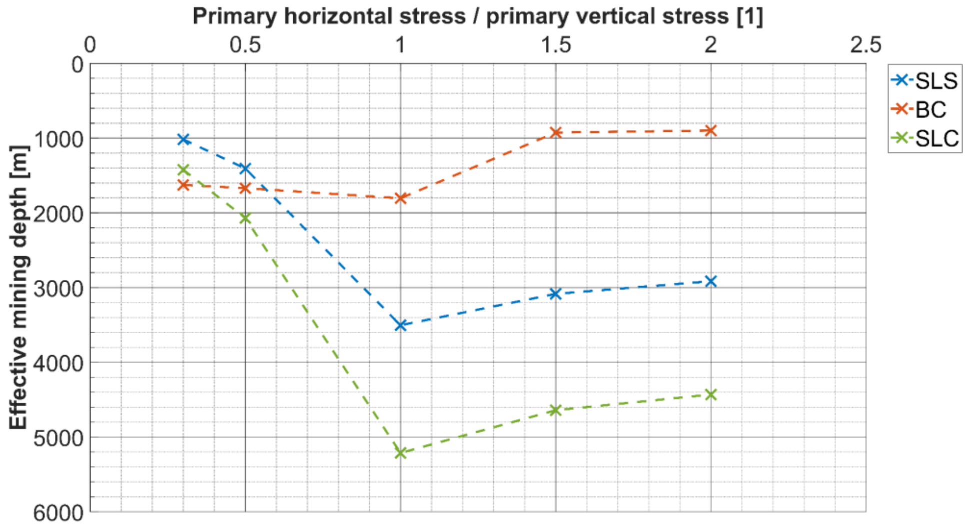


Figure 12: Effective mining depths for the considered drifts at a depth of 1000 m in the sublevel stoping (SLS), block caving (BC) and sublevel caving (SLC) situation. The effective depth is independent of the rock mass strength, but for lower strength rock masses the RCF is higher and hence the drift conditions are poorer.

In conclusion, the provided simple models outline that a deep mining situation can be artificially generated through an improper mine layout and mining sequence. Thus, rock pressure phenomena and rock pressure problems can occur at shallow depths as well and the severity and frequency of rock pressure problems can be higher than it would be expected from the primary stress situation. Accordingly, an improper stress management can create difficult and hazardous mining environments.

2.3.3 Advantages of a proper stress management

This section outlines the advantages and chances of a proper stress management based on two illustrative, simple examples. First, the protection of excavations by providing a de-stressed zone is shown. Second, the advantage of forming a highly stressed pillar behind an advancing mining face is highlighted.

2.3.3.1 De-stressing of rock mass

De-stressed zones in the rock mass of considerable extent can be established by extracting de-stressing excavations; compare section 7.3. The stress magnitudes in a de-stressed zone are either lower than primary stress magnitudes or lower than resultant stress magnitudes, which would be prevailing without the de-stressing excavation. A tabular slot is best suited to illustrate the principle and advantage of de-stresses zones. A tabular slot is an excavation with a considerable extension in two directions and a comparatively small extension in the third direction. The distribution of the major and minor principal stress near a horizontal, isolated two-dimensional tabular slot are shown in Figure 13 and Figure 14. The slot has length of 150 m and height of 1 m. The primary stresses are 54 MPa in vertical and horizontal direction corresponding to a depth of 2000 m below surface. The rock mass has a linear elastic material behavior with a Young's modulus of 40 GPa and a Poisson ratio of 0.2. The slot is unsupported and not backfilled. Total closure of the slot does not occur. Stresses are calculated with FLAC. From Figure 13 and Figure 14 it can be deduced that a zone of high stress concentration develops at the slot abutments, whilst a zone of reduced stress magnitudes, which is commonly referred to as stress shadow, develops below and above the slot. Obviously, excavations, which are placed inside the stress shadow, benefit from the provided stress reduction. In contrast, excavations situated either distant from the slot or in the slot abutments, where a stress reduction is not present or where stresses are elevated because of the slot extraction, do not benefit or are even exposed to higher stress magnitudes, respectively. The protection provided by the slot can be further highlighted with the RCF concept. Figure 15 outlines RCF factors for a tunnel situated in the vicinity of the tabular slot. The long tunnel axis is oriented out-of-plane. The uniaxial compressive strength of rock is 150 MPa and the degradation factor F is 0.75. Accordingly, a deep mining situation is present; compare Figure 3. The advantage of situating the tunnel in de-stressed ground is significant. The expected tunnel conditions improve considerably. Extensive use of tabular slots and their associated stress shadows has been made in deep South African gold mines; compare section 2.4.1.

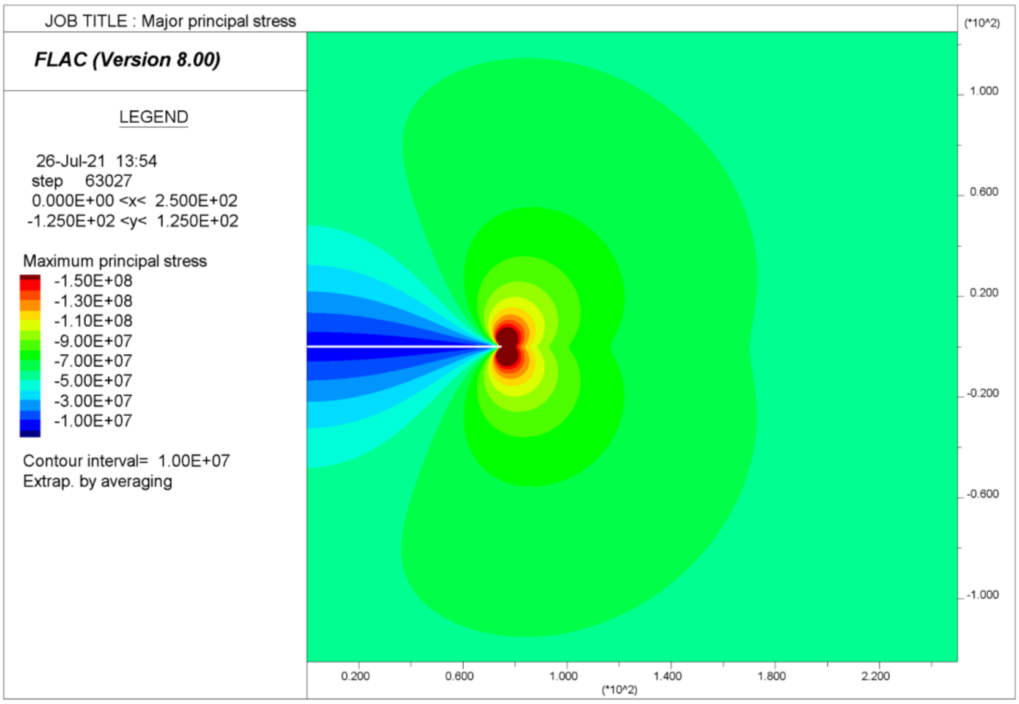


Figure 13: Resultant major principal stress redistribution near a two-dimensional tabular slot. Stress unit is pascal, compressive stresses are negative, axis unit is meter; one half of the slot is shown.

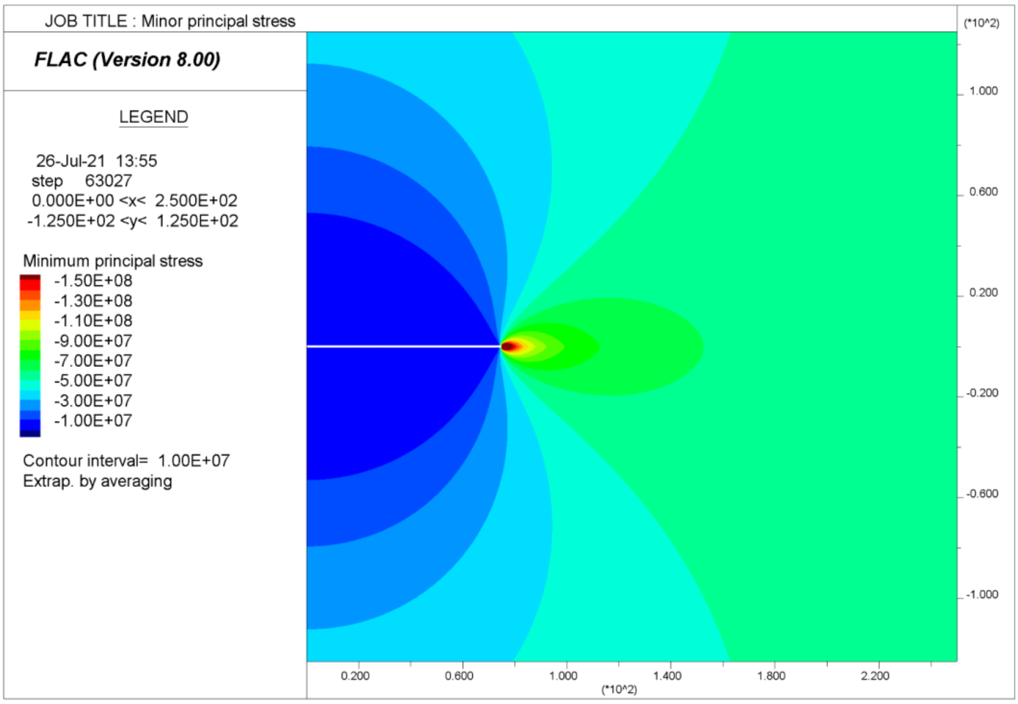


Figure 14: Resultant minor principal stress distribution near a two-dimensional tabular slot; Stress unit is pascal, compressive stresses are negative, axis unit is meter; one half of the slot is shown.

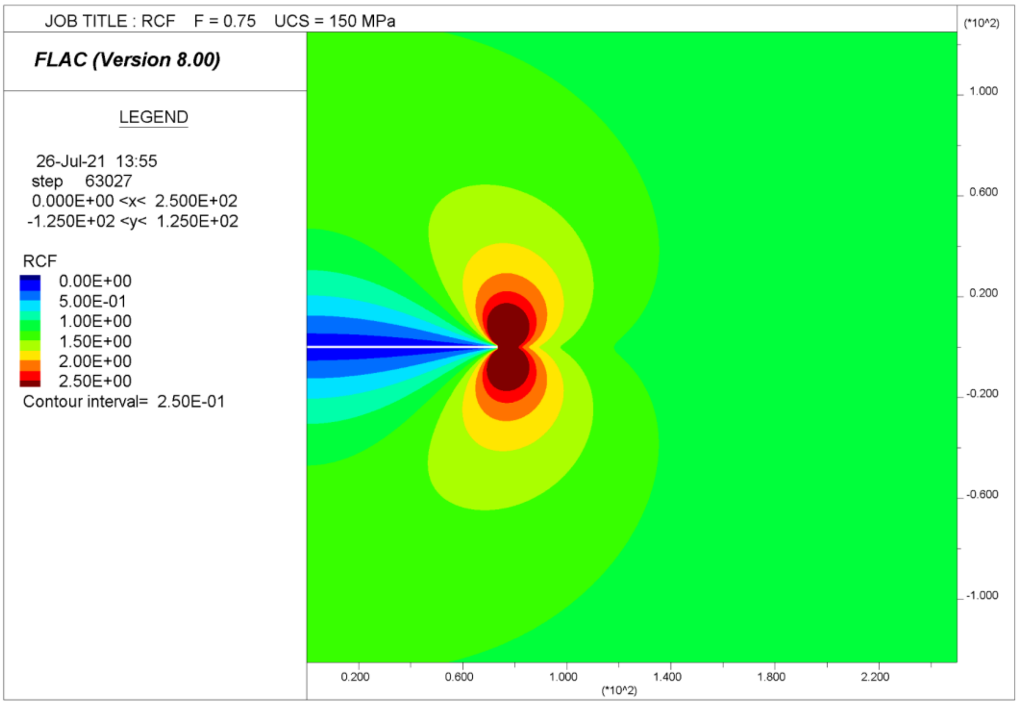


Figure 15: RCF for a tunnel in the vicinity of the investigated slot. The stresses are taken from Figure 13 and Figure 14. The long tunnel axis is oriented out-of-plane. Axis unit is meter; one half of the slot is shown.

The effective mining depth for the considered tunnel in the vicinity of the tabular slot is outlined in Figure 16. Distant from the tabular slot the effective mining depth corresponds the depth below surface, which is 2000 m. In the abutment areas of the slot, the effective mining depth is considerably larger. Accordingly, the abutment areas should be avoided and the tunnel should not be situated in the abutment areas. However, in the de-stressed zone the effective mining depth corresponds to a couple of hundred meters below surface. The examination of the effective mining depth outlines that the prevailing deep mining situation can be altered effectively and transferred to a shallow mining situation.

In conclusion, the tabular slot model demonstrates the significant advantages of providing de-stressed zones. The stresses acting on excavations inside the stress shadow decrease considerably. Despite great depths the stresses in the de-stressed zone correspond to a rather shallow mining environment. A critical aspect is the creation of the slot in the prevailing deep mining situation; compare section 8.1.3.

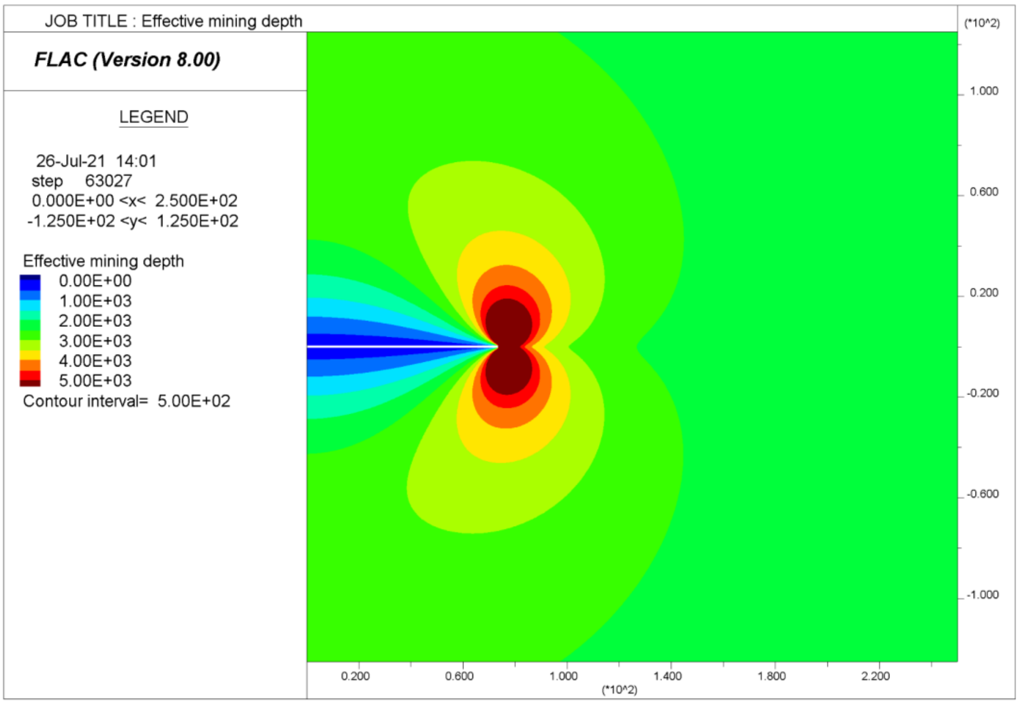


Figure 16: Effective mining depth in meter for a tunnel in the vicinity of the investigated tabular slot. The stresses are taken from Figure 13 and Figure 14. The long tunnel axis is oriented out-of-plane. Axis unit is meter; one half of the slot is shown.

2.3.3.2 Forming a highly stressed pillar behind an advancing extraction face

The second example outlines the advantages of forming a highly stressed pillar behind an advancing extraction face on basis of a vertical, tabular deposit with a thickness of 20 m. Two mining panels with a height of each 200 m are extracted. A sill pillar of 20 m separates the panels, after they were mined-out completely. For the analysis the upper mining panel is already completely extracted and the lower mining panel is extracted in 20 m high slices stepwise. Two different extraction sequences are compared, an overhand sequence and an underhand sequence. In the underhand sequence the pillar is formed with its final dimensions at the beginning and mining advances away from the pillar. Whereas, in the overhand sequence mining advances towards the upper, mined-out panel and the size of the sill pillar is reduced gradually, until the pillar reaches its final dimensions, after the extraction of the last slice. Figure 17 shows the analyzed geometry and considered mining sequences. The stress situation is derived by means of two-dimensional simulations with FLAC. The primary stress state corresponds to a depth of 2000 m with vertical and horizontal stresses being 54 MPa. The primary stresses are constant and a stress gradient is not considered. Rock mass is modelled linear elastic with a Young's modulus of 40 GPa and a Poisson ratio of 0.2. Extracted slices are not backfilled and remain an open void. Neglecting the influence of backfill is a simplification, but it does in general not affect the principal characteristics of the outlined aspect, namely forming the sill pillar ahead or behind the advancing extraction face.

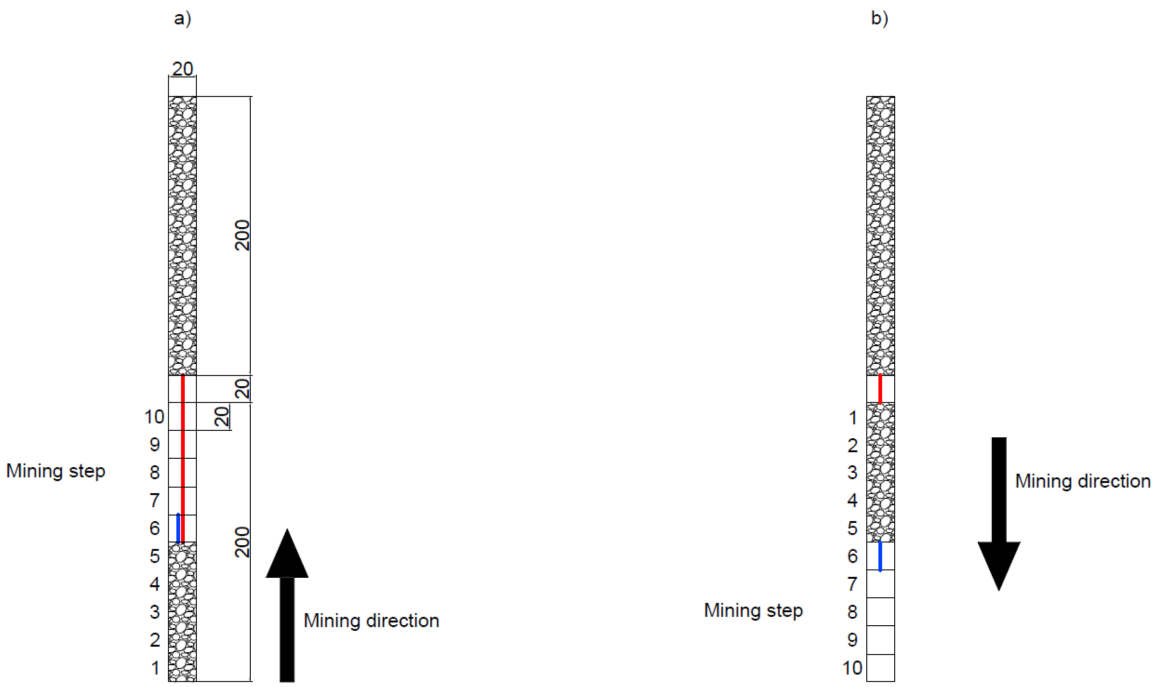


Figure 17: Investigated mining geometry and mining sequences (a) overhand sequence and (b) underhand sequence. The red line outlines the line used for determination of the average horizontal stress inside the sill pillar for mining step 5 and the blue line outlines the line used for the determination of the average horizontal stress in the next slice for mining step 5. Dimensions are in meter.

The horizontal stresses are used for the analysis of the results, because they are critical for the stress acting inside the pillar. Figure 18 provides the development of the average horizontal stress ($\sigma_{h,avg}$) inside the sill pillar for the overhand and underhand sequence as well as the average horizontal stress in the slice, which is extracted next. The average horizontal stress inside the pillar is derived from a vertical line positioned in the middle of the sill pillar and the average horizontal stress in the next slice is derived from a vertical line positioned in the middle of the next slice; compare Figure 17. Step 1 refers to the state, where the first slice was mined, and step 10 to the state, when the lower panel is completely extracted. In the underhand sequence the average horizontal stress inside the pillar and in the next mining slice is higher than in the overhand sequence at the beginning. As mining progresses, stresses start to increase. At an advance stage of mining the situation deteriorates in the overhand sequence. High stress magnitudes and rapid stress increases are encountered, because the pillar size is reduced and the advancing stope face is in the pillar. These significant stress increases in a sill pillar in an overhand sequence are reported by Labrie et al. (2007), who conducted stress measurements in a sill pillar. In contrast, stress increases in the underhand sequence are considerably lower and the highly stressed pillar is positioned distant from advancing stope face. Overall, the underhand sequence provides a more favorable stress situation than the overhand sequence particularly at an advanced stage of mining, where extreme stress magnitudes are prevailing in the overhand sequence at advancing extraction faces. Furthermore, the rapid stress increases of the overhand sequence can cause significantly more seismic energy release; compare Salamon (1983a), who outlines the effect of stress increases on the mining-induced seismicity at the advancing and still-standing mining face.

Note that the assumed linear elastic material behavior implies that the sill pillar can withstand all exposed loads. An overstressed and consequently yielding or crushing pillar may change the outlined stress situation significantly. However, in the underhand sequence such pillar crushing would occur behind and distant from the extraction face, whilst in the overhand sequence it would occur directly at the extraction face. In the overhand sequence, active mining infrastructure is then situated near and in the highly stressed and then crushing pillar.

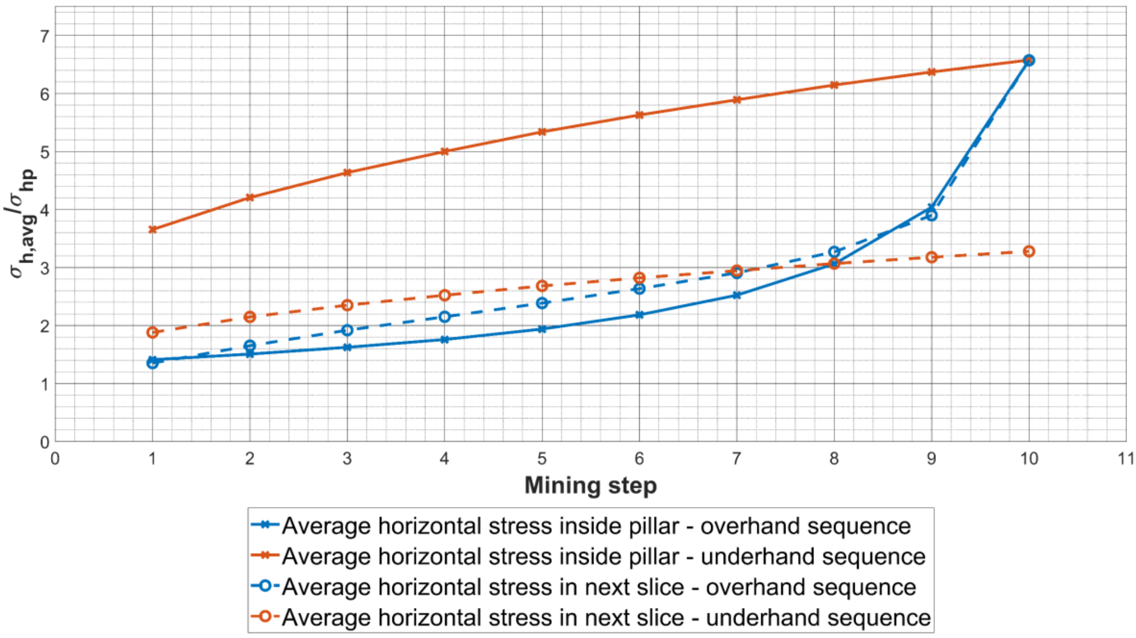


Figure 18: Normalized average horizontal stress inside the pillar and in the next slice for successive mining steps in the overhand and underhand sequence.

In conclusion, forming the sill pillar behind in an underhand sequence is of considerable advantage. The stress magnitudes at the advancing face in an advanced stage of extraction are lower than the stress magnitudes, which are reached in an overhand sequence. Moreover, the highly stressed pillar is left behind. Active infrastructure near the pillar is not required at this stage and potential sources of problems associated with the pillar, such as mining-induced seismicity or high stresses, are not located nearby active infrastructure.

Furthermore, a potential pillar failure takes place distant from active extraction faces and active infrastructure. The outlined sill pillar example is a common situation in the extraction of steeply dipping deposits. Rock pressure problems associated with the formation and eventual extraction of sill pillars in overhand sequences, such as rock bursting or extensive rock mass fracturing and the corresponding rock fall hazard, are well known; see for example Langston et al. (2006), Labrie et al. (2007) or Townend and Sampson-Forsythe (2014).

2.4 Stress management in current practice

Illustrative examples were utilized in the last sections to outline the effects of proper and improper stress management. An appropriate stress management offers considerable advantages. The stress magnitudes either drop below primary stress magnitudes or the increase of stress magnitudes can be limited. The effective mining depth can be reduced accordingly. In contrast, an improper stress management can result in the development of typical deep mining problems already at rather shallow depths. In this section an overview of current stress management practices in deep mining is given. Therefore, two cases are distinguished. First, deep South African gold mines, which have been applying stress control very successfully. Second, an outline on the general situation related to stress management in deep mining in other regions is provided, where most of the mines have not been using an advanced stress management approach so far.

2.4.1 Stress management applied in deep South African gold mines

The gold reefs in the Witwatersrand area are of tabular shape, dip with approximatively 20 ° to 30 ° and extent over several square kilometers. Reefs have been successfully mined up to depths of more than 3500 m below surface and over areas of several square kilometers. Extreme rock stress magnitudes and considerable mining-induced seismicity have been posing continuous challenges and the development of appropriate stress management techniques and concepts has been required. (Durrheim, 2010)

2.4.1.1 General stress control approach

The application of specifically designed mining methods, which are in accordance with an appropriate stress management, has enabled the successful extraction of deep gold reefs. These methods, layouts and sequences comprise scattered mining, longwall mining and sequential grid mining. Jager and Ryder (1999) provide an overview of the individual methods. All methods have in common that stopes are generally of tabular shape. The stope width is around 1 m and lateral extensions are up to several hundred meters or even kilometers. Stopes are extracted totally, thus no (stable) pillars are left behind in stopes. Instead, hangingwall support is provided by heavy areal support and backfill. Differences of individual mining methods can mainly by found in the position and orientation of stabilizing pillars, in the position of infrastructure and in the mining sequence. Longwall mining has been utilized for many decades. Indeed, there has been a trend towards sequential grid mining in recent decades, because sequential grid mining offers operational and rock mechanical advantages, such as application of dip stabilizing pillars, better control of mining-induced seismicity and better in-advance knowledge of geological conditions and structures. (Handley et al. (2000), Russo-Bello and Murphy (2000), McGill (2005))

The tabular slot shaped stope is used for stress management strategically. Figure 13 and Figure 14 outline the resultant stress distribution near a deep tabular slot. A stress shadow forms below and above the tabular slot, which is utilized for the protection of infrastructure. Therefore, a critical aspect is the time of infrastructure development respective to the advancing stope face. Two different situations can be distinguished, infrastructure developed behind the advancing face, so-called follow-on development or delayed developed infrastructure, and infrastructure developed ahead of the advancing face, so-called ahead developed or pre-developed infrastructure. In order to benefit from stress shadows, infrastructure must be developed delayed. Ahead developed infrastructure is exposed to primary stress magnitudes or even to the considerably higher abutment stress magnitudes of stopes. A further position of high stresses on infrastructure is present when passing above or below stabilizing pillars, which transfer high stress magnitudes. Longwall mining enables an efficient protection of infrastructure. Follow-on development can be used and at positions, where regional pillars must be passed, a slot is mined through the pillars, which provides the required stress shadow. However, follow-on development is not always possible. For example, in sequential grid mining most of the infrastructure must be developed ahead. The infrastructure could be damaged by the abutment stresses or regional pillar stresses. In order to protect the infrastructure from abutment stresses and pillar stresses, infrastructure is positioned remote from stopes, but then infrastructure can also not benefit from stress shadows. Obviously, siting infrastructure further away from stopes comes along with some operational disadvantages due to a higher development effort and increasing haulage distances. Damage to infrastructure, which provides access to the reef in sequential grid mining, can be limited with specific mining sequences near this infrastructure. (Handley et al., 2000) Another type of infrastructure that must be protected in all applied mining methods from high stresses and deformations is the main infrastructure, particularly shaft systems, for which prevention of deformations of the shafts is most critical. Shaft systems can be protected by shaft pillars, but the size of shaft pillars becomes excessive at great depths and considerable portions of the deposit are lost. (Wagner and Salamon, 1973) For this reason, shaft pillars in deep gold mines are nowadays normally extracted at an early stage of mining or during or before shaft sinking by utilizing infrastructure from neighboring mines. (McKinnon (1987), Leach (1990), De Wet (1997)). The stress changes and deformations resulting from shaft pillar extraction must be controlled. The utilization of a stiff, high-quality backfill is therefore of importance. Thereby, the shaft can be protected from ongoing mining activities without locking significant portions of the deposit.

In Figure 13 it can be further seen that high abutment stress magnitudes are present at an advancing stope face. Moreover, significant amount of energy changes and energy release take place at the advancing stope face. Limiting stress magnitudes at the stope face and the volume of highly stressed rock mass as well as limiting the seismic energy release are therefore further integral parts of the applied stress control measures in deep South African gold mines. (Salamon, 1983a) Further, the control of stope closure and control of large geological structures, such as faults or dykes, are decisive. (Gay et al., 1995) Different methods and approaches have been developed and applied successfully. They comprise:

- Massive stabilizing pillars (e.g. McGarr and Wiebols (1977), Salamon and Wagner (1979), Tanton et al. (1984))
- Bracket pillars (e.g. Napier (1987), Vieira et al. (1998))
- Narrow stope widths and backfill inside stopes (e.g. Ryder and Wagner (1978), Jager et al. (1987))
- Stope face pre-conditioning (e.g. Toper et al. (2000))

2.4.1.2 South Deep mine approach

Normally gold reefs occur in isolation and the spacing between reefs is relatively large so that the application of large-scale stoping methods is not possible. An exception therefrom is the deposit, which is extracted at South Deep gold mine. This ore body is characterized by a package of closely spaced gold reefs, which are separated by layers of waste rock. Instead of applying widely used methods of other gold mines and mining the ore body reef-by-reef, a different strategy is chosen for the extraction of the prevailing massive deposit. First, the ore body is de-stressed by creating of a de-stress cut; compare Figure 19. The objective of de-stressing is to provide a favorable stress situation for subsequently applied mechanized stoping methods. (Watson et al., 2014) Initially, one of the reefs was extracted by the widely used longwall mining method. This method was later replaced by a mechanized extraction of the de-stress cut in inclined and later horizontal direction. Further improvements were realized through the implementation of crush pillars and later yield pillars for creating the de-stress cut. (Andrews et al., 2019) Watson et al. (2014) outline the advantages of a crush pillar system for de-stressing. The effectiveness of de-stressing in South Deep mine and the significant reduction of the rock burst and rock fall hazard are reported by Joughin and Petho (2005).

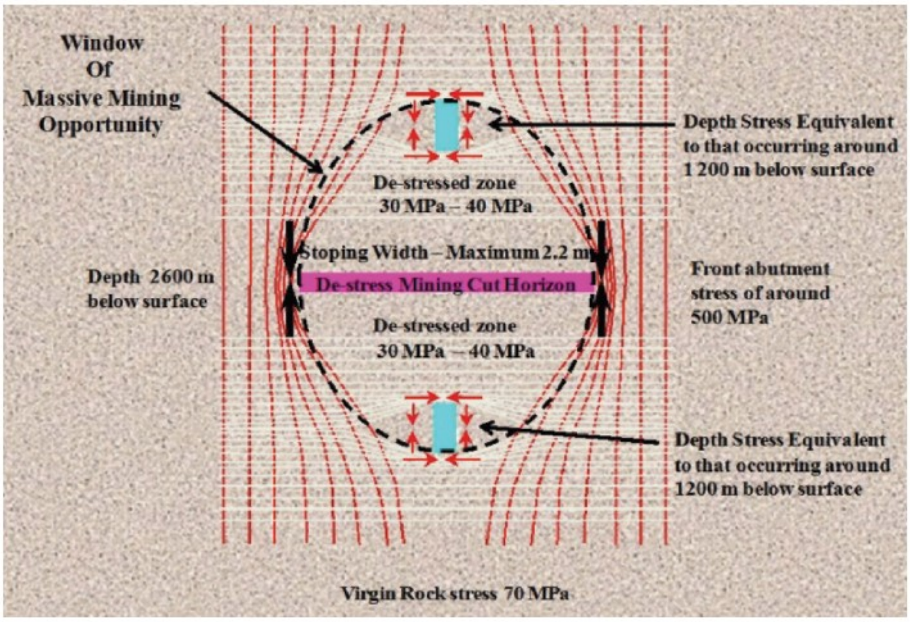


Figure 19: De-stressing principle applied in South Deep mine (Watson et al., 2014)

2.4.1.3 Summary stress management in deep South African gold mines

In summary, the applied stress management in deep South African gold mines is advanced and sophisticated. There have been continuous improvements and adaptations aiming on a further reduction of rock pressure related hazards and risks. The recent change from longwall to sequential grid mining, which offers improved stress and seismicity control, is one of them. According to Wagner (2021) there are two main reasons for the development, implementation and improvements of the stress management approach in deep South African mines:

- The well-structured, long-term research program of the Chamber of Mines in the second half of the last century. The important role of the long-term, strategic research is also acknowledged by Durrheim (2010), Riemer and Durrheim (2012), Durrheim (2014) and Stacey (2019b).
- The mining legislation in South Africa, which has recognized the importance of rock engineering as a discipline in deep mining. Examples therefore are the prescription of the employment of competent rock mechanics personnel (MHSC, 1996), which must pass a government examination confirming their competency, or codes of practices addressing rock mechanics risks systematically (e.g. DME (2002)).

Despite the offered advantages the stress management in deep South African gold mines is associated with a major drawback, namely that it relies in most instances strongly on non-mechanized work in relatively narrow stopes. Operational difficulties, a low productivity and a reduced competitiveness are the consequence. (Wagner (1986), Neingo and Tholana (2016)) The high-grade gold deposits and the circumstance that the actual extraction activities coincide with the de-stressing activities alleviate the operational disadvantage to some extent. However, even though the stress management proved to be successful for the extraction of deep gold reefs, its application potential for the extraction of lower grade or lower value deposits, for different rock mechanics environments or for different deposit shapes is rather limited. The main reason therefore is the labor-intensive, non-mechanized and cost-intensive method of operation. An interesting and promising enhancement of the stress management approach in longwall mining may though be the de-stressing approach utilized in South Deep mine. The South Deep approach enables mechanized de-stressing of large portions of the ore body, which are subsequently extracted by productive, mechanized stoping methods.

2.4.2 Stress management in context of the overall deep mining situation

This section emphasizes on the stress management in deep mining outside South African gold mines. In contrast to South African gold mines, which all operate in a relatively similar environment of tabular shaped gold reefs, a variety of different ore body sizes and shapes, geological settings and rock mechanical conditions are prevailing in the overall context of deep mining. The mining method should be chosen according to the characteristics of the deposit and the mining environment. Thus, different mining methods and variations of mining methods are utilized. It is far beyond the scope to discuss all of them and the associated stress management approaches in detail. Hence, a general discussion addressing important aspects and commonly applied approaches is made. Examples of certain mining methods, mining regions or mines are outlined for illustrative purposes.

2.4.2.1 Infrastructure and mining methods

Probably, the best point for starting the discussion is infrastructure, which is generally needed in all underground mines and mining methods. Furthermore, rock pressure problems affect infrastructure excavations often.

Different types of infrastructure are needed to access the deposit, to prepare the deposit for extraction and to extract the deposit; compare section 3.2.1. Active infrastructure must be protected from stresses and mining-induced seismicity. An approach is siting infrastructure distant from extraction areas so that they are only subjected to primary stress magnitudes. However, some infrastructure must be positioned in the vicinity of and inside extraction areas, which cause the regional stress and energy changes. For this infrastructure it is critical, whether it is developed ahead or delayed. Ahead or pre-developed infrastructure is infrastructure, which is developed before extraction in the corresponding extraction area or in a part of the extraction area commences. Therefore, pre-developed infrastructure is exposed to (usually high) abutment stresses, significant stress changes and areas of considerable energy changes and energy release. In contrast, delayed developed infrastructure is developed once production advanced in a certain extraction area or in a part of an extraction area. Accordingly, delayed developed infrastructure is not necessarily exposed to abutment stresses and can often benefit from a stress shadow. Critical issues could arise for both pre-developed and delayed developed infrastructure, if they are positioned near highly stressed pillars. The consequences of infrastructure position and time of infrastructure development were illustrated in the foregoing sections. The effective mining depth and thus the prevailing conditions and the encountered difficulties can be affected significantly by the infrastructure position and the time of infrastructure development.

Most commonly used mining methods require pre-developed infrastructure. The percentage of pre-developed infrastructure depends strongly on the mining method, the deposit conditions and operational considerations of the mine. Considering the percentage of pre-developed infrastructure is more reasonable than the actual amount of pre-developed infrastructure, which is strongly influenced by the mining method and particularly the stope design. In general, it is rather difficult to draw a general conclusion regarding the required percentage of pre-developed infrastructure. However, following trends and correlations can be recognized:

- The percentage of infrastructure pre-development can be reduced significantly, if infrastructure providing access to extraction faces can be integrated into extraction excavations. Room and pillar mining is a good example. Rooms are created as a result of the extraction and they provide access to the extraction faces. In general, non-mechanized mining allows for a better integration of infrastructure in extraction excavations. Large, heavy machinery does not need to be brought to the face, which removes restrictions in terms of cross-section and inclination of the face access as well as reduces its sensitivity to deformations. For mechanized mining an integration of face access infrastructure into extraction excavations is normally possible in flat-lying deposits or in flat-lying mining layouts. If access on several levels is required, such as in steeply dipping, thick or massive deposits, integrating the infrastructure becomes difficult in case of a mechanized extraction. Finally, the integration of infrastructure into extraction excavations is rarely possible for caving operations.

- The percentage of infrastructure pre-development increases with production capacity and productivity of a mine. A large production capacity and high productivity require normally that stopes and extraction areas are prepared for extraction in advance and that a high capacity transportation system is in place prior to commencement of extraction. The demand for infrastructure pre-development even increases, if a rapid ramp-up from production commencement to full capacity should be achieved. An exception may be mechanized mining methods, where the infrastructure for access to the extraction face can be integrated into extraction excavations.

Based on the observed trends above it can be concluded that the majority of mining methods and mines call for pre-developed infrastructure, particularly also because mechanized mining is nowadays commonly applied. Central issues therefore are thus the reduction of the percentage and amount as well as the protection of pre-developed infrastructure.

2.4.2.2 Protection of infrastructure

Pre-developed infrastructure, which is exposed to high stresses, stress changes and effects of energy release, is required by most mining methods and mines. This could also be a reason, why infrastructure is often affected by rock pressure problems. Accordingly, the protection of pre-developed infrastructure is essential. Different approaches and strategies have been in applied and they are reviewed below. Some of these measures provide protection for extraction excavations as well.

2.4.2.2.1 Position of infrastructure

Positioning of infrastructure distant from extraction areas outside zones of high stress and energy release is a measure, which is often utilized for the protection of long-term main and primary infrastructure. It is of limited use though for pre-developed infrastructure, which is required in or near extraction areas. This infrastructure could be severely affected by rock pressure problems. The undercut level infrastructure and the production level infrastructure in a post- or advance-undercutting strategy of a modern block caving operation and the often encountered rock pressure problems emphasize this problematic. (e.g. Fernandez et al. (2011), Campbell et al. (2020), Nugraha et al. (2020)) As certain infrastructure, such as stope drifts in sublevel stoping, undercut and production level infrastructure in block caving or extraction drifts in sublevel caving, is required directly in or near extraction areas due to access and logistics reasons, relocating this infrastructure to other positions distant from extraction areas is simply impossible. Accordingly, other measure must be utilized for their protection.

Indeed, there is even a trend of placing infrastructure in the direct vicinity of extraction areas, although it does not need to be necessarily situated closely. Long-term access and transportation infrastructure is sometimes situated near ongoing extraction areas as well. In a steeply dipping deposit extracted by sublevel stoping or sublevel caving this infrastructure comprises for example drifts, which are positioned in the immediate footwall and oriented in strike direction of the deposit, ore passes near the deposit or ramps near the deposit. The reasons behind are typically to save development meters, to reduce the ramp-up time and to shorten haulage distances. Rock pressure problems in such infrastructure are commonly encountered. (e.g. Mercier-Langevin (2010), Kalenchuk et al. (2017)) Positioning this infrastructure further away from the deposit can alleviate stress related problems. An example for this is Kiruna mine, where footwall drifts in striking direction and ore passes have suffered rock pressure related damage due their proximity to the ore body. (Sjöberg et al. (2011), Dahnér et al. (2012), Edelbro et al. (2012), Dahnér and Dineva (2020)). In order to address these problems, a project and field test, which aim on situating infrastructure deeper into the footwall and introducing an improved transportation system to make up for the additional transportation distance, are currently conducted. (Quinteiro (2018), Quinteiro (2020))

Prominent geological structures, such as faults, dykes or localized formations of weak rock mass, can cause rock pressure problems on infrastructure, which is positioning inside them or in their vicinity. The adverse effect of these structures can be avoided by shifting the position of infrastructure. (e.g. Varden and Esterhuizen (2012)) Besides changing the infrastructure position their orientation relative to rock mass structures and stress directions can be adapted to reduce rock pressure problems. (e.g. Yao and Moreau-Verlaan (2010), Hadjigeorgiou et al. (2013)) However, constraints arise from the ore body geometry and the chosen mine layout. Even though the last two measures can be quite effective, they do not resolve the general problem of pre-developed infrastructure in highly stressed or seismically active ground.

2.4.2.2.2 Stope size (extraction unit size), extraction area size and production

The stope size and extraction unit size, which is considered to be the size of a single production blast, influence the change resulting from every advancing extraction activity. Large extraction units cause larger, more drastic changes than smaller extraction units. The size of extraction areas, such as mining panels or block dimensions, has a direct influence on the spatial extent of the resulting stress magnitudes and on the energy changes in their vicinity. The shape of stopes and extraction areas are of importance as well. Finally, a larger production causes also faster changes over time.

From a rock mechanics perspective smaller extraction units and extraction area sizes and a lower production are mostly preferable. First, the stability of extraction excavations and extraction areas is usually improved. Second, induced changes in the rock mass are slower and less drastic. Consequently, the likelihood of rock pressure problems decreases. The energy release rate decreases, if an excavation is enlarged in smaller steps, and if stress changes are smaller. (Salamon (1983a), Salamon (1984)) Joughin and Petho (2005) report on extracting a remnant, which showed an unexpected low seismic response, at South Deep mine. They conclude that the slow extraction may be a reason therefore. Reducing the stope heights has most likely contributed to a significant reduction of mining-induced seismicity at Creighton mine. (Morissette et al., 2014b) Panel caving at El Teniente mine was associated with considerable stability problems and large-scale collapses. (Jamett and Alegría (2014), Orellana et al. (2014)) Subsequently, the panel cave was divided into several smaller extraction areas, which measure allowed to continue mining activities successfully.

Overall, decreasing the rate of changes has a positive influence from a rock mechanics perspective. However, it effects the production and productivity often rather negatively and it is thus mostly of rather limited use. The issue of production and productivity is further discussed in section 2.4.2.3.

2.4.2.2.3 Mining sequence

Besides the mine layout discussed above the mining sequence governs the spatial and temporal formation of highly stressed zones and seismic energy release. Accordingly, the mining sequence is commonly used to alleviate rock pressure problems. Some examples are given in the following. Varden and Esterhuizen (2012) report on a modified sequence, where pillars between stopes in a sublevel stoping operation are not created anymore. Similar stoping sequences without pillars between stopes are also outlined by Andrieux and Simser (2001). Mining activities in certain parts of an ore body or in certain adjacent ore bodies are delayed to avoid an unfavorable stress situation. (Yao et al. (2009), Counter (2014)) A top-down (underhand) extraction sequence is applied to avoid the formation of a sill pillar or to improve the stability of excavations. (Langston et al. (2006), Mercier-Langevin (2010), Moulding and Andrews (2015)) The just-in-time and delayed development of some portion of the infrastructure is reported by Jalbout and Simser (2014) and Woods et al. (2018). A mining sequence, which is preferable for the control of regional structures, is described by Esterhuizen (2018). Generally, adaptations to the sequence are quite often conducted and, in most instances, based on mining experience, back analyses and numerical modelling. Thus, adaptations are usually rather site-specific. However, from an overall perspective the adaptions of the mining sequence aim usually on:

- Limiting abutment stress magnitudes near pre-developed infrastructure
- Avoiding the formation of highly stressed pillars near pre-developed or active infrastructure
- Approaching and advancing along regional structures prone to seismicity in a favorable direction
- Developing infrastructure just-in-time or, if possible, delayed in de-stressed ground

Despite the positive effect that has been generated through the adaptation of the mining sequence in many cases most of the changes to the mining sequence are rather of an alleviating nature. The main cause of the rock pressure problem is addressed seldom, namely, the requirement of a significant percentage of pre-developed infrastructure. This infrastructure is still exposed to considerable stress magnitudes and mining-induced seismicity, though the stress magnitudes and experienced level of mining-induced seismicity are reduced (slightly) due to the sequence modifications. The possible success is often strongly governed by the mining method as well as the prevailing geological and geotechnical conditions.

2.4.2.2.4 *De-stressing and pre-conditioning measures*

Different de-stressing and pre-conditioning measures are conducted in highly stressed or seismically active areas to reduce rock pressure problems. De-stressing provides a zone, where the stress magnitudes are lower compared to the situation without de-stressing. Pre-conditioning alters the rock mass properties to alleviate consequences of high stress magnitudes, mining-induced seismicity and rock mass failure.

De-stressing is applied in specific situations, where infrastructure must be protected or where highly stressed portions of a deposit are planned to be extracted. Different methods of de-stressing have been applied. In the following a short overview is provided. At Golden Giant mine an approximatively 90 m high and 70 m wide de-stressing slot was excavated to protect a shaft from future mining activities. The effect of de-stressing and the design of the slot are discussed by Curran et al. (2001). McMullan et al. (2004) report on the successful construction of the slot and its effect on the shaft. Galvin (1992) outlines the utilization of sacrificial tunnels in coal mining in a high horizontal stress environment. First, a tunnel is excavated, which is allowed to cave. As a result, this tunnel generates a stress shadow for a second tunnel, which is developed afterwards in the vicinity of the first tunnel. Townend and Sampson-Forsythe (2014) outline the application of a drill hole curtain for successful de-stressing a sill pillar. Therefore, drill holes are drilled with a close spacing. The remaining rock mass between the drill holes yields and crushes. A similar concept for de-stressing sill pillars and remnants is de-stress blasting. Confined explosive charges are detonated in a concentrated volume of rock mass. The detonation fragments the rock mass and thereby reduces its strength and stiffness, causes deformations in the nearby rock mass and results in associated stress changes. (Andrieux (2005), Andrieux et al. (2010), Yao et al. (2019)) Another comparable concept is, so-called, tight slot blasting, which was applied at Mt Charlotte mine. (Mikula et al. (2005), Kempin et al. (2007)) The discussed de-stressing applications have in common that they were applied for a specific purpose on a rather localized scale. An example for de-stressing on the scale of a mining panel is the excavation of a slot at Creighton mine. (Wiles and MacDonald (1988), Landriault and Oliver (1992)) This slot as well as a zone of yielded rock mass near the slot de-stressed the rock mass for subsequent stoping activities. Ongoing stoping activities enlarged the stress shadow further. Other examples of de-stressing on a larger scale can be found in sublevel stoping and block caving. However, these de-stressing applications are principally the consequence of ongoing mining activities and not the result of a targeted de-stressing program. Jalbout and Simser (2014) outline the de-stressing effect of a primary-secondary sequence in a deep sublevel stoping operation. Pillars between primary stopes yield and push stresses into the abutments. Yao et al. (2009) select a mining sequence, where mining commences in an ore body first, which de-stresses then an adjacent ore body that is extracted afterwards. Undercutting in block caving generates a stress shadow below the undercut, which can be utilized for infrastructure protection in a pre-undercut strategy. (e.g. Jofre et al. (2000), Rojas et al. (2001)) In summary, various de-stressing methods have been applied. Indeed, the focus has mainly been on small scale, localized de-stressing of specific areas, or de-stressing has been the by-product of a certain mine layout and mining sequence.

Pre-conditioning is conducted before mining commences in a certain area and its objective is to induce or facilitate rock mass failure in designated areas or to mitigate rock burst risk. Most common pre-conditioning methods are hydraulic fracturing and confined blasting. Both methods create additional fractures or extent and weaken existing discontinuities. Possible resulting effects of pre-conditioning are a reduction of rock mass strength, a reduction of the post-peak strain softening rate and an initiation of slip along fractures and discontinuities. Consequently, rock mass failure is promoted, the stability of rock mass failure is improved and the stress magnitudes may be reduced. Moreover, seismic energy may already be released during pre-conditioning. Pre-conditioning has been widely utilized. On a local scale near advancing stope faces, near advancing infrastructure faces or in highly stressed remnants pre-condition blasting is applied as a rock burst mitigation measure. (e.g. O'Donnell Sr (1999), Toper et al. (2000), Morissette et al. (2014b), Vennes et al. (2020)) On a larger scale, pre-conditioning is nowadays commonly applied in cave mining. Hydraulic fracturing and confined blasting are deployed to facilitate caveability and to improve fragmentation. (e.g. Talu et al. (2010), Catalan et al. (2012), Catalan (2015), Simanjuntak et al. (2020)) Furthermore, pre-conditioning has been applied to decrease mining-induced seismicity near active mining levels. (e.g. Morales et al. (2007), Catalan et al. (2017), Nugraha et al. (2020)) Recently Orrego et al. (2020) outline the intention to pre-condition the production level of a deep block caving operation to reduce the likelihood of a damaging seismic event during undercutting. In summary, various pre-conditioning methods have been deployed as an improvement or mitigation measure successfully. Indeed, the focus is often on a local scale for specific purposes, such as mitigating the rock burst risk near advancing stope faces or preparing remnants for extraction. Large-scale, expensive pre-conditioning campaigns have been introduced in cave mining though.

Concluding, comparable to the mining sequence most of the applied de-stressing and pre-conditioning measures alleviate rock pressure related problems. An often rather unfavorable mining environment is tried to be improved. However, the main cause of the potential problem is generally not addressed directly. Despite stress shadows, which are an effective measure against stress related problems and which are provided occasionally on a local scale, a regional de-stressing approach is principally not utilized. Such a large-scale de-stressing approach is applied in deep South African gold mines; compare section 2.4.1. Despite the offered advantages and positive mining experiences it has not been transferred to other mining methods and mining environments.

2.4.2.2.5 Support

Support and reinforcement systems are installed directly in infrastructure and extraction excavations. Their objective is to control the consequences of high stress and mining-induced seismicity and thereby to ensure the stability of excavations. Even though support is principally not addressing the sources of rock pressure problems, it is widely utilized. Numerous case studies point out that upgrading support is a (the) main measure against experienced rock pressure problems; see for example Jacobsson et al. (2013), Morissette et al. (2014b), Landry and Reimer (2019) and Potvin et al. (2019a). Despite the successful mitigation of rock pressure risks, which has been achieved by upgrading the support, the overall and long-term suitability of support as the main measures is questionable, because the sources of rock pressure problems are not addressed. Furthermore, there is a technical and economic limit for support systems. The commonly applied support strategy is further discussed in section 4.1.

2.4.2.3 General developments, trends and demands

Most mining methods require pre-development of infrastructure, which must be protected from high stresses and mining-induced seismicity. Possible protection measures have been outlined and reviewed. Although changes in the mine layout and mining sequence have been made and although de-stressing and pre-conditioning methods have been applied, the main approach against rock pressure problems has been support. Furthermore, trends and developments are prevailing, which on the one hand are responsible for challenging rock pressure conditions, and which on the other hand push the strategy against them towards support. These demands, trends and developments are outlined briefly.

2.4.2.3.1 Demand of a high production and productivity

As already outlined, there is a demand for a higher production and higher productivity in deep mining to compensate additional costs resulting from increasing mining depths. The mining method, mine layout and mining sequence are therefore critical. Principally, the requirements from a productivity and rock mechanics perspective are to some extent opposed. For example, larger sizes of stopes, extraction units and extraction areas provide a higher productivity. Moreover, situating infrastructure close to extraction areas and the ore body decreases the development time and transportation distances. Complex and sophisticated extraction sequences can affect productivity negatively. Accordingly, standardized mine layouts and sequences are preferable from a production point of view.

From a rock mechanics perspective most of the outlined options facilitating production and productivity are normally less preferable. Approaches for the protection of pre-developed infrastructure become limited. From the approaches, which were outlined in the foregoing sections, only the support approach, even though it slows down development rates, does not interfere with the requirements for a high production and productivity strongly. This could be a main reason for the preference of upgrading support. All of the other outlined measures are, depending on the circumstances, deployed to some extent as well. The demand for production and productivity limits though the possible utilization of the other approaches. Accordingly, other measures are mostly constrained to adjustments and modifications to improve the stress situation and mining-induced seismicity and to alleviate their consequences within an overall mining method, layout and sequence, which are prescribed by production and productivity demands. Far-reaching changes to mining methods, layouts and sequences, which can make an enhanced use of other measures besides support, have generally not been introduced so far. A further reason could be that the introduction of major changes in the mining method, layout and sequence in order to be consistent with an active stress management approach may require a high-level decision in a company. Such changes could affect the share value of a company, particularly in case they are associated with additional cost. In contrast, increasing cost of rising support demand or other short-term measures may not be recognized as additional, because they are considered to be the result of an increasing extraction depth.

2.4.2.3.2 Lack of recognition of importance of rock mechanics in deep mining

Whilst the rock pressure problems in deep mining are well known, the importance of incorporating rock mechanics demands and constraints in mine planning is often not recognized appropriately. The development of a rock pressure problem can be the consequence. In this matter, Potvin (2011) points out that the traditional parameters for selecting a mining method, namely ore body characteristics and rock mechanical environment, were to a large extent replaced by considerations related to production rate and unit cost. Consequently, open stoping methods and large-scale caving methods have been applied in conditions, which are more difficult for these methods. Stoping advanced to poorer ground conditions, whilst caving methods advanced to stronger ground conditions. Additionally, the mining depth has been increasing making rock mechanics aspects even more relevant.

It is unclear, whether the emphasis on production and productivity in combination with a limited incorporation of rock mechanics considerations yields overall the highest project value in terms of the aims of mineral extraction, which are a safe, as complete as possible and economic extraction. However, it is quite difficult to quantify the impact of rock mechanics on the latter, because there are considerable uncertainties regarding the prevailing geological conditions, the rock mass behavior as well as the stress situation. This issue could be a reason, why rock mechanics aspects are in many instances not considered to the same extent as production and productivity aspects in mine planning and decision making.

In summary, there seems to be a lack of appreciation of the importance of rock mechanics for the success of a deep mining operation. This missing appreciation concerns predominantly high-level management, which makes the (final) decision on mining projects. The decision is in most instances based on a cost, profit and risk perspective. As rock mechanics aspects are relatively difficult to quantify due to the prevailing uncertainties, they are often not considered in mining project decisions.

2.4.2.3.3 Lack of knowledge, information and methods

A proper understanding of the strength and behavior of rock mass as well as the prevailing stress situation is essential for many of the outlined approaches. However, our knowledge and understanding in these fields are limited and uncertainties exist. Ongoing mining activities enable to improve the understanding of the prevailing conditions. Mining experience is then utilized to adapt the design and thus to improve stress management. A critical aspect is that major design decisions are made at an early stage. Subsequent adaptions are then often constrained by the initial design. If major changes are though implemented, considerable additional cost arise usually. Accordingly, fixing the design early is delicate, on the one hand because of the limited knowledge related to the rock mass behavior and the stress situation and on the other hand because of the uncertainties regarding the prevailing geological conditions and rock mass formations. Inflexible mining methods are particularly affected. Options to overcome this issue are either flexible and adaptable mining methods, a better knowledge regarding prevailing geological conditions in the planning phase or an improved understanding of rock mass behavior.

Flexible and adaptable mining methods do not provide a high productivity and high production in most instances. Instead, a trend to more productive, high production, but inflexible methods is clearly visible. The remaining options are not ideal either. There is a lack of knowledge related to rock mass behavior and the geotechnical data and information collected in the exploration phase are limited. As mining advances to greater depths, exploration becomes even more expensive, which aspect could decrease the available data and information further. Summarizing, highly productive and high production mining methods call for an appropriate design, which is difficult to realize because of the limited knowledge and uncertainties. Once mine development started, the design is basically fixed. Possibilities for changes to the layout and sequence are then rather sparse. This issue could be a reason, why most stress management approaches are of local and rather reactive nature and why upgrading the support system, which can be done without significant changes to the layout and sequence, is often a preferred choice.

Following developments could assist to minimize the consequences and difficulties resulting from the limited knowledge:

- Improving the knowledge about rock mass behavior, increasing the exploration effort and improving exploration methods
- Developing flexible, but still highly productive mining methods
- Enhancing existing mining methods with an adaptable and flexible stress control approach

As the first point requires extensive research efforts, it is rather a long-term approach. The second and third point seem to be more feasible in a short to medium term. The flexibility would still allow modifications, which are based on mining experience. Knowledge and understanding of rock mass and prevailing conditions are then less critical.

2.4.2.3.4 Lack of research and development, education and training

The rock mechanics issues in deep mining necessitate long-term and strategic research and development. Fundamental questions, particularly related to rock mass behavior, need to be addressed. Additionally, practical mining layouts and sequences, which enable an appropriate stress management and which provide flexibility, need to be developed. Besides research and development a specific education and training in the field of rock mechanics for personnel working at or with mines is required. However, there has been a constant decline in research and development capacities as well as in education and training institutions; compare section 2.3.1. The availability of long-term, strategic, intensive and industry-wide research and development is considered to be a main contributor to the successfully implemented stress management approach in deep South African mines. (Wagner, 2021) Despite its importance such a long-term research and development approach is more or less absent. Most of the research and development work in rock mechanics is concentrated on topics, which are urgent at the moment to fight rock pressure problems. This approach is a similarity to addressing rock pressure problems themselves, where also a quite short-term, reactive approach by means of upgrading support, modifying and adapting layouts and sequences rather locally and applying specific de-stressing and pre-conditioning methods on a local scale is dominating. Examples therefore are the research and development efforts in support and reinforcement systems and the international cave mining studies. Although considerable progress was made in the past, the available support systems are not able to stabilize excavation in many situations of high stress and mining-induced seismicity. Excessive fracturing and deformation as well as rock burst damage still occur. The theoretical understanding of dynamic ground support as well as of support design methods are still deficient and require further development. (Potvin (2017), Potvin et al. (2019a)) The situation is similar in deep cave mining. Considerable progress was made, but the research and development concentrated mainly on pushing the existing cave mining methods and their layouts and sequences to greater depths and more competent rock masses; compare Brown (2007), Chitombo (2010), Flores (2014), Laubscher et al. (2017). Accordingly, improvements focused on alleviating and mitigating the consequences of high stress and mining-induced seismicity. The sources of rock pressure problems, which may be overcome by alternative mining methods, layouts and sequences, have not be addressed in these studies at a comparable scale. Thus, despite all the effort, rock pressure problems are still present in most of the deep cave mining operations. Instead of focusing on urgent problems and short-term solutions research and development should concentrate more on long-term solutions. Therefore, an appropriate research and development capacity as well as the commitment of the mining industry are necessary.

Concluding, the lack of a long-term research and development strategy as well as the diminishing capacities for education and training prevent that rock pressure problems are addressed by its roots. An active stress management approach, which eliminates the potential sources of rock pressure problems, is much more powerful. Finally, this lack of research and development as well as of education and training favors the application of short-term, reactive measures.

2.4.2.4 Summary stress management in overall deep mining situation

Overall, the demands on rock mechanics and production issues increase with mining depths. Mining started at shallower depths, where rock pressure and energy release are more easily manageable. Relatively successful mining methods and mining strategies have been developed for these conditions. However, mining methods, mining layouts and mining sequences have generally not been significantly changed and adapted to deep mining conditions, as mining progressed to greater depths. There is even a trend to utilize more productive and higher production methods in rock mechanical conditions, which are not preferable for them. Layouts and sequences are further optimized in terms of productivity and efficiency. In order to achieve a high productivity and production, a large percentage of the infrastructure, which is often situated close to or in extraction areas, must be pre-developed. This infrastructure is prone to rock pressure problems. The reaction on rock pressure problems is generally of passive nature. Measures, which alleviate and mitigate the consequences of high stresses and energy release, are implemented. Support and reinforcement systems have a principal role. A number of possible reasons for this passive reaction are identified. These reasons have in common that production and productivity considerations dominate over rock mechanics considerations, that a long-term strategy in research and development, which addresses the sources of rock pressure problems, is more or less absent and that education and training of personnel working at or with deep mines has room for improvement. On the long-run, stress management measures and strategies, which are implementable from a rock mechanics point of view and which do not contradict the need for higher productivity and for a high production, are required.

2.5 Objective of research work

The foregoing sections have outlined the consequences of increasing mining depths and the rising challenges in deep mining from a production and rock mechanics perspective. A number of critical points related to rock mechanics aspects of increasing mining depth are raised. These points must be addressed appropriately for a successful mining operation at great depths. For production, it is identified that increasing mining depths call for improved efficiency and productivity. In general, production aspects are encountered actively, whilst rock mechanics aspects are in most instances addressed rather passively. A number of possible reasons for this development is identified. One of them is the lack of suitable stress management approaches for many situations, which call for specifically designed mining methods and extraction strategies. These approaches must address rock mechanics aspects in deep mining actively, whilst they must still enable a productive and high production extraction at great depth. The availability of suitable stress management approaches becomes even more relevant in future because of a rising demand of raw materials and of increasing mining depths. Mining experience in deep South African gold mines and illustrative examples highlight the possible and often considerable advantages and improvements achieved by an active stress management. The deep South African gold mines have been using such an active stress management approach for several decades. However, the South African approach is of limited applicability in other mining environments, as it is mostly labor-intensive, low productive and constraint to flat-lying or slightly inclined deposits. Hence, there is a shortage of applicable active stress management approaches in many mining environments, in particular in steeply dipping and massive deposits.

The present research work addresses the identified shortage of applicable active stress management approaches in many mining situations. Therefore, the research aims on the development of a stress management concept for deep mining, where the control of high stresses and mining-induced seismicity are crucial for a successful operation in accordance with the objectives of mineral extraction. An emphasis is thereby put on steeply dipping and massive deposits, in which the shortage of active stress management approach is particularly prominent. The stress management concept should either enable or improve mineral extraction at great depths by controlling high stresses and energy release in a systematic and strategic manner. The actual implementation of the stress management concept should be adaptable to the local mining environments and the local production requirements. Therefore, an essential, integral part of the concept is its applicability in practice without affecting the demands for higher efficiency, higher productivity and a high production at great depths adversely.

3 Consequences and causes of rock pressure problems

Rock pressure phenomena and rock pressure problems are discussed in this chapter. Differences between rock pressure phenomena and rock pressure problems are outlined and the significance of rock pressure problems and their possible consequences on mineral extraction are highlighted. Overall, rock pressure phenomena and problems are caused by stress driven fracture and failure processes. Therefore, the governing rock mechanics parameters of these stress driven fracture and failure processes are outlined and discussed briefly. Thereby key parameters for the stress management concept are identified. Key parameters comprise amongst others the stress situation, the rock and rock mass strength and behavior, the structural element strength and behavior and the loading system. Parameters can be further divided into so-called natural parameters and parameters, which can be influenced. The stress management concept must be adapted to the former, whilst the latter can be used actively for stress control. Besides rock mechanics parameters other key parameters are the ability to recognize rock pressure problems, deposit properties, flexibility, monitoring and data analysis. The identified key parameters are essential for the investigations and analyses in the subsequent chapters and for the development of the stress management concept.

3.1 Rock pressure phenomena and rock pressure problems

Stress magnitudes and released seismic energy rise, as mining progresses to greater depths. Increasing stresses and rising amounts of released energy may manifest themselves in the occurrence of rock pressure phenomena and rock pressure problems. A “rock pressure phenomenon” is in this research work defined as an (observable, visible) consequence of high stresses or seismic energy release. (If rock pressure phenomena are not directly visible and if a targeting monitoring program is not set up, rock pressure phenomena may not be detectable. An example therefore are microseismic events, in case a seismic monitoring system is not installed.) Accordingly, rock pressure phenomena are usually related to fracturing, failure and deformation of rock, rock mass and structural elements. Examples for rock pressure phenomena are the development of a zone of fractured rock mass in the vicinity of an excavation, the occurrence of mining-induced seismicity or plastic deformations resulting from rock mass failure and associated bulking. Rock pressure phenomena are indicators of changes in the rock mass or mine, which can alter the stress distribution and energy release characteristics. In general, rock pressure phenomena are a common feature in deep mining conditions and may not necessarily affect an operation negatively. However, they are early indicators of changes or processes, which could become so intense or severe that they cause significant operational problems. The term “rock pressure problem” in this research work is defined as the effect of the changes and processes in the rock mass or mine as indicated by the phenomena, which puts the objectives of mineral extraction (safe, as complete as possible and economic extraction) at risk. The impact of rock pressure problems onto the objectives of mining are discussed in the following briefly.

- Impact on safety: Rock pressure problems could affect the safety of mining personnel negatively. As rock pressure problems are caused by fracture and failure of rock, rock mass and structural elements, unstable ground conditions are present. The consequence therefrom is that excavations or other mine structures become unstable and collapse. Support systems aim on stabilizing such unstable ground and on preventing collapse. However, if the support system capacity is exceeded, fall of ground or the ejection of rock mass due to seismic loading can occur. A notable feature is that fall of ground accidents below a certain depth remain virtually constant, whereas there is a significant increase in rock burst accidents with depth. (Jager and Ryder, 1999) Obviously, the fall of ground and ejection of rock mass pose a safety risk for mining personnel. Furthermore, it can damage equipment or infrastructure, which is installed in excavations.
- Impact on profitability: Rock pressure problems could decrease the profitability in different ways, namely costs for repair of encountered damages, costs for additional measures addressing rock pressure problems and costs resulting from a loss of income. Costs for repair can arise for example because of rock pressure related damage in infrastructure and extraction excavations (e.g. rock falls, excessive fracture zones, excessive deformations, rock burst damage), damage and overloading of installed support systems or damage to equipment. Costs for additional measures arise for example because of upgrading support and reinforcement systems, increasing haulage distances due to positioning infrastructure further away from extraction areas, re-development of collapsed infrastructure excavations at another position and special de-stressing and pre-conditioning measures. Costs resulting from a loss of income arise for example because of shutdown times for repair work and the associated production loss, smaller and less productive stope sizes, lower productivity of damaged infrastructure and equipment or loss of contract due to supply difficulties. In summary, rock pressure problems could cause considerable costs. Accordingly, it would be preferable and, in most instances, finally cheaper to address the sources of rock pressure problems rather than fighting its consequences. A critical issue is though that the extra costs of rock pressure problems are seldom known or outlined as such.
- Impact on completeness of extraction: The impact of rock pressure problems on the completeness of mineral extraction is more difficult to determine and highlight. In general, it can be considered to be a result from the consequences of safety and economics. For example, if rock pressure problems add additional cost and thereby prevent the profitable mineral extraction in certain parts of the mine, the affected portion of mineral resource may be left in place and it is thus lost. (At least temporarily, extraction may become economic at a later stage again for example due to increased commodity prices.) From a safety perspective rock pressure problems could prohibit further extraction and they would subsequently cause a loss of resources due to inacceptable high risks. Another adverse effect of poorly managed rock pressure could be that in order to overcome rock pressure problems

or in order to constrain rock pressure problems to certain areas in the mine problematic areas are abandoned and that furthermore an unplanned safety pillar is left between these abandoned areas and other extraction areas. This safety pillar has normally to be of considerable size that it can fulfill its desired function appropriately and hence it adds besides the abandoned areas further resource losses.

The given examples show that rock pressure problems can have adverse effects on an operation and may cause its termination in extreme cases. For this reason, the question arises, what differentiates a rock pressure problem from a rock pressure phenomenon. Understanding these differences is important for implementing stress control and stress management. This knowledge may further on be used to prevent that rock pressure phenomena become rock pressure problems.

- Spatial extent of rock pressure phenomena: An important point is on how many locations a rock pressure phenomenon occurs. It makes a considerable difference, whether the spatial extent is rather confined and limited or whether the rock pressure phenomenon occurs over larger areas. For example, intense rock fracturing constrained to a short section of a stope access drift may be manageable and thus not critical for the overall objective of mineral extraction. However, if the same intense rock fracturing would occur in many drifts or in a whole mining section, it may put the objectives of mineral extraction at risk and it thus becomes a rock pressure problem. The occurrence of rock pressure phenomena over larger areas implies usually a general rock pressure problem. However, there may also be particular situations, where a large areal extent of rock pressure phenomena would not be regarded critical; for example, the use of crush pillar systems to improve hangingwall control in the face area.
- Intensity of rock pressure phenomena: The intensity or magnitude of rock pressure phenomena is critical. For example, a small fracture zone near an excavation may be easily managed with support and it would therefore not cause any further problems. In contrast, a large, intense fracture zone may lead to excessive deformations, dilution or safety hazards. Experienced deformations in squeezing ground conditions are therefore illustrative. Karampinos et al. (2015) and Varden and Woods (2015) report on thresholds for squeezing conditions in mining tunnels, when measures must be taken to control deformations. Another example is the magnitude of seismic events. Events below a certain magnitude may not be critical at all.
- Position of occurrence of rock pressure phenomena: The position of occurrence has to be put in context to active mining areas and active mining infrastructure. Rock pressure phenomena occurring remote from active areas and infrastructure may not result in any complications at all. Moreover, the importance of infrastructure has to be considered. Small fracture zones or deformations in a main shaft may have severe consequences on the operation (Wagner and Salamon, 1973), whilst the same fracture zone or deformations in primary or secondary infrastructure may not

be critical at all. As mining advances, the position of active mining areas changes. Therefore, this point has also a temporal aspect.

- Stability and instability of fracture and failure processes of rock pressure phenomena: Fracture and failure processes in rock mechanics could be either stable or unstable. Principally, stable processes and mechanisms are slow and controlled, whilst unstable ones are associated with rapid, violent failures. The mode of fracture and failure and the transition from stable to unstable fracture and failure are critical issues particularly in deep mining. An illustrative example is the controlled and slow yielding and crushing of pillars (stable process) compared to the sudden collapse of pillars (unstable process). Another example for a common, unstable deep mining problem are rock bursts. The stability and instability of fracture and failure processes are especially important for rock pressure phenomena, which are implemented on purpose; compare next point.
- Active, controlled implementation of rock pressure phenomena: Certain rock pressure phenomena may be implemented on purpose. The reason behind is that such rock pressure phenomena are used actively in the mineral extraction and they are therefore an integral, strategic part of a certain mining layout and mining sequence. An illustrative example is the use of stress caving in cave mines operating at considerable depths. (Duplancic and Brady, 1999) Another one are sacrificial excavations, which are allowed to cave in order to provide an improved stress situation in other excavations nearby. (Galvin, 1992) The application of crush pillars is another example. (Ozbay et al. (1995), Watson et al. (2010), Watson et al. (2014), Du Plessis and Malan (2018))

Overall, the above-mentioned points are critical for the transition of rock pressure phenomena to rock pressure problems. Several of these points need to be fulfilled for the development of a rock pressure problem. Therefore, the occurrence of rock pressure phenomena per se is not critical. The key aspect is, whether rock pressure phenomena evolve to rock pressure problems. Controlling and constraining rock pressure phenomena call thus for a proper mine planning. Finally, it has to be mentioned that the active use of rock pressure phenomena may be a strategic element in deep mining and the proposed stress management concept.

3.2 Consequences of rock pressure problems

3.2.1 Importance of infrastructure and structural elements

As outlined in the foregoing section, a rock pressure problem is present, if the stress situation or energy release jeopardize the objectives of mineral extraction, namely a safe, as complete as possible and economic extraction. Therefore, several points need to be fulfilled. One of these points is the position of rock pressure phenomena relative to active mining infrastructure and active extraction areas. The position of rock pressure phenomena is well suited to discuss possible consequences of rock pressure problems. For the related, following discussion it is convenient to distinguish between different excavation and infrastructure types. Following infrastructure categories are considered:

- Main infrastructure: The main infrastructure is required for accessing and developing a mineral deposit from surface. Main infrastructure is utilized usually over long periods or the lifetime of the mine. It is central for the production and used as access for handling and for transportation of material, machinery and personnel. Moreover, it provides space for critical installations, such as cooling facilities or crushing and processing plants. Main infrastructure comprises shafts, raises, ramps, tunnels, caverns or chambers.
- Primary infrastructure: The primary infrastructure is developed from the main infrastructure. It divides the deposit into different mining areas and prepares these areas for later extraction. Primary infrastructure serves therefore as access from the main infrastructure to extraction areas and is important for the overall production, namely for transportation and supply purposes. Primary infrastructure may also be utilized for rather long periods or the lifetime of a mine. It comprises tunnels, ramps, shafts or raises.
- Secondary infrastructure: The secondary infrastructure is the infrastructure within individual mining areas and required for mineral extraction in these areas. It serves as access to individual stopes. After the extraction of an area finished, secondary infrastructure is usually abandoned. The lifetime is typically in the range of months or years.
- Stope infrastructure: Stope infrastructure is required for the extraction of single, individual stopes. Accordingly, the lifetime is normally rather short and may only be some days or weeks. Stope infrastructure is often “consumed” during the extraction of corresponding stopes.

The actual position, size, shape and layout of infrastructure depend on several parameters, such as for example the depth of the deposit, the geology, the prevailing rock mass and stress conditions, the deposit size and shape and the mining method. Certain infrastructure types and their functions may also be combined. However, for rock pressure problems it can be concluded that the criticality and sensitivity of infrastructure to rock pressure is highest for main infrastructure and decreases towards stope infrastructure continuously.

Furthermore, it is necessary to distinguish between entry and non-entry excavations.

- Entry excavations: Entry excavations are excavations, which are entered and used by personnel in the process of mining. Infrastructure is mostly of entry type, whereas stopes are either entry or non-entry depending on the mining method, mine layout and type of stope.
- Non-entry excavations: Non-entry excavations are excavations, which are not entered by personnel. Remote-controlled machinery is though operated often in non-entry excavations. The most common non-entry excavation types are (large) open stopes, which cannot be supported by practical means, and caving stopes. Some infrastructure, such as for example rock passes, storage bins or ventilation raises, is also of non-entry type.

Entry type excavations are likely to be more sensitive to rock pressure phenomena and rock pressure problems, respectively. Personnel is using these excavations (regularly) and therefore the acceptable risk of fall of ground or other instabilities is lower than in non-entry excavations. In contrast, local rock pressure phenomena and associated potential instabilities in a non-entry excavation may not pose a direct safety risk. An exception are though rock pressure phenomena, which also affect nearby infrastructure, or which cause indirect safety hazards, such as for example windblasts in entry excavations. Moreover, rock pressure phenomena in non-entry excavations may damage remote-controlled or automated machinery or may slow down or prohibit the overall extraction process. Accordingly, rock pressure phenomena affecting non-entry excavations may still become rock pressure problems. Concluding, an emerging rock pressure phenomenon in a non-entry excavation may in general not be as critical as the same phenomenon in an entry excavation. Thus, the application of non-entry excavations in certain areas of the mine or for certain purposes is preferable. This circumstance is of importance for stress management and the proposed stress management concept.

Besides different types of infrastructure or different types of excavations rock pressure phenomena and problems may also affect structural elements of the mine, such as pillars or pillar foundations. If these structural elements cannot fulfill their desired purpose, the objectives of mineral extraction could be at risk. As structural elements are often nearby excavations or form the immediate vicinity of excavations, rock pressure phenomena occurring in structural elements may have a direct, visible impact on excavations. Depending on the excavation type and structural element the situation can arise that rock pressure acting in a structural element may cause unstable and unsafe conditions in an adjacent excavation, whilst the structural element itself is not significantly impacted and so it is still fulfilling its original function well. For example, fracturing in and subsequent rock fall from a pillar sidewall can result in unsafe conditions in an adjacent entry drift or entry stope. Contrary, fracturing and rock falls may not affect the function of the pillar adversely.

Structural elements are required for local load transfer inside mining panels or mining areas and regional load transfer in the entire mine. Accordingly, if their function is lost, infrastructure and stopes in individual mining panels could be affected or even infrastructure and other mining areas remote from the problematic area. The latter circumstance results from a changed load transfer and corresponding stress situation in the mine. Thus, the loss of the function of structural elements due to rock pressure problems may have far-reaching consequences. Examples therefore are rock bursts resulting from pillar bursting or pillar foundation failure (e.g. Lenhardt (1992), Labrie et al. (2007)) or significant, regional stress changes in the mine and changes of the stiffness of the loading system, which could result in sudden and unexpected overloading of other structural elements; see for example Coalbrook accident (van der Merwe, 2006).

Rock pressure phenomena and potential subsequent rock pressure problems are in general caused by fracture and failure processes in rock and rock mass and associated (large) plastic deformations. Accordingly, the main consequences arise due to the presence of a fractured zone and deformations near excavations or in structural elements. In the previous section several criteria are outlined, which have to be met that a rock pressure phenomenon evolves to a rock pressure problem. The tolerable degree of fracturing and deformations depends on the importance of the affected excavation or structural element as well as on the stability of fracture process. Figure 20 sketches the sensitivity of various excavations and structural elements to rock pressure phenomena illustratively. Long-lasting main infrastructure, regional stress transfer structures and regional loading systems are usually most critical.

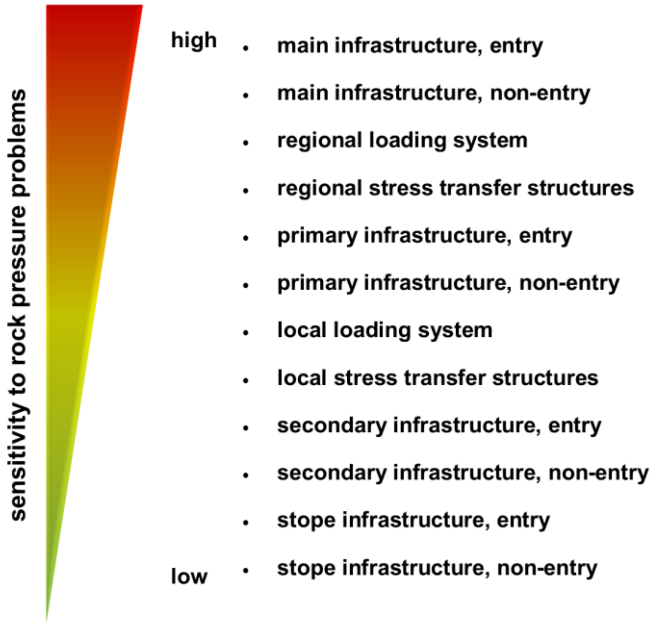


Figure 20: Schematic outline of sensitivity of various excavations and structural elements to rock pressure problems

3.2.2 Identification of rock pressure problems

Rock pressure phenomena occur in deep mining conditions usually regularly. Potentially, rock pressure problems may also develop. A delicate question is though, whether an evolving or existing rock pressure problem is detected and recognized as such. A key issue therefore is, whether the consequences can be quantified in terms of production, economic figures or safety statistics well. In case of major consequences on the safety or production, the quantification is usually straightforward. The following list provides an overview of some of these easily recognized and quantifiable rock pressure problems:

- <u>Damage to critical, main infrastructure:</u> Damage to main and critical infrastructure causes in most instances production disruptions or lowers production capacity. Reasons are a reduced amount of functional infrastructure and the required repair work. Accordingly, such rock pressure problems are normally recognized, because they bring about a loss of income. Damage to rock passes are an illustrative example and widely experienced. (Joughin and Stacey (2005), Hadjigeorgiou et al. (2008), Hadjigeorgiou and Stacey (2011), Quinteiro (2018)) Besides the rock stress related damage the flow of material in the pass can aggravate the problems significantly. (Hadjigeorgiou and Mercier-Langevin (2008), Esmaieli et al. (2013)) Furthermore, damage to main ramps and shafts, which are required for access and hoisting, (e.g. Yao et al. (2009), Potgieter (2015), Hopkins et al. (2018)) belongs to this category.

- Occurrence of rock bursts: Rock burst damage is generally easy detectable. Furthermore, seismic monitoring systems are a standard monitoring tool in most deep mines and these systems allow to detect potentially damaging seismic events immediately. Rock bursts are normally classified as a rock pressure problem, as they impose a serious safety hazard and as they can cause major damage to infrastructure and extraction excavations. The mitigation of seismic risk has been intensively worked; see for example Durrheim (2010), Potvin et al. (2019a).
- Collapse of mining sections or considerable damage in mining sections: Collapses of or damage in mining sections have, similar to damage to critical infrastructure, a direct influence on the production. Repair work is required in affected sections or in case of collapses or extensive damage the affected sections may have to be abandoned. If there are not sufficient other areas prepared and ready for production, production and thus income is lost. This production loss can be significant. Furthermore, collapses and instabilities in larger areas affect the safety adversely. Collapses of mining sections or large-scale damage are amongst others reported by Pardo Mella (2015) in the Esmeralda section of El Teniente mine or by Dubinski (2013) in Rudna mine.
- Large deformations preventing efficient operation of equipment: The consequence of this issue is that the production and productivity drop, which make it easily recognizable as a rock pressure problem. Moreover, additional costs arise because of the required rehabilitation. Excessive deformations are often encountered in squeezing ground conditions. (e.g. Fernandez et al. (2011), Mercier-Langevin and Wilson (2013), Karampinos et al. (2015), Woolley and Andrews (2015))
- Frequent support failure and rehabilitation demand: Ongoing overloading and subsequent failure of support systems impose a safety hazard, as an adequate protection of personnel and equipment is no longer provided. Costly and time-consuming rehabilitation measures are required, which cause further a lower productivity and potentially a reduced production. Support failure is often associated to foregoing points, where support acts as a last row of defense, but where it is not able to withstand the prevailing forces or deformations.

However, certain rock pressure problems may not be identified easily. These rock pressure problems comprise typically situations, where either the consequences are not severe or where they can be managed reasonably well. Accordingly, these types of problems may also be classified as rock pressure phenomena, as they do not put the objectives of mining at risk directly. A prominent example of such rock pressure problems is the development of a stress driven fracture and deformation zone, which can be stabilized with available support systems. It is common practice to modify and if necessary to improve ground support systems to meet the requirements of the prevailing mining environment. (Potvin and Hadjigeorgiou (2016), Potvin et al. (2019b)) As the mining depth increases or as the stress situation worsens because of ongoing nearby mining activities, the required support system capacity increases. Accordingly, stronger support systems are quite often installed. The higher associated cost, longer development times, lower production rates and potential rehabilitation efforts are mostly accepted and the main cause of the difficult situation, namely improper stress control, is addressed seldom actively. A similar example is the occurrence of mining-induced seismicity and the associated dynamic loading of excavations and installed support systems. A trend to heavier and better suited support systems for dynamic loading conditions can be observed as well; see for example Simser et al. (2002), Jacobsson et al. (2013), Morissette et al. (2017a). The examples given above outline a clear passive strategy against increasing rock pressure or increasing energy release; compare section 4.1.

Another comparable type of rock pressure phenomena or problems may also be accepted, namely the occurrence of high stress and seismicity in situations, which seem to be inherent to certain mining methods or mining situations. Examples therefore are undercutting in block caving, the abutment problematic in sublevel caving or sill pillar issues in steeply dipping deposits. Again, such situations are often addressed by strategies, where the passive component (support and rehabilitation) dominates or where another specific, but mostly reactive measure such as pre-conditioning or de-stress blasting is implemented. Examples are increasing support capacity in sill pillar areas (Simser (2005), Landry and Reimer (2019)), installing heavy support systems in undercut and production levels (Campbell et al. (2018), Stegman et al. (2018), Mühlenbrock et al. (2020)), deploying hydraulic fracturing in block caving as a rock burst mitigation measure (Pardo and Rojas (2016), Cuello and Newcombe (2018), Orrego et al. (2020)) and utilizing de-stressing methods in sill pillar areas (Kempin et al. (2007), Andrieux et al. (2010), Townend and Sampson-Forsythe (2014)).

All of the above-mentioned, accepted or improperly recognized rock pressure problems have in common that their corresponding additional cost or their safety implications are rather difficult to outline and quantify. For this reason, such stealthy rock pressure problems are commonly accepted. A contributing factor is probably is that there is a lack of practically implementable measures and strategies for stress and seismicity control in some of such situations. Another factor is that the implementation of active rock pressure control strategies is more often than not a decision, which has to be taken on the board level of mining companies. The background is that an active stress management often involves major departures from approved company practices and potentially a loss of mineral reserves, which may have to be brought to the attention of shareholders of the mining company and thus can have consequences for the share value of the company. In contrast gradual increases in cost fall under changes in operating costs, which can be attributed to increases in depth without necessarily appreciating the long-term consequences of these increases.

So far the aspects related to the consequences of rock pressure problems on safety and profitability have been in the focus. The consequences on the completeness of extraction are even more difficult to quantify. Thus, occurring problems related to safety and profitability are in the foreground and the impact of rock pressure problems on the completeness of extraction may be rarely recognized properly. Furthermore, a lower extraction ratio may be accepted in order to minimize the (quantifiable) consequences of rock pressure problems on safety and profitability.

Finally, it can be stated that potential rock pressure problems are in many situations not identified as such due to a lack of quantification scales or rock engineering understanding and knowledge. Therefore, consequences of rock pressure problems, namely increased mining cost, increased safety hazards and reduced extraction ratios, are often not properly recognized and hence accepted. The roots of rock pressure problems may not be questioned further. This instance can change rapidly, if the consequences of rock pressure problems become obvious, if they impose a major thread to the operation and if they can be clearly attributed to rock pressure. A pressure for change and improvements is subsequently present in these situations.

3.3 Causes of rock pressure problems

Rock pressure problems are caused by fracture and failure processes in rock and rock mass and the corresponding plastic deformations. It is of interest, which parameters drive these fracture and failure processes. Knowledge of the driving parameters allows on the one hand identifying potentially critical situations (in advance) and on the other hand outlining key parameters, which may be used to influence the rock pressure situation positively. The following considerations and discussions provide a brief overview of fracture and failure processes and their main parameters. The emphasis is on the requirements for the proposed stress management concept. A detailed discussion of rock and rock mass fracture and failure is beyond the scope and can be found elsewhere, for example Brady and Brown (2006), Jaeger et al. (2007) or Ryder and Jager (2002). The prevailing stress state and the strength of rock, rock mass or structural elements are decisive, whether stress driven fracture and failure occur or not. Moreover, the stability or instability of the fracture or failure process has to be considered. A potential stabilization and halt of a fracture or failure process are of interest as well. For the development of a stress management concept, knowledge regarding the main parameters influencing the stress situation, the behavior of rock mass and the stability of processes is essential. Of particular importance for the stress management concept are parameters, which can be influenced by mining activities actively. Furthermore, it is important to note that the discussion focuses on stress driven processes, such as for example fracturing through intact rock or shear failure along existing discontinuities. Failure processes due to confinement loss, such as for example wedge failures resulting from a loss in clamping stresses, are not considered, even though confinement loss may contribute to the (final) collapse of a stress driven fracture zone. However, the main cause of the collapse are still the initial stress driven failure processes.

3.3.1 Fracture and failure processes

3.3.1.1 Fracture and failure in rock

Fracture and failure processes are driven by stresses overcoming the strength of rock. A compressive strength test of rock is well suited for outlining fracture and failure. The stress strain curve of a compressive strength test is shown Figure 21. The axial stress, the axial, radial and volumetric strain and the number of acoustic emission (AE) events, which are generated due to cracking, are displayed. Except of some settling and crack closure effects, the rock deforms elastically with a relatively linear behavior until about 40 % - 60 % of the peak stress (σ_p, strength of rock). At this point, fracturing and crack formation commences and continues at a low rate until approximatively 70 % - 90 % of σ_p. In this range the linear (elastic) stress strain relation is lost, particularly the radial strain deviates from linearity because of crack formation. At the final stage, fracturing intensifies significantly. The behavior becomes strongly non-linear and the number of cracks increases drastically. Finally, the stress inside the rock reaches the peak stress (rock strength), because cracking becomes such intense and because individual cracks grow together forming larger cracks. This is also the point of rock failure. After the peak strength of the rock is exceeded, the post-peak region is entered. Therein, three different types of behavior can be distinguished, namely a strain softening, a yielding and a strain hardening behavior; compare Figure 22.

- In a strain softening behavior the strength drops with increasing strain with a specific softening rate. A larger softening rate implies a larger strength decrease. Eventually, the strain softening stops and a relatively constant residual strength is reached.
- In a yielding behavior the strength remains constant with increasing strain.
- In a strain hardening behavior the strength increases with increasing strain with a specific hardening rate. A larger hardening rate implies a larger strength increase. For the strain hardening case the peak strength is rather difficult to define, because the stress does not drop at all. Accordingly, the peak strength in case of a strain hardening behavior is represented by the point in the stress strain curve, where the curve becomes markedly flatter.

The actual post-peak behavior depends strongly on the rock type, the prevailing stress regime and the sample shape and size. Fracturing can continue in the post-peak region. Besides forming new fractures sliding along distinct fracture planes can take place. At some point, sliding becomes the prominent mechanism and the formation of new fractures is stopped.

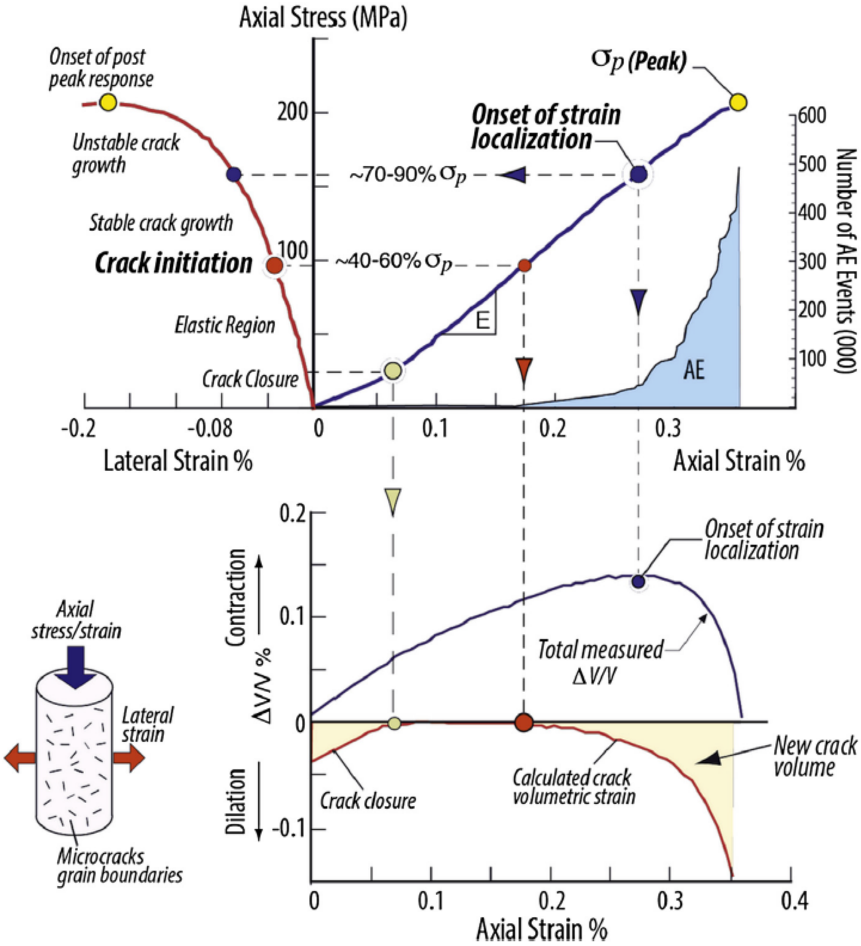


Figure 21: Fracture and failure of a rock specimen in a compressive strength test (Hoek and Martin, 2014)

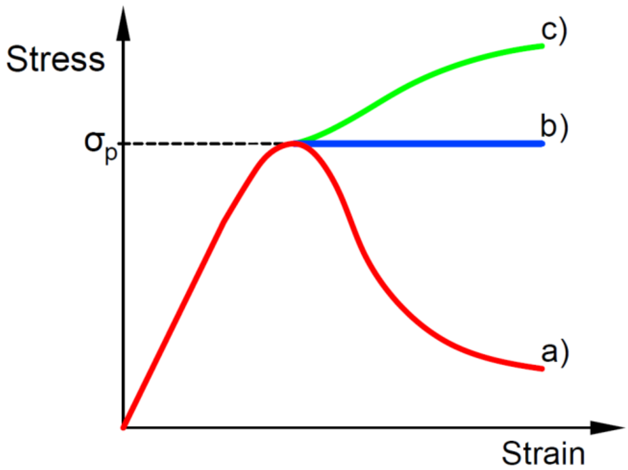


Figure 22: Post-peak behavior of rock: (a) strain softening, (b) yielding, (c) strain hardening

Overall, fracture and failure of rock are a complex process, which has been extensively studied (e.g. Hallbauer et al. (1973), Martin et al. (1997), Paterson and Wong (2005), Hoek and Martin (2014)). It is beyond the scope to go into details. For the present work and following discussion relevant points are:

- Fracturing commences at a specific stress state and results in the formation of new cracks and fractures. It intensifies when reaching the peak strength. Fractures are initially microscopic, but become macroscopic later.
- Fracturing leads to failure, which occurs at the point of peak strength. As fracturing occurs before failure, it is an indicator and precursor for a potential failure.
- The post-peak region is entered after the point of failure. Three different post-peak behaviors are distinguished: strain softening, yielding and strain hardening.
- Fracturing may also occur in the post-peak region. However, at some point sliding along existing cracks becomes the prominent mechanism and the formation of fractures is stopped.
- The principles of fracture, failure and post-peak behavior are not only relevant for rock. The behavior of rock mass and distinct structures, which fail because of sliding, can be described with these principles as well.

3.3.1.2 Fracturing and failure along discrete discontinuities and in rock mass

The principles of fracture and failure were discussed on basis of a compressive strength test in rock. The same principles can be applied to fracturing and failure of discrete discontinuities, such as faults or shear zones, and of rock mass. Figure 23 displays a typical shear stress shear displacement curve of a distinct plane, along which a sliding failure takes place. Initially, the relation between shear stress and shear displacement is approximatively linear, but it becomes non-linear close to the failure point. Fracture processes along the failure plane may take place as well, for example fracturing of rock bridges. After the peak strength (τ_p) is exceeded, the post-peak region is entered. A strain softening behavior is outlined in Figure 23. Depending on the properties of the failure plane and of the surrounding rock mass the post-peak behavior can also be yielding or strain hardening.

For a rock mass, which is comprised of rocks and discontinuities, fracture and failure processes are a combination of fracturing and failure through rock and along discontinuities. The same principles apply accordingly, but the actual mechanisms of fracture and failure become much more complex.

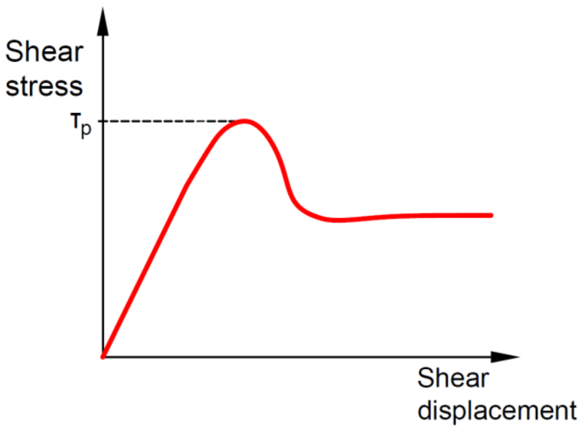


Figure 23: Shear stress – shear displacement curve for sliding along a discontinuity with a strain softening post-peak behavior

3.3.1.3 Fracture and failure of excavations and structural elements

Excavations and structural elements, such as pillars or beams, are comprised of rock mass. Discrete discontinuities may be present as well. Hence, fracture and finally failure of excavations and structural elements are comparable to fracture and failure in rock mass. Fracturing is initiated at certain stress magnitudes and occurs before failure. In most instances even macroscopic fractures can be observed before actual failure takes place. Figure 24 displays pillar stress – pillar compression curves of in-situ coal pillar tests. (Wagner, 1974) The vertical stress distribution inside the pillar is outlined as well. At the beginning, the pillar shows a relatively linear behavior. As the pillar stress increases, fracturing starts at the corners and boundaries of the pillar and moves further inwards. Close to the peak pillar strength the behavior becomes non-linear. After the pillar was overloaded, the pillar stress drops. However, fracturing continues, which can be seen by the changing stress distribution inside the pillar. The core of the pillar is highly stressed, even though the pillar is quite far into its post-peak region. The given example highlights the parallels between the compressive strength test of rock in the laboratory and the behavior of a complex structural element, namely a pillar, in a mine. It confirms further that fracture processes occur before actual failure and therefore that fracturing is well suited as an indicator for the development of a potential rock pressure problem.

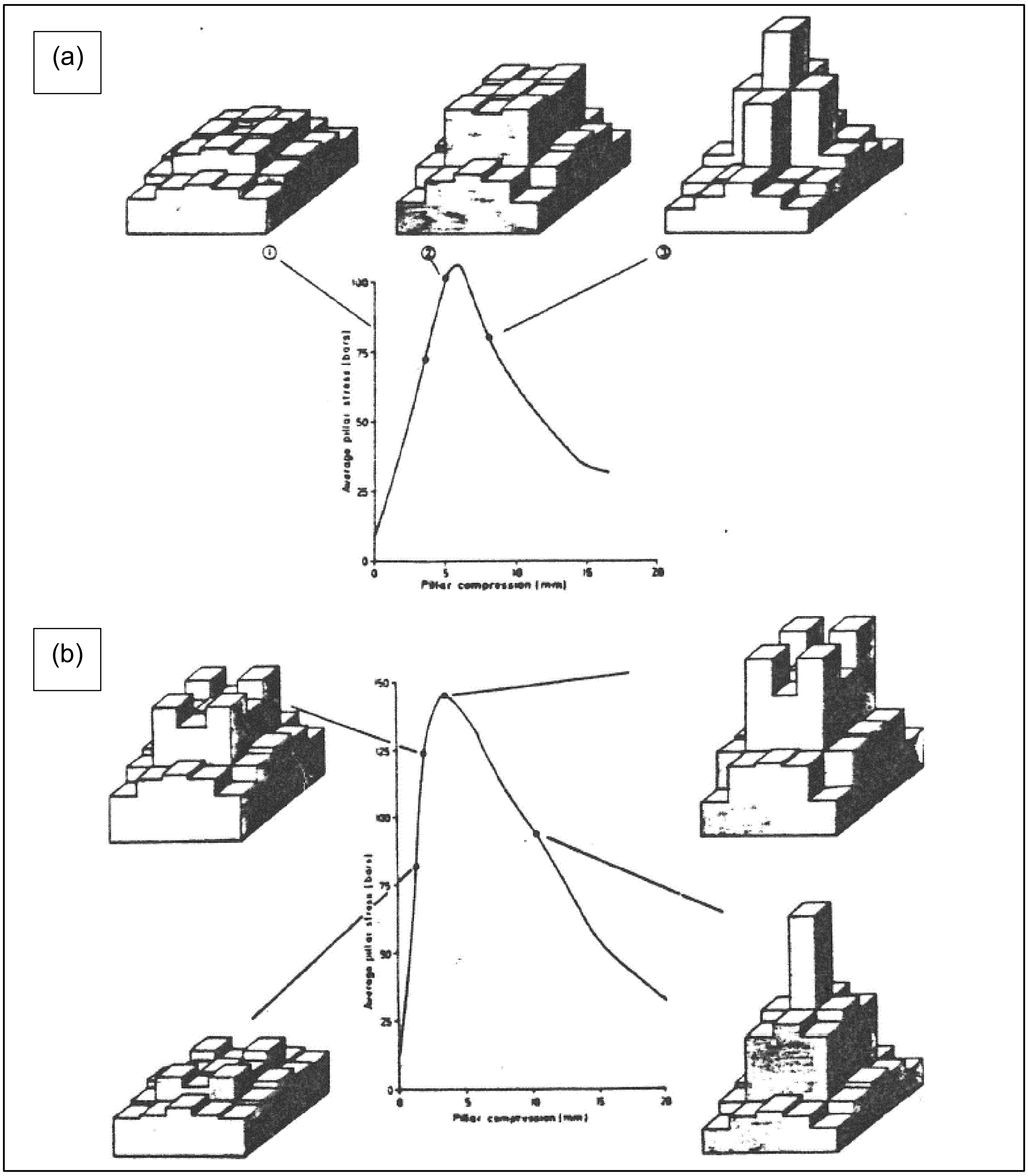


Figure 24: Average pillar stress – pillar compression curves of coal pillars and vertical stress distribution at half height of the pillar at selected points on the stress – compression curve; (a) pillar with width-to-height ratio of 1; (b) pillar with width-to-height ratio of 2; (Wagner, 1974)

In contrast to rock, rock mass and discrete discontinuities the term failure is not necessarily denoting that structural elements or the rock mass near excavations are loaded beyond their peak strength. Failure of excavations or structural elements can also denote that the excavation or structural element is no longer able to fulfill its desired purpose. This instance is referred to as functional failure. Functional failure is normally indicated by fracturing as well and it is further often associated with the actual failure of rock mass. Depending on the purpose the sensitivity of the excavation to fracture processes and potential overloading (failure) of rock mass are quite different. Illustrative examples are:

- A main hoist shaft and a tunnel used for extracting a stope: Whilst even a minimum amount of fracturing near a main shaft could impose a major problem, the stope tunnel may be exposed to considerable amount of fracturing and deformations without further issues. In the first case, the rock mass near the shaft is not (or only a very small zone) in its post-peak strength region, whereas for the stope tunnel a large volume of rock mass entered the post-peak region.
- A stable panel pillar and a crush panel pillar: Stable panel pillars are used in room and pillar mining, where pillars are required to support the hangingwall strata. As these pillars are usually quite small and as they therefore show typically a strain softening behavior, they must not be loaded beyond their peak strength. Otherwise, a collapse of the concerned mining section is very likely; see for example Zipf and Swanson (1999), van der Merwe (2006). Thus, the point of functional pillar failure corresponds to the pillar failure in terms of its peak strength. Contrary, crush pillars must be loaded beyond their peak strength and they must reach their residual strength. (Watson et al. (2010), Du Plessis and Malan (2015b), Du Plessis and Malan (2018)) Otherwise, crush pillars fail from a functional perspective. In order to fulfill their function, the crush pillar and the rock mass forming the crush pillar are in a failed state though.

Using the term failure for the actual overloading of rock mass or structural elements as well as for the disability of excavations or structural elements to fulfill their desired functions can be misleading. Normally, the context clarifies, whether it is referred to an actual failure of rock mass or to a functional failure. If not, the functional failure is mentioned in this work explicitly.

3.3.1.4 Summary fracture and failure processes

Rock pressure phenomena and rock pressure problems are caused by fracture and failure processes. Either the actual failure of the rock mass or the functional failure of an excavation or structural element can be the source of a rock pressure problem. For fracture and failure on the hand the prevailing stress situation is of interest and on the other hand the strength and behavior of a rock mass or of a structure. Furthermore, the stability of fracture and failure processes is decisive. Stable fracturing and failure may not be critical, whereas an unstable, violent failure causes quite often a rock pressure problem. In order to control rock pressure problems efficiently and foresighted, the sources of fracture and failure processes must be addressed. Therefore, an understanding of stress, rock mass strength and behavior and stability of fracture and failure processes is necessary. In the following sections a brief overview of stresses, strength and behavior of rock mass and structural elements and the stability of failure is provided. The objective is to prepare the basis for the proposed stress management concept as well as identifying most important parameters for the control of rock pressure.

3.3.2 Stresses

Primary stresses are prevailing in the earth crust prior to mining. They originate of the weight of the rock mass, plate tectonics and geological processes, such as erosion, cooling or intrusions. ((Fairhurst, 2003), Brady and Brown (2006)). The local primary stress state is significantly influenced by the prevailing conditions, such as the composition of the rock mass, the geological history, surface topography and geological structures. Accordingly, the primary stress state varies spatially, often over quite short distances. As the mine is built into the primary stress field, the primary stresses constitute the loads on the mine structure, which must be handled by mine design.

3.3.2.1 Stress changes resulting from isolated excavations

Mining activities, which comprise the continuous creation of new excavations, disturb the primary stress state and cause stress alteration. Figure 25 provides a conceptual model proposed by Salamon and Oravecz (1976) of the impact of an excavation on the primary stress field. The excavation is situated in a rock mass, which is subjected to primary vertical (σ_{vp}) and primary horizontal stresses (σ_{hp}). The primary stresses act on the boundaries of the model. Prior to the creation of the excavation the primary stresses are present at any point in the rock mass and in equilibrium. The stresses, which are perpendicular to the excavation boundary, correspond to the primary stresses at the future excavation boundaries (indicated by lines) (Figure 25a). The equilibrium is disturbed by the excavation, because the volume of the excavation becomes stress free. The primary stresses, which act at the model boundaries, are not altered and remain constant. As a result, stresses must redistribute near the excavation to generate a new equilibrium, wherefore stresses are induced in the vicinity of the excavation. The induced stresses at the excavation boundary and in perpendicular direction to the boundary are of equal magnitude as the primary stresses but in opposite direction. (Figure 25b) The induced stresses cause deformations in the rock mass as well as the generation of resultant stresses, which cause rock fracturing and failure. The resultant stresses are the sum of the primary and induced stresses. Accordingly, the resultant stresses at the excavation boundary, which are perpendicular to the excavation boundary, are zero. (Figure 25c) As the induced stresses pull the excavation boundaries inwards, relatively high resultant stresses are generated near excavation boundaries in tangential direction. Distant of the excavation the resultant stresses correspond to the primary stresses due nonexistent induced stresses.

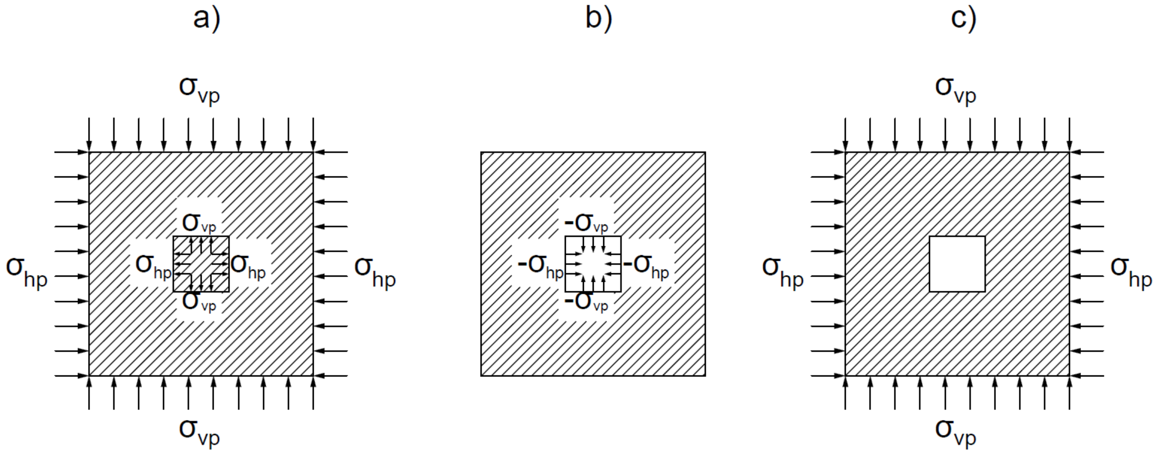


Figure 25: Effect of an excavation on the stress field; (a) primary stresses, (b) induced stresses, (c) resultant stresses

3.3.2.2 Influence of excavation size, shape and orientation

From the model shown in Figure 25 it can be seen that the resultant stresses depend on the primary stress state and the excavation. For the excavation the size, shape and orientation are central. An illustrative example for the impact of these parameters is an infinitely long excavation with an elliptical cross-section. Jaeger et al. (2007) provide a generalized solution for the stress state near an infinitely long tunnel with elliptical cross-section. The resultant tangential stress in point A ($\sigma_{A,ell}$) and point B ($\sigma_{B,ell}$) of an ellipse, which axes are in direction of the far-field principal stresses, can be calculated after Equation 7 and Equation 8. (Brady and Brown, 2006) Figure 26 displays the ellipse geometry, the far-field stress state and the variables: σ_{vp} is the primary vertical stress, σ_{hp} is the primary horizontal stress, k is the ratio of primary horizontal to primary vertical stresses, W_{ell} is the width of the ellipse and H_{ell} is the height of the ellipse. The primary horizontal and primary vertical stresses are the primary principal stresses.

$$\sigma_{A,ell} = \sigma_{vp} * (1 - k + 2 * \frac{W_{ell}}{H_{ell}})$$

Equation 7

$$\sigma_{B,ell} = \sigma_{vp} * (k - 1 + 2 * k * \frac{H_{ell}}{W_{ell}})$$

Equation 8

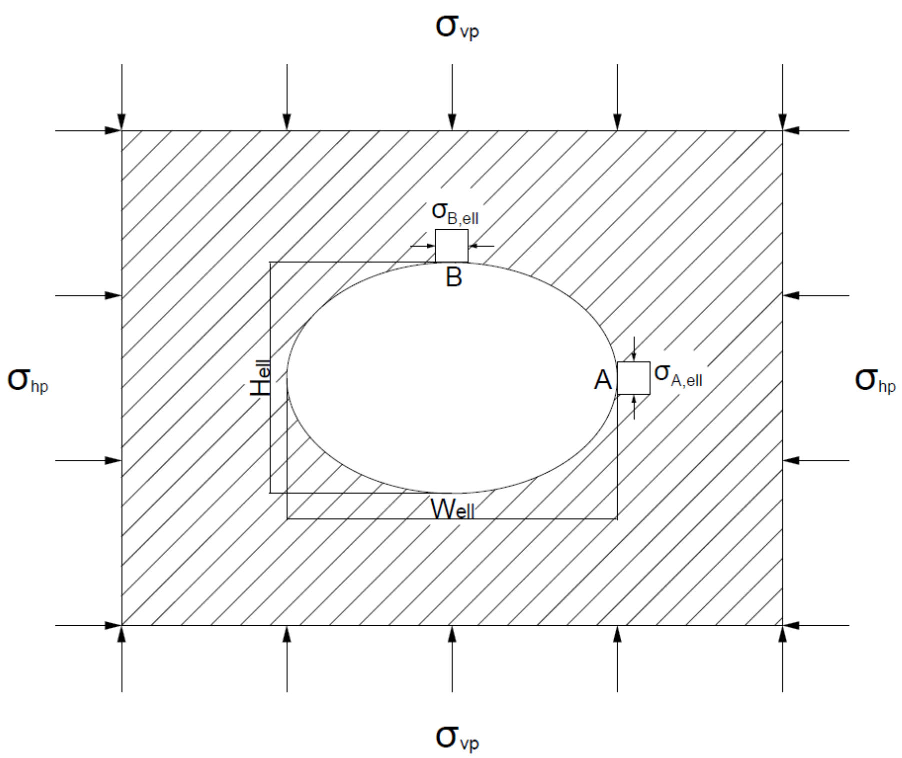


Figure 26: Ellipse geometry, far-field stress state and variables

Figure 27 outlines the influence of the primary stress state and the shape and the orientation of an infinitely long elliptical opening on the resultant tangential stress in point A and B. An aspect ratio (W_{ell} / H_{ell}) larger than one describes a "lying" ellipse. The resultant tangential stresses in point A for ellipses with a large aspect ratio are considerably high, whereas the resultant tangential stresses in point B are much lower. An aspect ratio of one refers to a circular opening and the resultant tangential stresses correspond to the stresses derived with Kirsch equations. Aspect ratios smaller than one characterize a "standing" ellipse. Accordingly, the stresses in point B increase drastically and the resultant tangential stresses in point A decrease with decreasing aspect ratios (smaller than one). The ratio of primary stresses has a noticeable impact on the stress magnitudes, but does not alter the general trend of the stress magnitudes. Figure 27 does not show the influence of the size of the ellipse, because the resultant tangential stress magnitudes in points A and B are independent of the size. However, as shown in Figure 6 for a circular tunnel, the spatial extent of stress changes increases with increasing excavation dimensions.

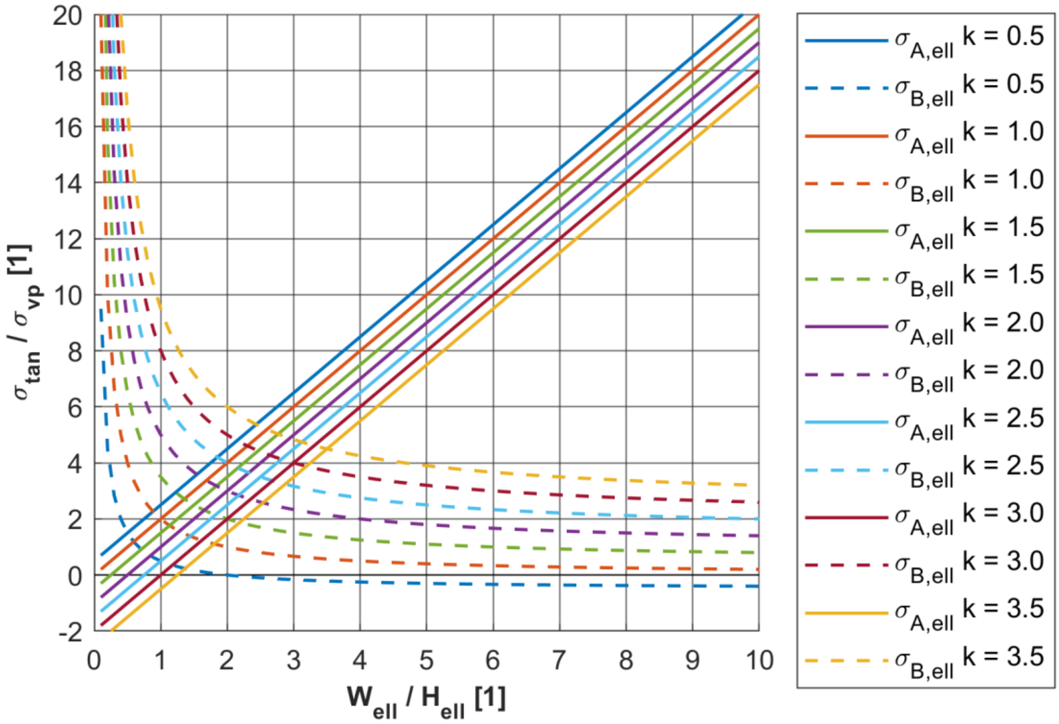


Figure 27: Normalized resultant tangential stresses in points A and B of an ellipse (Figure 26) for different primary stress states and ellipse aspect ratios

3.3.2.3 Influence of interactions between excavations

So far the effect of a single, isolated excavation on the stress situation in a homogenous, linear elastic rock mass and the main influencing parameters have been outlined. However, a mine is a complex building comprised of numerous excavations, which may interact with each other. This interaction alters the stress distribution further. For this an illustrative example are two horizontal tunnels at the same depth with a certain tunnel center spacing (S_{tunnel}). The tunnel center spacing is the horizontal distance between the two tunnel centers; compare Figure 28. The effect of the tunnel spacing on the stress distribution is demonstrated by means of a two-dimensional numerical simulation, where the tunnel center spacing is varied between 8 m and 40 m. Calculations are conducted with FLAC. The tunnels have a cross-section of 4 m x 4 m, rock mass is simulated with a linear elastic behavior, a Young's modulus of 40 GPa and a Poisson ratio of 0.25 and the primary stress state is hydrostatic with 54 MPa. The normalized resultant tangential stresses (σ_{tan}) along a horizontal line in a tunnel sidewall, which is oriented away from the second tunnel, and the normalized average vertical stress ($\sigma_{v,avg}$) calculated along a horizontal line at half height of the pillar between the two tunnels are outlined in Figure 29 and Figure 30. The position of the line in the tunnel sidewall (line 1) and the line, along which the average vertical pillar stress is calculated (line 2), are shown in Figure 28. Furthermore, the resultant tangential stress in the tunnel sidewall of an isolated tunnel is shown for comparison.

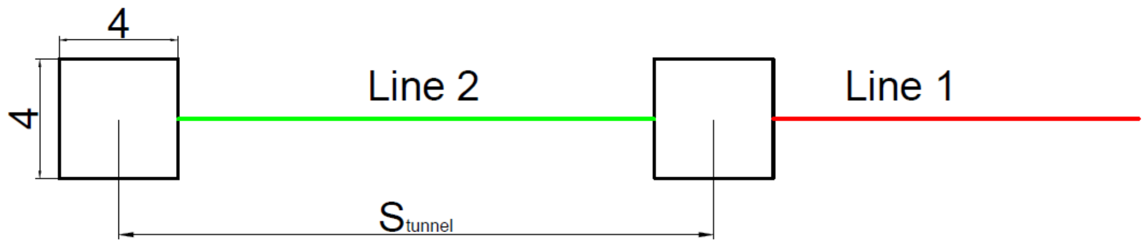


Figure 28: Two horizontal tunnels at the same depth separated by a certain distance S_{tunnel}. The tunnel dimensions in meter and the line for determining the resultant tangential stresses in the tunnel sidewall and the average vertical pillar stress are outlined.

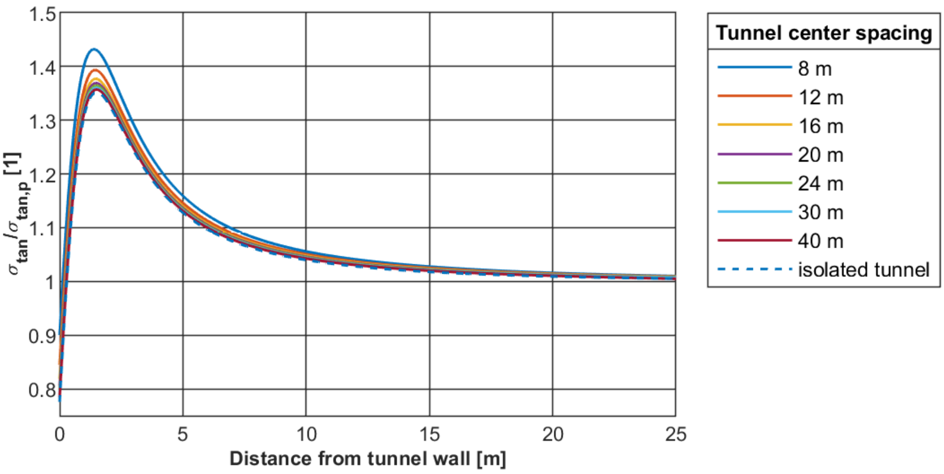


Figure 29: Normalized resultant tangential stresses in the tunnel sidewall for different tunnel center spacings

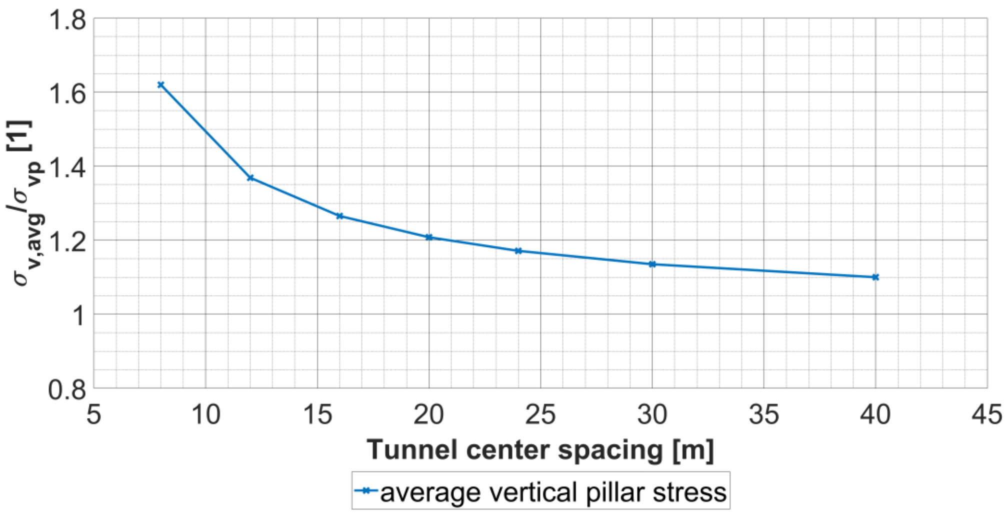


Figure 30: Normalized average vertical pillar stress for different tunnel center spacings

Figure 29 and Figure 30 show that there is no interaction between the tunnels and hence that the stress changes are comparable to an isolated tunnel, if the tunnel center spacing is sufficiently large. However, if the tunnels are moved closer together, interaction starts and stress changes are different. Resultant tangential stresses in the sidewall as well as the average vertical pillar stress rise. The effect of interaction on the stress situation is particularly prominent in the pillar. The reason for the interaction is that the tunnels are inside their zone of influence. For comparison, Brady and Brown (2006) define the zone of influence for circular tunnels in a hydrostatic stress field as a tunnel center spacing of three times the diameter of a the larger tunnel. In general, the zone of influence in an elastic rock mass depends strongly on the excavation shape, orientation and particularly size and the far-field stress state.

3.3.2.4 Influence of fracture and failure

Rock mass fracture and failure cause a departure of the so far anticipated linear elastic rock mass behavior. Correspondingly, fracture and failure have also an influence on the stress redistribution. Failure followed by a strain softening behavior has a prominent effect. Illustrative examples are a zone of overloaded rock mass near an excavation and the failure of a pillar. Figure 31 provides the stress at the face of a deep tabular longwall stope. For the elastic situation, the stresses rise towards infinity near the stope face. In contrast, a fracture zone at the face reduces the stress magnitudes significantly. At some distance from the face the influence of the fracture zone ceases and the stresses correspond to the elastic solution. Furthermore, Figure 31 shows that the effect of the fracture zone on the stress distribution is for the case of a deep tabular stope very localized.

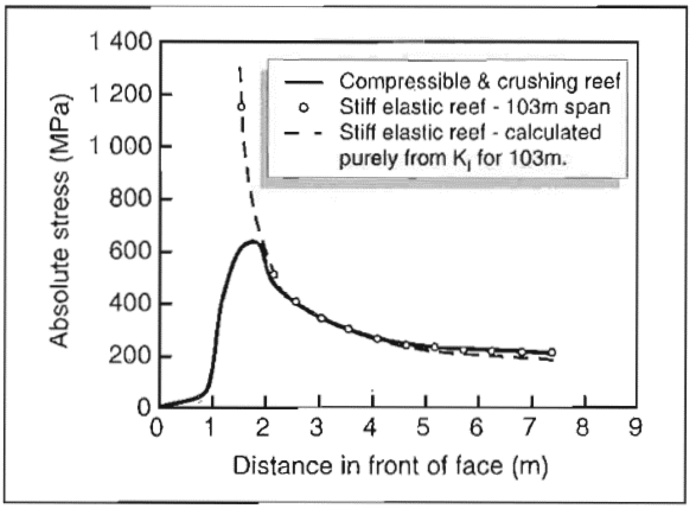


Figure 31: Modelled stresses at the face of a deep tabular longwall stope (Jager and Ryder, 1999)

The second example is the failure of a pillar, which is located between two tunnels. The considered geometry is shown in Figure 32. The tunnels have a cross-section of 4 m x 4 m and the pillar between them has a width of 4 m and a height of 4 m. The model setup and utilized parameters are the same as for the analysis of the interaction between these two tunnels (section 3.3.2.3). The pillar failure is simulated by removing the pillar and replacing it with a boundary stress in vertical direction, which corresponds to the anticipated pillar residual strength. Following pillar residual strengths are considered: 0 MPa (complete pillar failure), 5 MPa, 10 MPa, 20 MPa and 50 MPa. Figure 33 displays the normalized resultant tangential stresses (σ_{tan}) in a tunnel sidewall. The position of the line is shown in Figure 32. The resultant tangential stresses for the case of an intact pillar and an isolated tunnel are shown for comparison. Overall, pillar failure causes a significant stress increase in the sidewalls. The area of influence of the tunnels increases slightly. The lower the pillar residual strength is, the more prominent are these effects.

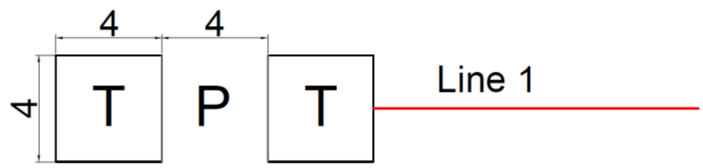


Figure 32: Two horizontal tunnels (T) separated by a pillar (P). The tunnel dimensions in meter and the line for determination of the resultant tangential stresses in a tunnel sidewall are outlined.

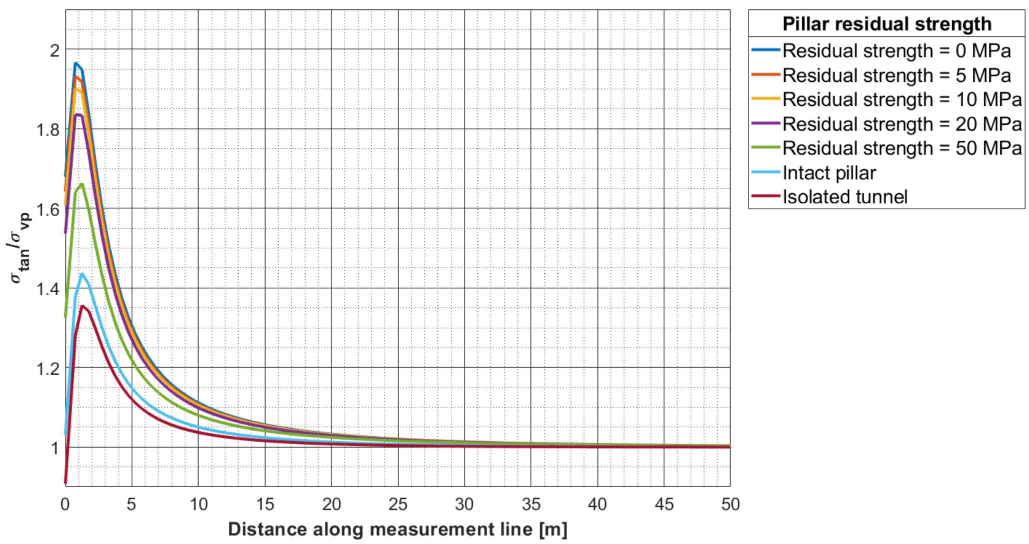


Figure 33: Normalized resultant tangential stresses in a tunnel sidewall for a failed pillar with varying residual strength

Fracture and failure of rock mass near excavations and of structural elements can have a significant impact on the resultant stress distribution. If the effect of fracture and failure on the resultant stress distribution is constrained to the vicinity of an excavation or structural element, it is referred to be local. Contrary, if the fracture and failure affect the resultant stress distribution even at large distances, the effect is regional.

3.3.2.5 Summary stress changes

The foregoing sections highlight the stress changes due to mining activities on basis of simple models and examples. Relevant points for the stress management at great depths are:

- Primary stresses impose the load acting on the mine structure. Generally, primary stresses cannot be modified by mining activities and must therefore be managed by mine design. (An exception may be vertical stresses in large-scale caving operation, which may be reduced by some extent due to the large volumes of rock mass, which are removed.)
- The excavation size, shape and orientation are critical for the resultant stress distribution.
- Excavations positioned within the zone of influence of another excavation interact and alter the resultant stress distribution. Such interactions make the resultant stress distributions normally more complex.
- Fracture and failure processes alter the resultant stress situation further. A differentiation between localized effects, which are relevant in the vicinity of an excavation, and regional effects, which change the stress situation even at a large distance of excavations and overloaded structures, is reasonable. Regional effects of fracture and failure are usually more important for the overall mine stability and stress management.

Besides the mentioned points the resultant stress redistribution is influenced by further aspects. The geological conditions, the stiffness of individual formations and the stiffness of individual structures have an influence. If stress redistributions take place, stiffer rock mass portions attract usually higher stress magnitudes. Another aspect is the loading system of the mine structure and the associated load transfer to the abutment areas. Overall, the stress situation is a complex function and depends amongst others on the primary stress state, the prevailing rock mass properties and the mining activities, which cause ongoing stress changes. Nowadays stresses are normally estimated by means of numerical simulations and compared with the in-situ performance of mine structures. This process is known as back analysis and widely used in the mining industry. An accurate determination of the resultant stress situation is though difficult, because the primary stress state is associated with uncertainties and the actual properties and behavior of rock mass are generally uncertain too. As the mine layout and mining sequence influence the stress situation in the mine strongly, they can therefore be utilized for controlling the stress flow through the mine and for dealing with uncertainties. Accordingly, the mine layout and mining sequence can therefore be utilized to prevent the occurrence of rock pressure problems by controlling the stresses acting on excavations and structures actively. Hence, they address the driving forces of rock pressure problems. But, on the other hand, an improper mine layout and sequence can be the source of considerable rock pressure problems.

3.3.3 Strength and stress strain behavior

In combination with the prevailing stresses the strength and behavior of rock, rock mass, distinct geological structures and structural element determine the occurrence of stress driven fracture and failure, which are the root of rock pressure phenomena and rock pressure problems. In the following sections, relevant aspects for rock pressure problems and stress management in deep mining regarding the strength and behavior of rock, rock mass and structure elements are outlined. A detailed discussion of strength and behavior is beyond the scope and can be found elsewhere (e.g. Ryder and Jager (2002), Brady and Brown (2006), Jaeger et al. (2007)).

3.3.3.1 Rock

From a rock mechanics point of view rock is the smallest unit of rock mass. It can be considered as homogenous in comparison to rock mass. Relevant rock properties in relation to rock pressure phenomena and problems are the elastic properties of rock, fracturing and failure of rock under different loading conditions and the post-peak behavior. Fracture and failure in rock under compressive loading as well as possible post-peak behavior were discussed in section 3.3.1.1.

3.3.3.1.1 <u>Determination of rock properties and associated uncertainties</u>

Rock properties are typically determined in the laboratory with different, standardized test arrangements and procedures. (e.g. Ulusay and Hudson (2007), Ulusay (2015)) Samples taken from drill cores are used. The standardized procedures as well as the small sample size provide repetitive conditions and thus enable to determine rock properties on a laboratory scale relatively well. The derived rock properties in the lab are in most instances a major (the main) input parameter for stability calculations concerning stress driven failure processes.

At this point, it must be noted that most data, information and knowledge regarding the behavior of rock have been derived in the laboratory in small-scale conditions. The behavior of larger volumes of rock, which is found in-situ, can be expected to be different. For example, Bieniawski (1968) investigated the impact of specimen size on coal strength and found that the strength decreases with increasing specimen size. Another example is the influence of dilation on rock strength and behavior in large-scale, in-situ conditions. The pillar strength tests of Wagner (1974) demonstrated that the presence of fractured and accordingly dilated portions of rock mass at pillar boundaries influences the behavior of inner rock mass portions significantly. This effect is not recognized properly in widely used strength criteria; see for example Wagner and Schümann (1971), who conducted stamp-load bearing tests on rock samples. The observed fracture zones were smaller than the fractures zones calculated theoretically on basis of elastic stress analysis. They attribute this circumstance to the effect of dilation of the fractured rock in the prevailing confined conditions.

Despite the importance of size on rock behavior there is only limited information on this aspect available. The reason for this is the force, which is required to test large rock specimen. Hence, structured and controlled investigations on rock strength and behavior on large specimen or in-situ experiments have not been widely conducted. Most noticeable for large-scale in-situ tests are probably coal pillar strength tests (Bieniawski (1968), Wagner (1974), Bieniawski and van Heerden (1975), van Heerden (1975)) and the work conducted in the underground research lab on massive granite. (e.g. Martin (1989), Martin et al. (1997), Martino and Chandler (2004), Read (2004)) Accordingly, the knowledge of the strength and behavior of large volumes of rock is limited and the appropriate quantification of the in-situ rock behavior remains difficult. The circumstances that the available information at the mine planning stage is rather limited and that drill cores are in most instances the only available data source add further uncertainties.

3.3.3.1.2 Effect of stress conditions

An important aspect is that the rock strength and behavior depend strongly on the prevailing stress conditions. The tensile strength and shear strength are considerably lower than the uniaxial compressive strength. The compressive strength increases further with increasing confining pressure. The confinement alters the post-peak behavior as well, namely the rate of strain softening decreases and the strain softening behavior transitions to a strain hardening behavior at a certain confining pressure. (Ryder and Jager, 2002) These influences of the confinement on rock strength and behavior depend on the rock type.

The relevant aspect for the stress management is that the rock strength and behavior can be influenced by the mine layout and mining sequence, because the layout and sequence have a considerable impact on the prevailing stress situation. Furthermore, the stress state and thus the strength and behavior of rock change over the lifetime of a mine.

3.3.3.2 Rock mass

The differences between rock and rock mass are strongly related to the presence of discontinuities, which alter the rock behavior and which make the rock mass inhomogeneous. Discontinuities comprise amongst others faults, folds, joints, bedding planes or schistosity. On a larger scale rock mass is even more inhomogeneous because of amongst others different geological formations, varying degree of jointing and different geological features, such as dykes or sills.

Two different types of discontinuities have to be distinguished, namely small discontinuities and large discontinuities in relation to the considered volume of rock mass; compare Figure 34. Individual small discontinuities do not dominate the rock mass behavior. Instead all small discontinuities in combination with the intact rock between them determine the rock mass behavior. The rock mass can be replicated as a continuum in this case. In contrast, the mechanical properties of large discontinuities have a distinct effect on the rock mass and must therefore be considered explicitly. For this reason, it is necessary to distinguish between the effect of small and large discontinuities. For the first the resulting, overall properties of the rock mass are of interest, whereas for the second the properties of individual discontinuities are of interest.

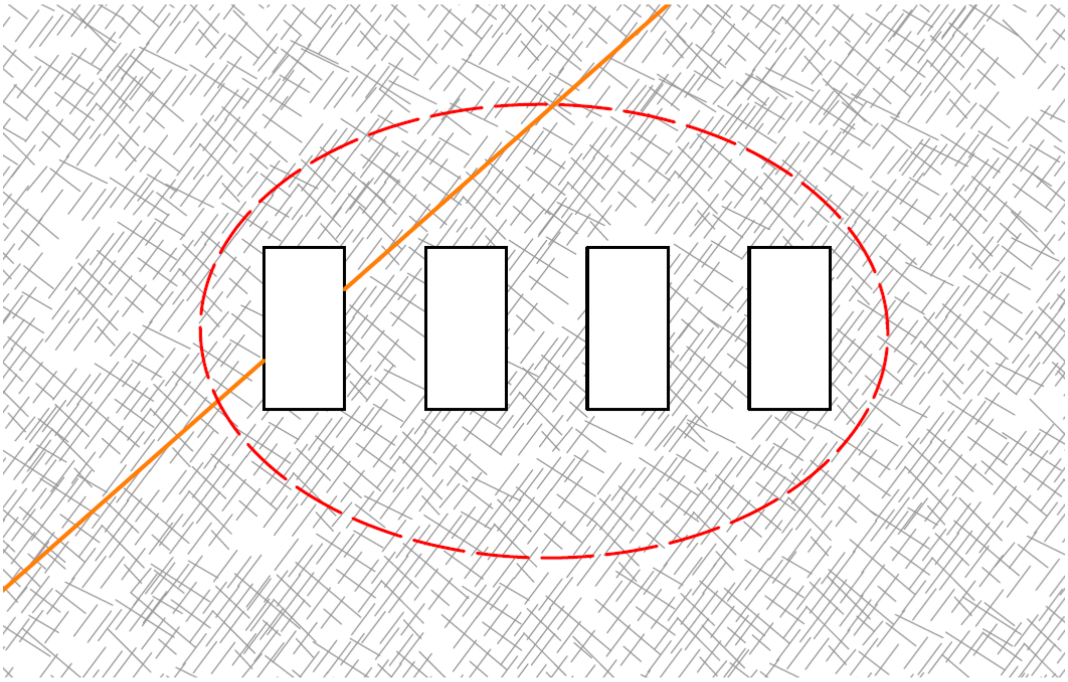


Figure 34: Schematic sketch of small (grey color) and large (orange color) discontinuities in relation to the considered volume of rock mass, which is indicated by the dashed red line, near a stoping panel

3.3.3.2.1 Large discontinuities (properties of individual discontinuities)

Large discontinuities have a discrete effect on the rock mass and must be considered explicitly. They comprise persistent, large faults, dykes, sills or shear zones. Discontinuities fail either in tension by overcoming their tensile strength or in shear by overcoming their shear strength. For large discontinuities the shear failure is principally most relevant, because tensile stresses do normally not occur over larger areas. A typical shear stress shear displacement curve for a discontinuity is shown in Figure 23. Of interest for stress management are the peak strength, post-peak behavior and residual strength, which are influenced by the nature of the discontinuity itself as well as the constraint of the discontinuity. Constraint conditions hinder dilation of the discontinuity during fracture and failure and increase therefore the strength. (Brady and Brown, 2006)

The shear strength of a discontinuity (τ_{sh}) can be described with a Mohr-Coulomb strength criterion; compare Equation 9. Whilst the cohesion (c) and the friction angle (φ) are depending on the conditions of the discontinuity, the effective normal stress (σ_n') can be influenced by the mine layout and mining sequence significantly. Besides the effective normal stress the mining activities have an impact on the shear stress acting along the discontinuity and on the constraint of the discontinuity. Therefore, the mine layout and mining sequence can be utilized for the control of large discontinuities. Mine design according to the excess shear stress criterion after Ryder (1988) makes use of this control possibility.

$$\tau_{sh} = c + \sigma_n' * \tan(\varphi)$$

Equation 9

Important to note is that the normal stress, the shear stress and the constraint on the discontinuity may change noticeably with time, especially if the discontinuity is close to active mining areas because of the ongoing stress changes resulting from the creation of new excavations.

Large discontinuities cannot be tested in a laboratory or in-situ with practical means. Therefore, their properties must be determined with indirect methods (see for example Barton (1973), Barton and Choubey (1977), Bandis et al. (1981), Barton and Bandis (1982)) or through back analysis, once mining progressed. As large discontinuities can have a major impact on the stability of the mine and as they can be a source of major rock bursts, an in-advance knowledge of the location and orientation as well as of the discontinuity properties is essential. However, this knowledge is often not available in a mine planning stage or associated with considerable uncertainties.

3.3.3.2.2 Small discontinuities (properties of rock mass)

Individual small discontinuities do not influence the rock mass behavior significantly. It is rather the entirety of small discontinuities, which dominate the rock mass behavior and which alter the rock behavior to rock mass behavior. The rock mass behavior depends strongly on the degree and orientation of jointing as well as on the properties of discontinuities. Depending on the degree and characteristics of jointing different generic rock mass types can be distinguished; see for example Brady and Brown (2006), who distinguish between massive, elastic rock mass, stratified rock mass and blocky rock mass.

3.3.3.2.2.1 Determination of rock mass properties

Comparable to rock properties the elastic properties, fracturing and failure under different loading conditions and the post-peak behavior of rock mass are relevant for the occurrence of rock pressure phenomena and rock pressure problems. In order to determine these properties, the properties of intact rock as well as the properties, orientation, number etc. of discontinuities and the water conditions have to be considered. Different methods can be applied for the determination of rock mass properties. Methods comprise direct methods, which are basically strength tests of rock mass, and indirect methods, which describe and determine rock mass properties with assistance of other methods and approaches. Indirect methods comprise rock mass classification systems, numerical rock mass replications and back analyses.

The direct method, namely conducting strength tests on rock mass samples or conducting in-situ rock mass tests, is in general either unfeasible or impractical. Large samples, which are difficult to create and handle, and large forces, which are difficult to generate, are required. The direct method has been applied for specific studies, which have been mainly of scientific nature; compare for example pillar strength tests (Wagner (1974), Bieniawski and van Heerden (1975)). However, for the regular application in practice, direct methods are principally not applicable. Hence, indirect methods are dominant.

The most prominent indirect methods are rock mass classification systems and the subsequent derivation of rock mass properties from the classification results. Rock mass classification systems describe the rock mass in a structured and systematic way. Individual parameters, which influence rock mass properties, are rated and combined according to fixed schemes. Parameters comprise amongst others rock strength, discontinuity spacing, discontinuity properties, ground water conditions and the stress situation. Various rock mass classification systems have been developed. Widely used systems are RQD (Deere et al., 1966), RMR (Bieniawski (1979), Bieniawski (1989)), Q (Barton et al. (1974), Barton (2002)), MRMR (Laubscher (1990), Laubscher and Jakubec (2001)) and GSI (Hoek (1994), Hoek and Brown (1997), Marinos and Hoek (2000)). The results can then be utilized amongst others for the estimation of rock mass strength (e.g. Bieniawski (1989), Barton (2002) Hoek et al. (2002)), the estimation of rock mass elastic properties (e.g. Bieniawski (1978), Sonmez et al. (2004), Hoek and Diederichs (2006)) or as input in design charts or design criteria (e.g. Potvin (1988), Grimstad and Barton (1993), Laubscher (1994)). A drawback of all rock mass classification methods is that they do not allow to determine rock mass properties accurately. Contrary, they are in most instances only a rough estimation of a probable property range.

Numerical rock mass replications are utilized to derive rock mass properties by means of numerical strength tests. The principle of this method is to determine the properties and characteristics of prevailing rocks and discontinuities. Then, the rock and discontinuity behavior are replicated numerically. Finally, a rock mass model comprised of the rocks and discontinuities is generated. Discrete fracture network techniques are applied to replicate jointing. The numerical model allows then to determine the combined behavior of rock and discontinuities. This concept has been developed for the synthetic rock mass modelling approach. (Pierce et al. (2007), Mas Ivars (2010), Mas Ivars et al. (2011)) A similar approach is presented by Elmo and Stead (2010). Although numerical replications of rock mass have been applied successfully (e.g. Reyes-Montes et al. (2007), Mas Ivars et al. (2008), Sainsbury et al. (2008)) and although they are considered to be an important factor in improving our understanding of rock mass (Brown (2008), Fairhurst (2017)), the numerical replication of rock mass is associated with some distinct drawbacks. First, the meaningfulness of the results relies on the quality of the input parameters, the knowledge of rock and discontinuity behavior and their numerical representation. (Elmo et al., 2016) Furthermore, it is not possible to confirm the results from numerical models with in-situ tests. Second, the method requires specific codes and skills to utilize them as well as high computing capacities. These aspects may not be easily and readily available in many situations in practice.

Back analysis can be utilized to improve the understanding of rock mass behavior. Mining experience and rock mass response are described and investigated systematically. As a result, rock mass properties are derived based on site experience. Overall, back analysis is a powerful tool and it enables a more accurate rock mass property determination than rock mass classification and numerical replication methods, because actual site observations are used as input parameters. The reliability of rock mass properties is therefore increased significantly.

In summary, the determination of rock mass properties is not straightforward and relies generally on indirect methods. Furthermore, the available data is often limited particularly at an early stage. Rock mass classification methods and numerical replication methods suffer from the drawback that they cannot make use of observations regarding the actual rock mass behavior. They rather estimate the properties based on field and lab data of rock and discontinuities, empirical relations and numerical descriptions of rock and discontinuities. In contrast, back analysis relies on the observed response of rock mass to mining activities. Accordingly, back analysis enables a better, more reliable estimation of rock mass properties. However, at a design stage, where in many instances the mine layout and sequence are fixed to a large extent, rock mass properties derived from back analysis are often not available.

3.3.3.2.2.2 Effect of stress conditions

Comparable to rocks, the rock mass strength and behavior depend on the prevailing stress conditions. Rock mass has generally a very low tensile strength and its compressive strength increases with increasing confining stress. The post-peak behavior may be influenced as well by the confinement. In contrast to rocks the actual extent of these effects are not as properly known and more difficult to quantify. The complexity of rock mass and of its behavior and the missing possibilities to test rock mass directly are main reasons for this. However, the mine layout and mining sequence can again be utilized to influence the rock mass strength and behavior, because the layout and sequence influence the prevailing stress situation. Further, the strength and behavior of rock mass change over time, because the stress state is altered constantly, while mining activities are ongoing.

3.3.3.2.2.3 Uncertainty and variability

Rock mass properties cannot be determined accurately and are therefore associated with uncertainties. Furthermore, the rock mass properties can vary over short distances. The variability and uncertainties can be considerable, which instance is critical in mine design, particularly if the data base and available experience are rather limited. This circumstance is commonly present in the planning stage of a mine or a mine extension. The observation, monitoring and back analysis of rock mass properties during ongoing mining activities can improve the understanding of rock mass and thereby reduce the related uncertainties. However, in order to react to new knowledge and experience and in order to implement corresponding adaptions in the mine, a certain flexibility in the applied mining method, mine layout and mining sequence is necessary. This flexibility improves further the adaptability to changing and locally variable rock mass conditions.

3.3.3.3 Structural elements

Structural elements are comprised of rock mass and part of the mine structure. They are required mainly for local and regional load transfer and they are important for maintaining the stability of the mine. Structural elements are for example pillars, pillar foundations, abutments, abutment foundations and beams. Figure 35 outlines these structural elements on basis of two room and pillar mining panels in stratified conditions.

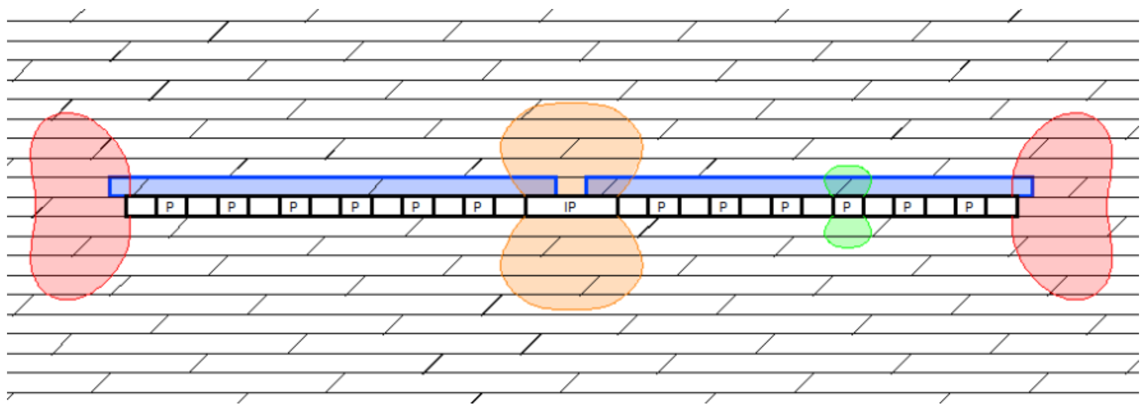


Figure 35: Structural elements in two room and pillar mining panels separated by an inter-panel pillar in stratified rock mass conditions. Pillars are denoted with P, the inter-panel pillar with IP, the red shaded areas outline abutments and abutment foundations, the orange and green shaded areas foundations of the inter-panel and a panel pillar, respectively, and the blue shaded areas beams in the immediate hangingwall.

Fracture and failure of structural elements are again critical for a potential occurrence of rock pressure problems. In general, the behavior of structural elements is often quite complex and dependent on several parameters. A discussion of the comprehensive topic of the properties of structural elements is not the objective of this section. However, structural elements can be divided into three components, which enable a targeted discussion of structural elements in respect to rock pressure problems. These components are:

- the rock mass comprising the element,
- the stress situation inside and near the element and
- the characteristics of the element.

As outlined in the following sections, the mine layout and mining sequence are of particular relevance and they can be utilized to influence the strength and behavior of structural elements positively. Hence, the layout and sequence have an important role in addressing rock pressure problems related to structural elements.

3.3.3.3.1 Rock mass comprising the structural element

Structural elements are comprised of rock mass. Accordingly, the considerations outlined related to rock mass refer also to structural elements. The uncertainties associated with rock mass properties are transferred to structural elements. Thus, the properties of structural elements are also uncertain. Most likely the uncertainties are larger, because the characteristics of the structural element add usually further uncertainties.

3.3.3.3.2 Stress situation inside and near the structural element

The stress situation has two effects, namely, first it imposes the load on the structural element and drives therefore fracture and failure, but second it has an influence on the strength and behavior of the structural element, because the rock mass strength and behavior depend on the prevailing stress state. Hence, controlling the stress state in and near structural elements has two effects. On the one hand, the stress magnitudes may be kept within certain limits to avoid fracture and failure. On the other hand, the stress state may be altered such that the strength of the element is enhanced. The stress situation is often though strongly linked to the characteristics of the element.

3.3.3.3.3 Characteristics of the structural element

The characteristics of the element are element specific and comprise the geometry of the element and the type of connection to the surrounding rock mass. Therefore, they govern the stress strain behavior of the element. Accordingly, the element characteristics distinguish between different element types and element behavior. For example, a beam and a pillar in the same rock mass have a different geometry and a different connection to the surrounding rock mass. The stress strain behavior of the pillar and beam is different. The prevailing rock mass properties, which emanate from the rocks and local jointing, the presence of large, distinct discontinuities and the prevailing stress situation may alter the stress strain behavior of the structural element further. Regarding the stress state it must be considered that it is often strongly influenced by the structural element characteristics.

Summarizing, the structural element characteristics can be utilized in the design to create structural elements of certain properties. However, the effect of element characteristics on the strength and behavior of structural elements is not fully understood. An illustrative example therefore are pillars; compare section 6.1.2.2.

3.3.3.3.4 Uncertainty in design

The strength and behavior of structural elements are associated with uncertainties. The uncertainties result from the uncertainties related to the rock mass properties and the uncertainties related to the influence of element characteristics. Similar to rock mass these uncertainties are particularly critical in the design stage, where the element characteristics and element position are fixed. During ongoing extraction uncertainties can be reduced. Experience is gained and back analysis specifically targeting considered structural elements can be conducted. Flexibility in the mine layout and mining sequence is necessary to implement design changes easily, quickly and at reasonable cost.

3.3.3.4 Summary strength and stress strain behavior

The strength and behavior of rock, rock mass and structural elements in relation to rock pressure problems have been outlined briefly. Following general conclusions can be drawn:

- Importance of strength and behavior: Rock pressure problems are caused by fracture and failure processes. Accordingly, the strength and behavior are of paramount importance. The prevailing rock, rock mass and discontinuities have strong effect. As they are part of the natural mining environment, they cannot be influenced and utilized for stress control actively. Rather, the stress management must be adapted to the prevailing rock, rock mass and discontinuities.
- Influence of the stress situation: The stress situation has a strong effect on the strength and behavior of rock, rock mass, large discontinuities and structural

elements. Providing favorable stress conditions affects strength and behavior positively, whereas providing unfavorable stress conditions has adverse effects and can cause significant rock pressure problems. Favorable stress conditions correspond in this respect in most instances to highly confined stress conditions and unfavorable conditions are low confinement or tensile stress conditions. For this reason, controlling the stress situation implies, besides limiting high stress magnitudes, that the strength and behavior of the prevailing material is influenced positively.

- Influence of structural element characteristics: The design of structural elements can be utilized to modify their strengths and behavior.
- Consequences of uncertainty: Uncertainty has a dominant role. The in-situ strength and behavior of rock, rock mass, structural elements and large, discrete discontinuities cannot be determined accurately and hence they are at least to some extent unknown. Uncertainties are usually largest at an early stage. As mining commences, experience is gained and back analyses can be conducted with the objective of reducing uncertainties. However, the design is fixed at an early stage, where data and knowledge are limited and uncertain. A false estimation and assessment of the prevailing properties can be a major contributor to rock pressure problems. Probably, the best approach to deal with uncertainties is to provide flexibility in the mine layout and mining sequence so that adaptions and modifications can be implemented easily, quickly and at reasonable costs. As outlined, modifications of the layout and sequence can address both the stresses driving fracture and failure and the strength and behavior of rock, rock mass, large discontinuities and structural elements.

Concluding, the mine layout and mining sequence are important for influencing and controlling the strength and behavior of rock, rock mass, large discontinuities and structural elements. A flexible layout and sequence are further necessary, because the flexibility enables adaptions to address uncertainties and unknowns in the design stage.

3.3.4 Stability and instability

Besides the occurrence of fracture and failure processes their stability is relevant for rock pressure phenomena and rock pressure problems. Stable fracture or failure is slow and gradual, whereas unstable fracture or failure is sudden and violent. Unstable processes are generally more likely to cause rock pressure problems. Stable processes may cause rock pressure problems as well, however, they have the advantage that fracturing and failure develop gradually leaving time to react.

3.3.4.1 Principles of the stability and instability of fracture and failure

Stability and instability of fracture and failure processes and their background have been recognized and discussed in relation to compressive strength tests of rocks and pillar systems. (Cook (1965), Wiebols et al. (1968), Salamon (1970)). A comprehensive discussion of the underlying principles is given by Salamon (1970), which discussion is the basis for the following outline.

The stability of fracture and failure depends on the characteristics of the fracturing and failing rock mass or structural element as well as on the characteristics of the loading system. A uniaxial compressive strength test of a rock specimen with a strain softening post-peak behavior is best suited to outline these dependencies and the stability of failure. Up to the point of failure the resistance against deformation increases with deformation and, after the maximum resistance against deformation (peak force) was reached, the resistance against deformation drops with deformation; compare Figure 36a. The slope of the force displacement curve of the specimen at any point in the post-peak region is denoted with k_S. In the test the rock specimen is loaded by a loading machine. As the forces, which are applied to the specimen by the machine, deform the machine itself, the machine can be represented by a spring with a specific stiffness k_M. The specimen – machine system can be simplified as shown in Figure 36b. The force F_M generated by the machine loads and deforms both the specimen and the machine. Accordingly, energy is stored in the system. The system is stable as long as additional energy must be put into the system for a further deformation of the specimen. This implies that the loading system itself cannot deform the specimen further.

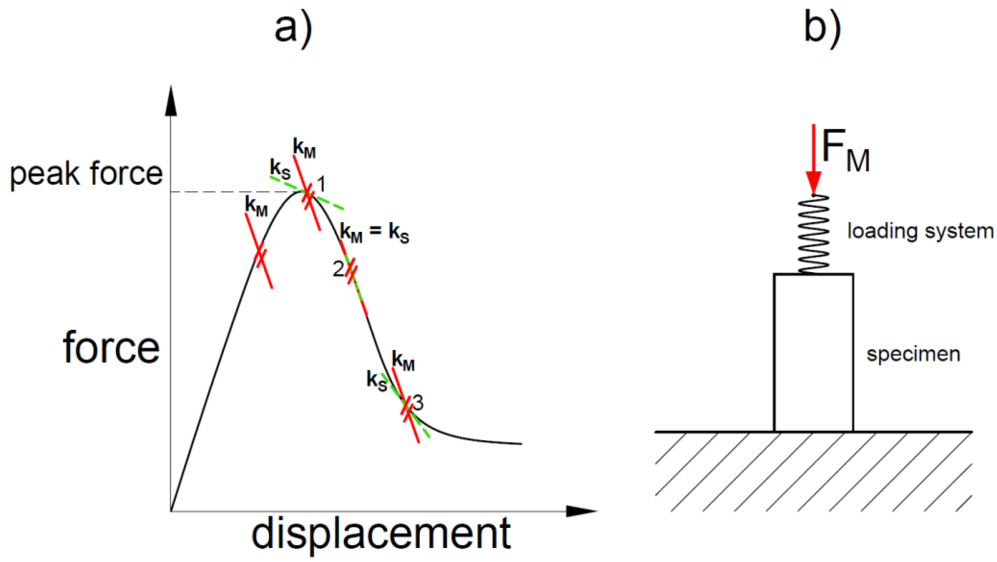


Figure 36: (a) Force displacement curve of a rock specimen in a compressive strength test. The machine stiffness k_M and the slope of the force displacement curve k_S at selected points in the post-peak region are outlined. (b) Model of the specimen – machine system

For the stability of the system two different regions can be distinguished:

- <u>Pre-peak region:</u> In the pre-peak region the resistance against deformation of the specimen increases with deformation. Energy is put into the specimen and the machine by increasing the force F_M. As the stored energy in both, the specimen and the loading system, is always increasing, there is no excess energy available and the system is stable. All fracture processes in the specimen before reaching peak strength are therefore stable.

- Post-peak region: In the post-peak region the situation changes. The resistance against deformation of the specimen decreases with deformation and the force F_M must therefore be reduced. Consequently, the stored energy in the loading system becomes available and it can do work on the specimen. Critical is, whether additional energy must be put into the specimen – machine system. In case additional energy must be put into the system, the system is stable, because the stored energy, which becomes available from the machine, cannot deform the specimen further. On the opposite, if the stored energy, which becomes available from the machine, can deform the specimen further, the system is unstable, because additional energy does not have to be put into the system, because the excess energy from the machine accelerates the failure and causes a quick and sudden failure. Salamon (1970) showed that the system will become unstable, when the machine stiffness k_M becomes tangent to the slope of the force displacement curve k_S of the specimen; compare Figure 36a point 2. The failure of the specimen and additional fracture processes in the post-peak region are therefore stable, as long as the machine stiffness k_M is larger than the slope of the force displacement curve k_S of the specimen in the post-peak region; compare Equation 10.

$$k_M > k_S$$

Equation 10

The above outlined principles of stability and instability are relevant for fracture and failure of rock, rock mass, structural elements and large, discrete discontinuities. Both, the post-peak behavior of rock, rock mass, structural elements and large, discrete discontinuities as well as the loading system properties are important. Figure 22 outlines three generic post-peak behavior types, namely strain softening, yielding and strain hardening. In the yielding and strain hardening case violent, unstable failure cannot occur, because additional energy must always be put into the system. For strain softening violent failure can occur depending on the stiffness of the loading system. A lower strain softening rate is though preferable for stability.

For mine design two possibilities for preventing unstable fracturing and failure exist. Either designing mine layouts and sequences with a high loading system stiffness or designing mine structures with a preferable post-peak behavior. The prevailing rock mass conditions though still have a considerable impact on the stiffness of the loading system and the post-peak behavior of mine structures and hence limit design possibilities.

3.3.4.2 Important situations in practice

The relevance of the principles of stability and instability are highlighted on three practical situations, which are an isolated excavation, a pillar and a fault. The isolated excavation represents thereby an example for the failure of rock mass, the pillar represents an example for the failure of a structural element and the fault represents an example for the failure of a large, discrete discontinuity.

3.3.4.2.1 *Isolated excavation*

The stability of rock mass fracturing and failure near an isolated excavation is discussed on basis of an isolated excavation. In the sidewalls of a tunnel rock mass fracturing and failure occurs; compare Figure 37. The failed rock mass shows a strain softening behavior and the stresses in the failed rock mass decrease. Whether failure is stable or unstable, depends on the strain softening rate of the rock mass and the stiffness of the loading system. The loading system is formed by the immediate hangingwall and footwall, which move downwards and upwards, respectively.

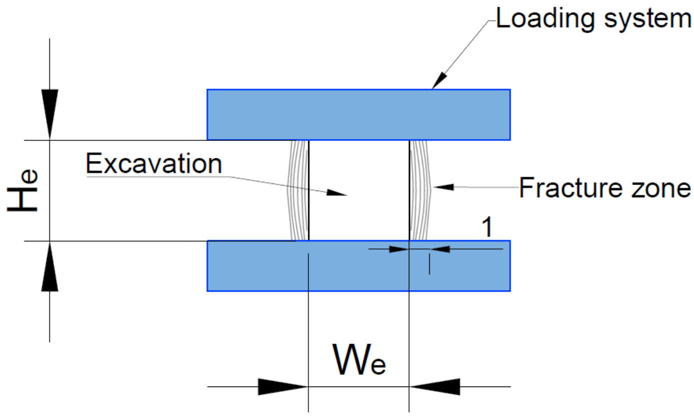


Figure 37: Fractured zone of rock mass with an extent of 1 m in the sidewall of an excavation and the corresponding loading system.

The prevailing rock mass properties have a major influence on the stiffness of the loading system as well as on the post-peak behavior of the rock mass. Minimizing the likelihood of unstable fracturing and failure of an isolated excavation can be achieved by reducing the brittleness of the rock mass or by increasing the stiffness of the loading system. Pre-conditioning blasting could be applied to decrease the brittleness. The far-field stress state and the excavation geometry have further an influence on the loading system stiffness. This influence is outlined with two-dimensional numerical simulations. Table 3 shows the considered excavation widths (W_e) and excavation heights (H_e) and the types of excavations, which are represented by these geometries. The primary vertical stress is 54 MPa, the ratio of primary horizontal to vertical stresses is 0.5 and 1, respectively, the fracture zone depth in the sidewalls is 1 m for all excavations. Thus, the loading system stiffness is calculated for a nominal roof (floor) area of 1 m². The rock mass has a linear elastic behavior and the Young's modulus is 40 GPa and the Poisson ratio 0.25.

The calculation of the loading system stiffness is outlined in section 6.1.3.2 and it is carried out with numerical simulations conducted with FLAC. In the simulations a number of simplifications are made, namely:

- Assuming a fracture zone depth of 1 m for all situations is a simplification, because the fracture zone depth is influenced by the excavation geometry and the stress state. However, this simplification makes the calculated loading system stiffnesses comparable.
- Pillars are not left inside or backfill is not placed into the considered mined-out panels.

Width W_e [m]	Height H_e [m]	Represents
4	4	Mine tunnel
6	6	Mine tunnel
30	10	Stope
50	30	Mined-out panel
100	30	Mined-out panel

Table 3: Considered excavation widths, excavation heights and represented excavation types for the calculation of the loading system stiffness of isolated excavations

Figure 38 displays the loading system stiffness for a fractured zone of rock mass of a width of 1 m in the sidewall of excavations with varying geometries and in varying primary stress conditions. The loading system stiffness decreases with increasing excavation dimensions. The influence of the ratio of primary horizontal to primary vertical stresses is negligible for smaller excavations, which represent mine tunnels and a stope, but becomes relevant for the larger excavations, which represent mined-out panels. Accordingly, the likelihood of unstable fracture and failure in excavation sidewalls increases with increasing excavation size. Besides the excavation size and primary stress situation the rock mass properties and the excavation shape have an influence on the loading system stiffness. If the Young's modulus of the rock mass decreases, the loading system stiffness decreases as well. Therefore, in order to determine the loading stiffness, site-specific conditions have to be considered and individual analyses are necessary.

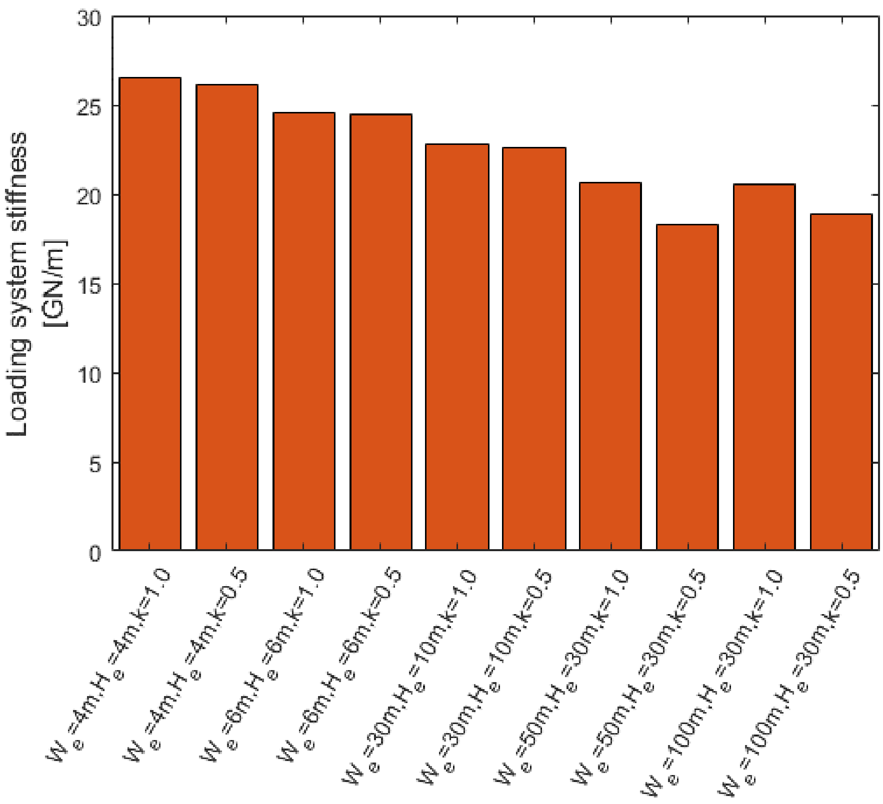


Figure 38: Loading system stiffness in the sidewall of considered excavations and for considered stress situations

The loading system stiffness in an excavation sidewall is generally a comparatively stiff one. This instance can be highlighted by comparing the loading system stiffness of a fracture zone in the excavation sidewall with the loading system stiffness in the middle of the excavation. For comparison purposes the loading system stiffness in the middle of the excavation is calculated for a nominal roof (floor) area of 1 m². Therefore, the loading system stiffness for the excavations representing the mined-out panels (Table 3) is calculated at half width of the panel. Figure 39 shows that the loading system stiffness in the middle of the panels is considerably softer than in the sidewall of the panels. Consequently, an unstable failure for a pillar situated in the middle of a panel is more likely than for the fractured rock mass portion in the sidewall presupposed that the pillar and failed rock mass in the sidewall show the same post-peak behavior.

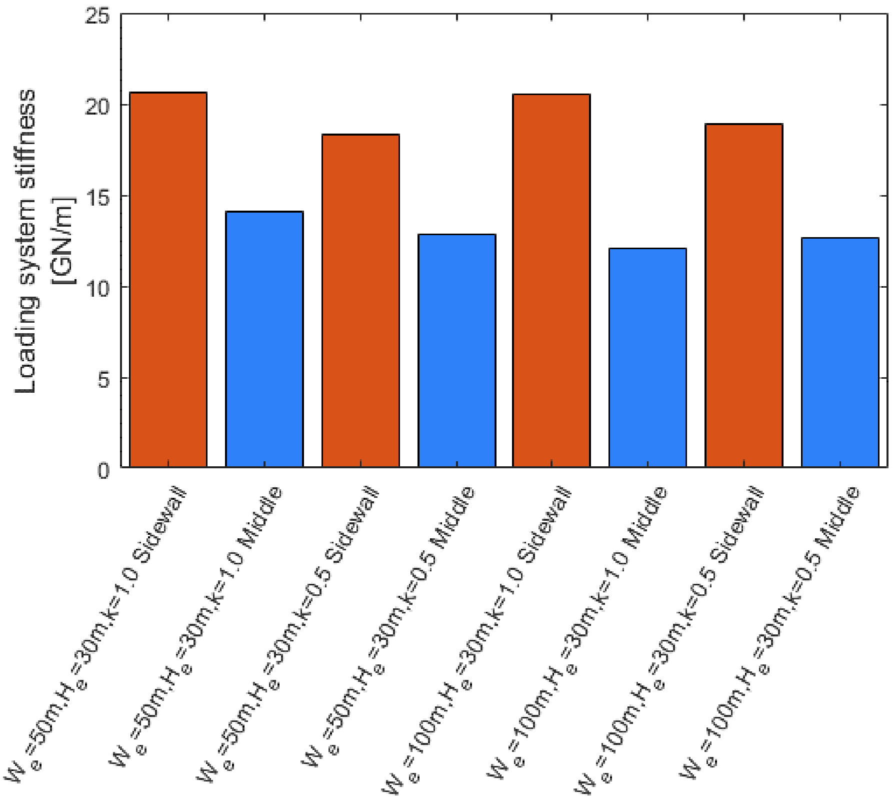


Figure 39: Comparison of the loading system stiffness in the sidewall and in the middle of a mined-out panel. The loading system stiffness is calculated for a nominal roof (floor) area of 1 m².

In summary, the stiffness of the loading system for a fractured rock mass portion near and in an excavation is a function of several parameters. The loading system stiffness can be actively influenced to some extent by the excavation size and shape. Indeed, the prevailing rock mass properties have still a dominant effect on the loading system stiffness; compare section 6.1.3.2.2. Important is also that the loading system stiffness in sidewalls is larger than inside the excavation, which circumstance make unstable failure more likely for structures inside excavations or mined-out areas, respectively. This aspect is particularly relevant for pillars.

3.3.4.2.2 Pillar

Pillars are a widely used structural element in mines. Independent of pillar design and pillar purpose the stability of a potential pillar failure must be ensured. Otherwise, significant safety and production risks can occur. Experienced problems of an unstable pillar failure comprise the sudden collapse of mining sections (e.g. Zipf and Swanson (1999), van der Merwe (2006)) or pillar bursts (e.g. Ledwaba et al. (2012), Mark and Gauna (2016)). The model used for outlining the principles of stable and unstable failure (Figure 36) can be applied to pillars as well. In this instance the pillar represents the "tested" specimen and the surrounding rock mass the loading system. To prevent unstable pillar failure following possibilities exist:

- Increasing the stiffness of the loading system and ensuring that the stiffness of the loading system is always larger than the post-peak strain softening rate of the pillar; case (a) in Figure 40.
- Decreasing the post-peak strain softening rate of the pillar and ensuring that the post-peak strain softening rate of the pillar is smaller than the loading system stiffness; case (b) in Figure 40.
- Ensuring that pillar failure does not occur; case (c) in Figure 40.

The first measure aims on the stiffness of the loading system, the second measure aims on the pillar and the third measure aims on eliminating a potentially unstable pillar failure at all. All of the three options can be actively addressed with the mine layout and mining sequence.

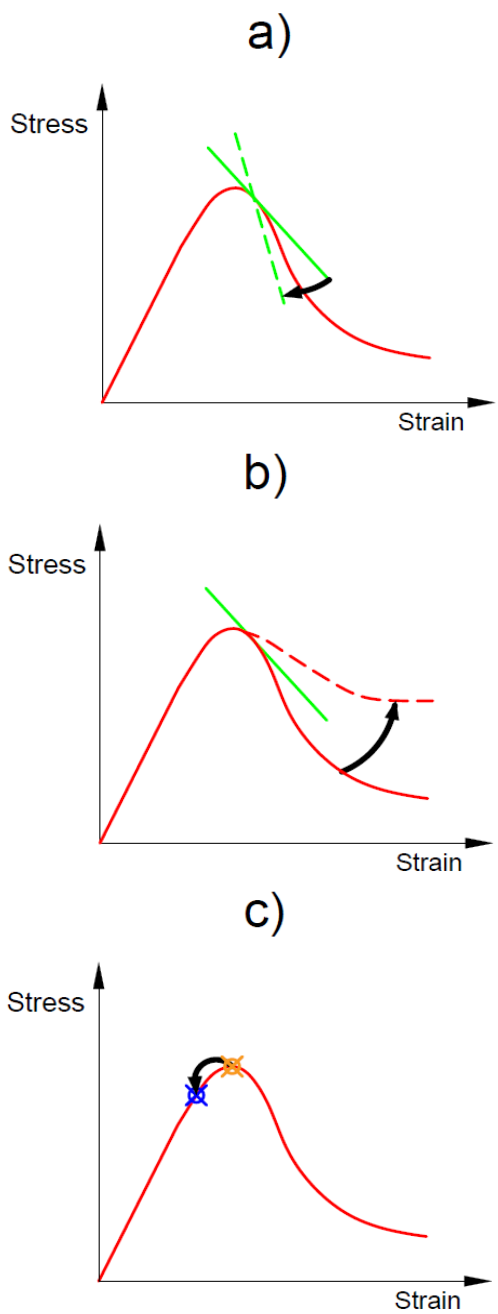


Figure 40: Possibilities to prevent unstable pillar failure: (a) increasing stiffness of loading system; (b) decreasing pillar strain softening rate; (c) ensuring that pillar does not fail by keeping the pillar stress below the pillar strength; Stress strain curve of pillar is shown in red and loading system stiffness in green.

3.3.4.2.2.1 Influencing the stiffness of the loading system

The loading system stiffness of pillars is governed by the composition and properties of the surrounding rock mass, the mine layout and the depth below surface. The mine layout comprises the size, shape and orientation of mining panels or of closely situated groups of excavations and the overall extent of mine workings. Whatever layout is relevant for the loading system stiffness depends on the considered pillar. For example, mining panels are relevant for panel pillars, groups of neighboring excavations are relevant for pillars between corresponding excavations and the overall mine workings are relevant for regional pillars.

A critical question for the loading system stiffness is, whether the surrounding rock mass is capable of bridging and to what extent bridging takes place. Figure 41 outlines the implications on basis of a room-and-pillar panel schematically. Situation (a) represents a dead-weight loading situation. Two weak faults prohibit bridging and the weight of the overburden rock mass must be transferred through the pillars inside the panel. Any further displacements of the pillars would not result in a lower weight that must be transferred through the pillars. Accordingly, the loading system stiffness is very (infinitely) soft. In situation (b) the rock mass bridges the panel and hence the situation is deformation-controlled. The deformation of the surrounding rock mass causes that the weight of the overlying rock mass is partially diverted into the abutment areas. The amount of deformation, which occurs for this load diversion, determines the loading system stiffness. The smaller the deformations and the larger the load diversion, the stiffer is the loading system. The stiffness of the loading system depends besides the prevailing rock mass composition and rock mass properties on the span of the panel. As the span of the panel increases the deformation-controlled situation transforms to a dead-weight loading (stress controlled) situation. The depth below surface has also an impact on this transition, whereby the transition occurs at shallower depths for lower spans. (Salamon and Oravecz, 1976)

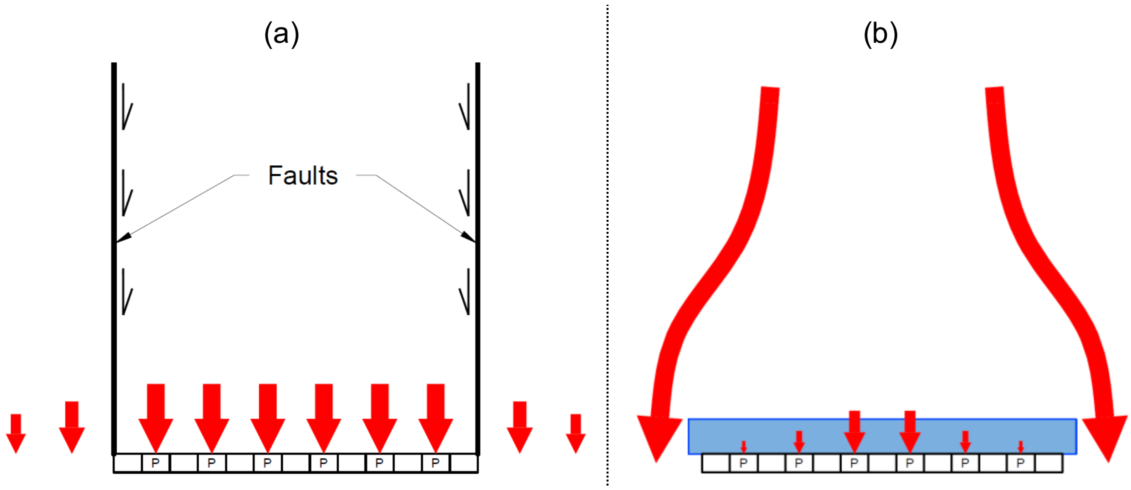


Figure 41: Isolated room-and-pillar panel: (a) presence of faults prevents bridging; (b) rock mass bridging a mining panel with pillars; pillars are indicated with "P", stress flow and pillar stresses are indicated with red arrows, the movement along faults is indicated with black arrows and the rock mass bridging the panel is indicated as blue beam.

To sum it up, limiting the span or in general adapting the mine layout can be utilized to influence the stiffness of the pillar loading system. The mining sequence changes the loading system stiffness over time. However, the possibilities are limited, particularly in weak rock masses or in geological conditions preventing bridging or if larger spans are required from an operational perspective.

3.3.4.2.2.2 Influencing post-peak strain softening rate

Various researchers have shown that the post-peak strain softening rate of pillars decreases with increasing pillar width-to-height ratio. (e.g. Wagner (1974), Ozbay (1989), Mark (1999), Zipf (1999)) These studies outline as well that beyond a certain width-to-height ratio, which is considered to be around four to five, the post-peak behavior transforms to a yielding and strain hardening behavior. The practical conclusion is that unstable pillar failure becomes less likely and at some point impossible with increasing pillar width-to-height ratio. Accordingly, the pillar shape is an effective measure to control the stability of pillar failure. However, this measure is in practice associated with limitations. First, larger width-to-height ratios imply that pillars must become wider for a constant pillar height. Consequently, the extraction ratio drops. Second, the actual post-peak pillar behavior is especially for hard rock pillars relatively poorly understood; compare section 6.1.2.2. Third, failure may be shifted into the pillar foundations for pillars with a large width-to-height ratio. The pillar foundation behavior governs then the stability of the failure process.

3.3.4.2.2.3 Ensuring that pillar failure does not occur

Pillar strength and pillar stress are critical for this option. Either the stress acting on the pillar can be reduced that the pillar stress remains below the pillar strength, or the pillar strength can be increased that the pillar strength is larger than the pillar stress. Both aspects can be influenced by mine design. The extraction ratio and bridging capabilities of the surrounding strata are critical for the pillar stress. Furthermore, positioning of pillars inside de-stressed zones reduces stress magnitudes in pillars drastically. The pillar strength is strongly dependent on pillar size and geometry especially the pillar width-to-height ratio; compare section 6.1.2.2. Pillar strength increases with increasing pillar width-to-height ratio, which aspect can be utilized effectively for ensuring that pillars do not fail. However, similar limitations related to increasing the pillar width-to-height ratio as for decreasing the post-peak strain softening rate apply. The extraction ratio drops and the strength of hard rock pillars is relatively poorly understood; compare section 6.1.2.2. In view of the many uncertainties governing pillar strength and pillar stress it is appropriate to design pillar systems with high factors of safety to reduce the probability of failure significantly.

3.3.4.2.3 Fault

The activation of a fault followed by an unstable slip along the fault can release considerable amounts of seismic energy. Ryder (1988) discusses the activation of faults and the corresponding slip along faults in detail. Figure 42 outlines a shear stress ride curve of a plane of weakness (a fault). Once the shear stress overcomes the static shear strength T_s, the fault is activated and slip occurs. The shear strength drops to the dynamic shear strength T_d and slip takes place as long as the shear stress is larger than the dynamic shear strength. The amount of ride, which is necessary therefore, is governed by the stiffness of the loading system. The area between the shear stress – ride curve of the fault and the loading line of the loading system is a measure for the released energy. A softer loading system causes a larger energy release. Besides the loading system stiffness and the stress drop due to slip the area of slip is decisive for the amount of released energy. The larger the area of the activated fault is, the more energy is released.

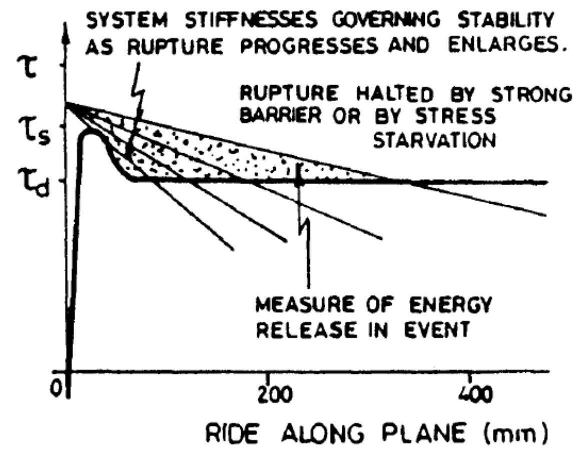


Figure 42: Unstable failure along a plane of weakness and associated energy release as a function of loading system stiffness and stress drop (Ryder, 1988)

For controlling the energy release generated in fault slip events different approaches are possible. They comprise:

- Providing a stiff loading system: The current mine layout is critical for the loading system stiffness. Experience shows that daylighting of large structures in excavations reduces the loading system stiffness considerably. (Napier (1991), Jalbout and Simser (2014)) Hence, daylighting of large structures in excavations should be avoided to increase the loading system stiffness. For this, leaving a protection pillar between the large structure and the neighboring excavation is an option. Furthermore, this protective pillar can also be used to influence the stress state on the structure positively; see next point.
- Controlling the stress situation: The stress situation at the position of the fault has two effects. The normal stress on the fault plane increases the shear strength of the fault and the shear stress along the fault plane triggers and drives fault slip. A control of the stress situation could therefore either address the strength of the fault or the driving shear stresses of fault slip. A loss of the normal stress on the fault plane is particularly critical, because it implies a loss of shear strength. The mine layout and mining sequence can be utilized for this stress control. The distance of extraction areas, which have regional effects on the stress distribution, to faults is critical, because the disturbances of the primary stress state resulting from extraction areas diminish with distance. Bracket pillars, which are used on a regular basis in deep South African gold mines, are a good example. (Vieira et al., 1998) However, keeping distance between faults and extraction areas is also associated with a loss of deposit.
- Limiting the area of slip: This measure is closely linked to the control of the stress situation. The smaller the area, where a critical stress state is present, is, the lower is the amount of released energy due to fault activation. The mine layout and mining sequence are again critical. Thereby, the sequence is of particular importance, because it determines the area of the fault, which is exposed to a critical stress state due to a mining step. Compare therefore the example of advancing an extraction area parallel or perpendicular to the strike direction of a fault. Advancing the extraction area parallel to the strike direction of the fault exposes a considerably

larger area of the fault to stress changes and thus to potentially critical stress states than advancing the extraction area perpendicular to the strike direction of the fault.

In-advance knowledge regarding the presence of a fault is critical for all of the above outlined measures, because they require adaptions of the mine layout and mining sequence. Further, the mining sequence has a dominant role, because it governs the temporal development of critical stress states and their spatial extent as well as the temporal stiffness of the loading system, whereas the (final) mine layout is usually strongly influenced by the deposit size and shape.

3.3.4.3 Unstable failure and seismic events

Salamon (1983a) defined four conditions, which must be fulfilled that a seismic event occurs, namely:

- A portion of rock mass must be very close to an unstable failure.
- A significant amount of energy must be stored in or near this portion of rock mass. This energy provides the source of the seismic energy.
- A change must take place to trigger unstable failure.
- The sudden stress change resulting from unstable failure must be able to initiate the propagation of seismic waves.

The conditions highlight the important role of unstable failure for seismic events. An unstable failure initiates a seismic event and the energy of the seismic event is linked to the released energy of the unstable failure. Seismic events with a larger energy content are more likely to cause rock burst damage. Accordingly, preventing unstable failure or, if unstable failure occurs, limiting the released energy during unstable failure is decisive for mitigating the rock burst risk. For this, the direction of mining is of particular importance. Mining towards highly stressed ground, such as for example a highly stressed pillar or a mined-out extraction panel, increases the likelihood of violent, unstable failure, because the rock mass, which is mined, stores a significant amount of energy and because the stress changes induced by mining are large. In contrast, mining away from highly stressed ground is preferable, because the rock mass, which is mined, is in a more favorable stress state (stress magnitudes are lower) and because the stress changes induced by mining are smaller.

3.3.4.4 Summary stability and instability

The stability of fracture and failure is a function of the loading system and the loaded rock mass or loaded structural element. Unstable failure is critical in deep mining, because it results in a sudden, often unexpected failure of rock mass or a structural element. Moreover, unstable failure can cause major rock bursts. The stability of failure should therefore be ensured. In order to influence the stability of failure either the stiffness of the loading system or the strength or post-peak stress strain behavior of the loaded rock mass or loaded structural element can be modified. A number of important situations in practice were outlined. All of them have in common that the mine layout and mining sequence can be utilized for controlling the stability of failure.

3.3.5 Direct and indirect sources of rock pressure problems

The sources of rock pressure problems can further be grouped into direct and indirect. This grouping relates to the relative position of the (main) driving source of the problem and the point of occurrence of the problem.

- An indirect source is a source of a rock pressure problem, where the source is located remote from the point of problem occurrence.
- A direct source is a source, where the location of the source and problem coincide or are relatively close.

For example, a fault slip event triggered by stoping activities may cause rock burst damage to stopes and infrastructure. Typically, the fault slip event occurs at some distance from the area, where the consequences are felt, and it is thus classified as an indirect source. Contrary, pillar bursts or face bursts cause damage directly at or relatively close to their positions of occurrence and they are therefore a direct source. An example related to stress damage is an infrastructure tunnel located in a high stress environment, which causes excessive rock fracturing resulting in poor tunnel conditions. If the tunnel is located remote from mined-out areas and it is therefore exposed to primary stresses, the rock fracturing is governed by the primary stress state and thus the source is direct. In contrast, if the tunnel is located close to a mined-out area in a high stress zone, such as an abutment of the mined-out area, then the fracturing is dominantly caused by the stress changes resulting from the mined-out area. Accordingly, the source of fracturing is indirect, because high stresses resulting from the extracted area and not the primary stresses cause fracturing. Moreover, it has to be noted that sources could be both direct and indirect. In this instance, a source causes a rock pressure problem directly at or relatively close to the source location as well as a rock pressure problem distant from the source location.

Identifying the source of a rock pressure problem is critical for addressing the rock pressure problem its consequences. Furthermore, grouping sources into direct and indirect allows outlining possible strategies and approaches against rock pressure problems. Indirect sources could more difficult or even impossible to tackle at the position of the rock pressure problem, because they have their origin distant from the location of the problem. Any measures, which are implemented at the position of the problem, do not have any effect on the source accordingly. Thus, at the location of the problem only its consequences can be alleviated, whilst the source and therefore the generally adverse circumstance cannot be addressed at the location of the problem. Addressing indirect sources requires in general an appropriately designed mine layout and mining sequence.

3.4 Key parameters for the stress management concept

The foregoing sections focused on rock pressure phenomena and rock pressure problems. Rock pressure phenomena and rock pressure problems were defined, their differences were outlined and their relevance in deep mining as well as possible sources and causes of rock pressure phenomena and problems were discussed. Based on these analyses key parameters for the proposed stress management concept are identified.

- Recognition of rock pressure problems: The first and possibly most critical parameter is to recognize the presence of a rock pressure problem. If the problem and its consequences are severe, it is in most instances easily realized. However, if the consequences are not severe or if the consequences can be managed without undue difficulties, a rock pressure problem is often not recognized appropriately. Moreover, potential rock pressure problems should ideally be identified in an early mine planning stage so that efficient measures and strategies against the potential problem can be set up in time.
- Importance of the mine layout and mining sequence: Rock pressure problems are characterized by stress driven fracture or failure processes, which are influenced by several key parameters. These key parameters can be classified into natural parameters and parameters, which can be influenced. The former can principally not be influenced by mine planning and mining activities and the proposed stress management concept must be adapted to natural parameters. In contrast, parameters, which can be influenced, are used actively in the proposed stress management concept. Considerations in this chapter show that natural parameters comprise mainly the primary stress state, rock and rock mass properties, major geological structures as well as their spatial distribution. The natural parameters have a significant influence on the resulting stress situation and prevailing loads as well as on the occurrence, the mechanics and the stability of fracture and failure. The mine layout and mining sequence were identified as most important parameters, which can be influenced. The layout and sequence influence amongst others the position and extent of high and low stress zones, the formation and properties of structural elements, the position and severity of fracture and failure zones and the stability or instability of failure. For this reason, the mine layout and the mining sequence influence the spatial and temporal occurrence of rock pressure phenomena. Moreover, they have a strong impact on, whether a rock pressure phenomenon evolves to a rock pressure problem or not, and on, whether a high stress situation can be managed properly or not. Another parameter, which can be influenced and which has not been discussed so far, is support and reinforcement. However, as shown in subsequent sections, support and reinforcement are rather measures against the consequences of rock pressure problems than measures addressing the source of rock pressure problems.
- Constraints resulting from the deposit characteristics: Overall, the mine layout and mining sequence were identified as an effective measure to control the stress situation and mining-induced seismicity. However, the control possibilities of the layout and sequence are often constraint by deposit characteristics, namely the size, shape and grade distribution of the deposit. The deposit characteristics have a significant impact on the (final) layout of extraction areas and the preferred mining sequence. Accordingly, they must be considered already in an early stage of the design of a stress management strategy.
- Presence and impact of uncertainties: The uncertainty related to stresses, rock mass and structural elements was identified as a key issue as well. On the one

hand, uncertainty is related to the spatial distribution of rock mass properties and primary stresses, and on the other hand, uncertainty is related to the stress strain behavior of rock mass and structural elements. Neither the stresses acting on and in rock mass and structural elements nor the strength and stress strain behavior of rock mass and structural elements can be determined precisely. The prevailing uncertainties prevent an accurate design of rock mechanics aspects in the mine planning stage. Accordingly, adaptions could become necessary, as mining progresses.

- Importance of continuous observation and monitoring: Such adaptions are based on an improved understanding and knowledge of the behavior of rock mass and structural elements as well as of the stress situation. The installation of a continuous observation and monitoring program and the subsequent structured data analysis are critical for collecting this knowledge and experience. Therefore, observation, monitoring and associated data analysis are considered a key issue in the stress management concept and have to be considered as essential components of rock engineering infrastructure in deep mines.
- Importance of flexibility: Finally, the mining method, mine layout and mining sequence must provide sufficient flexibility to implement gained experience and knowledge within short times and at reasonable cost. For this reason, the flexibility and possibility for changes in the mine layout and mining sequence are key parameters for the stress management concept.

4 Rock pressure control approaches

In this chapter, two general approaches addressing rock pressure problems are discussed, namely the passive and the active approach. The objective of the passive approach is to alleviate consequences of rock pressure problems on the objectives of mineral extraction, whereas the active approach aims on eliminating sources of rock pressure problems. The principles, advantages and disadvantages of both approaches are outlined and their possibilities and limitations against rock pressure problems are identified. Finally, the suitability of the active and passive approach for the stress management concept is discussed.

4.1 Passive rock pressure control approach

The passive approach concentrates on alleviating and minimizing the consequences of rock pressure problems. The actual sources of the rock pressure problem are generally not addressed. For this reason, the passive approach can also be considered reactive on encountered problems.

4.1.1 Role of support in the passive approach

As outlined, rock pressure problems are caused by various fracture and failure processes in rock, rock mass and of structural elements. These processes have in common that new fractures are created, that existing fractures are extended or that (healed) discontinuities are broken up. Moreover, movement of blocks along discontinuities and fractures can take place. The actual fracture and failure pattern depend amongst others on the prevailing stress situation, the rock mass type and properties and the size and shape of the excavation or structural element. The passive approach aims mainly on stabilizing and retaining the fractured and failed zone and on controlling the fracture and failure processes in order to ensure a stable fracture propagation and a stable failure. Different support and reinforcement measures and systems are installed to achieve the objectives from above. According to Wagner (2019) support systems must provide following functions:

- Maintaining the integrity of fractured rock in the immediate vicinity of the excavation
- Mobilizing frictional forces in the fracture zone
- Limiting post-failure deformation in the rock mass
- Absorbing considerable amounts of energy under extreme stress and seismic loading conditions

The support functions after Wagner (2019) above outline clearly that support systems do not address the source of rock pressure problems actively.

A critical point for the applicability of the passive approach is the functionality of the support and reinforcement systems. If the functionality is not provided, the fracture and failure zone is not controllable and the rock pressure phenomenon can evolve to a rock pressure problem. In order to evaluate the functionality, the support system itself and the characteristics of the fracture and failure process as well as the characteristics of the respective fracture and failure zones must be considered. Regarding support systems key issues are its capacity under static and dynamic loading conditions, its deformation properties and stiffness and its interaction modes with the fracturing and failing rock mass. (Wagner (1984), Kaiser et al. (1996), Li (2012)) Regarding fracturing and failing rock mass or structural elements key issues are the strength, fracture and failure behavior and the stability and instability of the failure. Support and reinforcement have been a focused research and development topic over the last decades. Wagner (2019) provides an outline of the development of modern support and reinforcement systems. Comprehensive summaries on support and on individual aspects of support in specific situations is given for example by Hoek et al. (1995), Kaiser et al. (1996), Ryder and Jager (2002) and Potvin and Hadjigeorgiou (2020).

Research and development activities have been concentrating on support and reinforcement systems; see for example Potvin et al. (2010), Stacey (2012), Villaescusa et al. (2013), Li et al. (2014) and Swan and Hedlin (2019). Main objectives have been to increase the static and dynamic support and reinforcement capacity so that installed systems can control larger and more severe fracture and deformation zones and so that they can absorb the energy from stronger seismic events and associated dynamic loading. However, mining experience shows that available support systems are not functioning properly in certain deep mining conditions. Especially difficult to manage seem to be dynamic loading situations; compare for example the rock burst databases of Heal (2010), Mikula (2012) and Morissette et al. (2014a). The reasons for this are various:

- The strength and behavior of rock and rock mass are not properly understood and the spatial distribution of their properties is uncertain, particularly in a mine planning stage; compare section 3.3.3.
- The actual dynamic load on support systems is not well understood and difficult to predict. (Stacey (2011), Potvin and Wesseloo (2013))
- Related to the support it can be concluded that individual elements of support systems are partly understood well. However, the overall capacity and functionality of support systems depend strongly on the combined behavior of the individual elements and the mechanisms of interaction between the support system and the failing rock mass. (Simser (2007), Wagner (2019), Stacey (2019a)) This combination of individual elements to support systems and the mechanisms of interaction are not investigated and understood well, which circumstance results in insufficient design methods and design guidelines. (Potvin et al. (2010), Stacey (2011), Potvin (2017))

Besides deficiencies in understanding support as a system and its interaction with rock mass support systems have in general the disadvantage that their capacity can only be increased to a certain level practically. Reasons behind are on the one hand limitations in the capacity of individual components and of connection elements between components. On the other hand, increasing the support system capacity is associated with rising cost. Therefore, the capacity of support systems has a technical and an economic limit.

4.1.2 Preference for the passive approach

Whether the passive approach is preferred for addressing rock pressure problems or whether not, cannot be clearly stated. However, there are developments and trends indicating that the passive approach is at least commonly applied or that it is at least dominant in the overall stress control approach. Trends comprise:

- More frequent occurrence of zones of intensely fractured rock mass and especially more frequent occurrence of rock burst damage with increasing severity (e.g. Varden and Esterhuizen (2012), Counter (2014), Morissette et al. (2014a))
- Development of support and reinforcement systems with increasing capacities (e.g. Cai et al. (2010), Li (2010), Darlington et al. (2018))
- Installation of support and reinforcement systems with higher capacities (e.g. Mercier-Langevin and Turcotte (2007), Jacobsson et al. (2013), Morissette et al. (2017b), Landry and Reimer (2019))
- Application of existing mining methods, mining layouts and mining sequences, which worked well at shallower depths, at increasing depths; compare section 2.4.2.
- Introduction of modifications or adaptions and application of specific measures, such as pre-conditioning or de-stress blasting, within established mining methods, mine layouts and mining sequences to alleviate the consequences of rock pressure problems, whereby the source of the problem is not addressed actively; compare section 2.4.2.

A (potentially) preferred application of the passive approach or a dominant share of the passive approach in the overall measures addressing rock pressure problems have their roots in various points:

- In comparison with the foresighted, active approach, the outlined passive measures, such as adapting and upgrading support or as introducing minor changes to the layout and sequence, can normally be implemented comparatively easily, once mining commenced. Accordingly, less information about the prevailing mining environment is required at an early stage. Therefore, exploration requirements are lower and rock mechanics mine planning is principally easier, as excavations, sequences or structural elements do not have to be designed as thoroughly as for the active approach. Regarding the latter point it has to be remarked that the successful application of the active approach requires a quite accurately designed mine layout and mining sequence. Limited knowledge regarding the prevailing rock mechanics conditions aggravates such an accurate design. Additionally, the deficiencies related to the knowledge of the strength, stress strain behavior as well as fracture and failure characteristics of rock and rock mass contribute to a more difficult rock mechanics mine planning for an active approach and these difficulties may thus facilitate the application of a passive approach.
- The requirements regarding the rock mechanics understanding and knowledge, the design tools and the personnel skills are lower for the passive approach than for the active approach. The reason for this is that implementing reactive measures is less demanding from a design perspective than the active prevention of potential

problems, which calls for detailed stress and stability analysis. If the required knowledge, understanding and design tools are not available, the passive approach is principally the remaining option. Research and development are an option to overcome this issue. Furthermore, personnel skills must be available to utilize available knowledge, understanding and design tools appropriately and thereby to implement the active approach. As highlighted in section 2.3.1 there has been a constant decline in research and development as well as education and training institutions, which instance limits the applicability of an active approach further.

- Another circumstance is that some of the available mining methods do not provide considerable flexibility for changes and adaptions in the mine layout and mining sequence at all or after mine development or extraction has started. Therefore, the passive strategy could be the only left, well-applicable strategy against rock pressure problems. Furthermore, the passive approach allows optimizing the mine layout and mining sequence from a production and extraction logistics perspective, because constraints and limitations imposed by rock mechanics considerations are smaller; compare section 2.4.2. In contrast, in an active approach rock mechanics demands on the mine layout and mining sequences are more dominant and govern the overall design; compare section 4.2.

4.1.3 Limitations of the passive approach

Even though the passive approach is commonly applied, it comes along with some significant disadvantages. The first and possibly most prominent one is that the actual source of a rock pressure problem is neither addressed nor eliminated. Accordingly, the passive approach is not suited to improve the overall rock pressure situation in the mine. Rather, the passive approach aims on alleviating consequences of rock pressure problems and thereby on providing safe and acceptable working conditions. The technological and economic limitations related to support and reinforcement systems constrain the severity of consequences, which can be managed. Another disadvantage of relying on a passive approach is that the application of the passive approach may result in the formation of a "hidden" rock pressure problem, which is not identified as a rock pressure problem and thought to be an inherent feature or characteristic in the prevailing mining environment or of the applied mining method. Such a hidden rock pressure problem is usually quite well manageable with support, as long as the problem does not become severe. However, a hidden rock pressure problem results in additional mining costs and may have implications on the safety of the operation, because stress driven fracturing or failure is present over larger areas. These instances can affect the safety, completeness of extraction and profitability of an operation especially on the long run negatively. Finally, above outlined disadvantages limit the applicability of the passive approach in practice.

4.2 Active rock pressure control approach

In contrast to the passive approach the active approach addresses the sources of rock pressure problems. The main objective of the active approach is to prevent rock pressure problems at all or at least to control the severity of rock pressure problems such that the remaining consequences can be managed with the passive approach relatively easily. In this case the active and passive approach are combined. Overall, the active approach is proactive and foresighted.

Rock pressure problems are caused by stress driven fracture and failure processes. The causes and key parameters for these stress driven processes were discussed in chapter 3. Parameters were grouped into natural parameters and parameters, which can be influenced. Parameters, which can be influenced, are essential for the active approach, because they can be utilized to influence the occurrence, extent and stability of fracture and failure processes actively. For this reason, parameters, which can be influenced, enable to address sources of rock pressure problems. The identified, most important parameters for the active approach are the mine layout and the mining sequence. Monitoring and observation, which enable to gain knowledge and experience regarding the prevailing mining environment and thereby to reduce uncertainties, are also relevant parameters. Furthermore, the flexibility of the layout and sequence are critical to implemented changes within short periods and at reasonable cost.

4.2.1 Role of the mine layout and mining sequence in the active approach

The design task and design challenge for an active approach are the design of a mine layout and mining sequence, which allow controlling the intensity, location, extent and stability of stress driven fracture and failure processes such that rock pressure problems do not arise. In order to fulfill this design task, a good knowledge of natural parameters, especially the rock mass properties and their spatial distribution, the primary stress state as well as the deposit size, shape and grade, is required. Furthermore, a proper understanding of the strength and behavior of rock mass and structural elements is necessary. Controlling the intensity, location, extent and stability of stress driven fracture and failure processes can be realized in different ways.

- Constraining the resultant (maximum) stress magnitudes acting in structural elements or around excavations. This measure can decrease the extent of fracturing or prohibit fracturing and failure to a large extent.
- Affecting the resultant stress situation to increase the strength of rock, rock mass or structural elements. In general, this option requires that the confinement in the rock mass is increased, whilst the (maximum) stress magnitude may not necessarily be reduced. Again, this measure can decrease the extent of fracturing or prohibit fracturing and failure to a large extent.
- Ensuring the stability of fracture and failure processes. Providing a stiff loading environment reduces the amount of released energy during fracture and failure and therefore the likelihood of an unstable failure decreases. Furthermore, designing structural elements such that their strain softening rate in the post-peak region is lower reduces the likelihood of an unstable failure as well, because more energy is required for driving the failure further. Additionally, a lower strain softening rate may provide a higher strength, after failure and fracture was halted. Ideally, structural

elements are designed such that they do not show a strain softening behavior, whereby an unstable failure is prevented.

The different outlined options can be implemented either individually or in combination to address the sources of rock pressure problems. Design measures aiming on the improvement of the stress situation can be referred to as providing a more favorable stress environment. A favorable stress environment is a stress state, which improves the strength of rock, rock mass and structural elements or which reduces (controls) the magnitude of the stresses driving the fracture and failure of rock, rock mass and structural elements. Besides providing a favorable stress environment the control of fracture and failure processes comprises to ensure their stability.

Moreover, controlling the location of rock pressure phenomena is also a key aspect in the active approach. As outlined in section 3.1, rock pressure phenomena occurring remote from active mining areas or active infrastructure are not considered being a rock pressure problem. This aspect highlights the importance of the temporal occurrence of rock pressure phenomena and thus the relevance of the mining sequence.

The rock engineering design of the mine layout and mining sequence in the active approach can be compared to the design of structures in other engineering fields such as mechanical engineering or surface construction. The designs have in common that the structure is designed such that the prevailing stresses are transferred according to a defined scheme and that individual components or zones of the structure are optimized for this stress transfer, that is to say that components or zones can withstand prevailing stresses with an acceptable risk of failure and with a preferably low material usage. However, there are major differences, which complicate the design in rock engineering, namely:

- The presence of natural parameters, which may constrain the structure from a geometrical point of view strongly. These natural parameters are mainly the deposit size, shape and grade distribution.
- The inherent uncertainties related to natural parameters, which govern the stresses that must be transferred and the strength and behavior of the structure, and which constrain the size and shape of the structure. These natural parameters comprise the rock mass properties, the primary stress state and the deposit size, shape and grade distribution.
- The possible use of components or zones, which are allowed to fracture or fail on purpose.
- The constantly changing mine layout because of ongoing mining activities and the associated change of the resultant stress distribution as well as the strength and behavior of the structure.

These aspects highlight the complexity of the active rock engineering design approach. Moreover, the limited knowledge related to the behavior of rock mass as well as the uncertainties related to natural parameters make the rock engineering design more difficult. The fact that the design is usually made at an early stage on basis of limited information complicates the design further. Incorporation of mining experience in the optimization and adaption of the mine layout and mining sequence is a powerful tool. An appropriate degree of flexibility for changes on preferably short term at reasonable cost is necessary though. A critical point is whether the applied mining method, mine layout and mining sequence provide the required flexibility.

4.2.2 Application of the active approach

Active stress control approaches have been used in a few mining environments and mining conditions extensively. Potentially, the most prominent application is found in deep South African gold mines; compare section 2.4.1. Various kind of stress control measures are implemented and thereby gold reefs up to depths of 4 km have been extracted successfully over areas of several square kilometers. Contrary, in many other mining situations the application of an active stress control approach is limited. This instance was discussed in section 2.4.2 thoroughly. Summarizing, the active rock pressure control approach has not been widely utilized. In contrast, the passive rock pressure control approach has been widely utilized and it is often preferred over the active approach; compare section 4.1.2.

4.2.3 Difficulties associated with the implementation of the active approach

Overall, the active rock pressure control approach is more sophisticated but also more complex than the passive approach. However, it offers considerable advantages over the passive approach, because the sources of rock pressure problems are tackled. Situations, where the active stress control approach has been implemented, highlight these advantages. Indeed, the application of the active approach is associated with some difficulties:

- The mine layout and mining sequence are critical for its successful application and require proper planning. Therefore, a good knowledge and understanding regarding the primary stress state, the prevailing rock mass and deposit properties as well as the strength and behavior of the rock mass and structural elements are essential. However, as outlined earlier, there are deficiencies in the understanding of rock mass and the determination of the spatial distribution of natural parameters is difficult. This instance results in inherent uncertainties for mine planning, but could be overcome partly with flexible mine layouts and mining sequences.
- Another critical circumstance is that the active approach is more demanding from a planning point of view. The rock engineering design of the mine layout and mining sequence must be based on detailed investigations, wherefore an appropriate rock mechanics understanding and knowledge, powerful design tools and advanced personnel skills are required.
- Furthermore, the more complex and variable the mining environment in terms of stress state, of rock mass properties, of large geological structures and of deposit geometry the more difficult is the implementation of the active stress control approach. On the one hand uncertainties are larger and on the other hand the applied mine layout and mining sequence require even more flexibility.

Overall, the difficulties in mine planning and the required flexibility of designs could be reasons, why the active approach is not that widely utilized and why there is a (potential) preference for the passive approach; compare section 4.1.2.

4.3 Suitability of approaches for the stress management concept

The stress management concept proposed in this thesis could make use of both the active and the passive stress control approach. Experience has shown that the passive approach has limitations and that it can only handle rock pressure problems up to a certain severity. In contrast, experience with the active approach has outlined that it can be used to tackle rock pressure problems well. Furthermore, the active approach is in general more effective, because it addresses the source of the rock pressure problem directly. For this reason, the proposed stress management concept relies mainly on an active stress control approach. Indeed, some aspects of the passive approach are incorporated in the proposed stress management concept as well. The proposed stress management concept and the application of active and potential passive stress control approach components are discussed in the further chapters in detail.

5 Stress management concept

In order to address the lack of foresighted, active stress control measures, which was identified in the foregoing chapters, a stress management concept is proposed and introduced in this chapter. First, the objectives of the stress management concept are outlined and discussed. Second, individual elements of the concept and their functions are highlighted. Individual elements and their functions are further described and investigated related to rock mechanics and production aspects in the subsequent chapters 6 and 7. The implementation of the stress management concept is afterwards outlined and discussed in chapters 8 and 9.

5.1 Objectives

The overall, main objective of the proposed stress management concept is to control the stress situation and energy release in deep mining conditions in a systematic and strategic manner. Therefore, the concept makes principally use of the active rock pressure control approach. Thereby, potentially adverse consequences of high stresses and mining-induced seismicity are reduced strongly or prevented to a large extent. Subsequently, the occurrence and severity of rock pressure problems are either reduced strongly or prevented to a large extent as well. The application of the stress management concept should therefore facilitate the extraction of mineral deposits at great depth or in some instances enable the extraction of deposits at great depth. It has to be remarked that the meaning of extraction is put in context to the objectives of mining, namely a safe, as complete as possible and economic extraction. In general, the stress management concept is an integral part of the mining process. Accordingly, it is connected to all mining activities and it cannot be seen in isolation. It has to be noted further that the proposed stress management concept is limited to high stress environments (at great depth). It is not a concept against instabilities and associated problems due to low stresses at shallow depths.

In order to achieve its overall objective, the proposed stress management concept must enable following points. A description of these points is provided in subsequent sections.

- Controllability of rock pressure phenomena
- Applicability from a rock mechanics perspective
- Applicability from a production perspective
- Adaptability to different mining environments and production requirements
- Flexibility during implementation to react on uncertainties

5.1.1 Controllability of rock pressure phenomena

The first and probably most important aspect is that the stress management concept is able to control rock pressure phenomena such that phenomena do not evolve to rock pressure problems. Therefore, following points are central:

- The application of an active stress control approach (section 4.2) is best suited to address rock pressure problems. Accordingly, the stress management concept relies principally on the active stress control approach and the passive stress control approach (section 4.1) is utilized only on a limited basis for certain aspects.
- Foresighted planning of the layout and sequence are central for a successful implementation of the stress management concept. Rock mechanics aspects must be studied in detail already at an early stage. The foresighted and detailed studies facilitate further the early identification of potentially critical issues or situations.
- An appropriate observation and monitoring program must be set up early. This program enables first to reduce uncertainties and to improve the understanding and knowledge of the prevailing conditions and second to identify potentially critical developments at an early stage.
- The mine layout and sequence must be continuously adapted to the improved knowledge and understanding regarding the prevailing mining environment and the gained mining experience. Hence, rock engineering design and optimization must be conducted continuously in the proposed stress management concept.

5.1.2 Applicability from a rock mechanics perspective

Rock pressure phenomena and rock pressure problems emanate from rock mechanics principles and conditions. Accordingly, rock mechanics considerations and mine planning are crucial for addressing them. A critical point for the application of the stress management concept is therefore, whether stress control measures can be designed and implemented appropriately from a rock mechanics perspective. The measures must be effective against rock pressure problems so that the objectives of mineral extraction can be achieved. In this regard, it is important to note that the safety objectives of mining must be achieved with the implemented stress control measures. If not, the operation cannot be commenced and the achievement of the other objectives (completeness of extraction and profitability), is irrelevant. Important considerations of stress control measures related to the objectives of mining are summarized below:

- <u>Safety:</u> Regarding the safety of extraction, the effectivity of measures as well as the establishment of measures against rock pressure problems are essential. Otherwise, the completeness of extraction and profitability objective are irrelevant. If measures cannot be set up in a safe manner, they are not appropriate even though, if they would be effective.
- <u>Completeness of extraction:</u> Stress control measures must still enable reasonable extraction ratios. Typically, a lower extraction ratio implies that experienced stress magnitudes and energy release levels are smaller, because more ground, which

can transfer stresses on a regional scale, is left in-situ. Thereby, rock pressure problems are better controllable, but at the expense of extraction ratio. This instance is critical for the stress management concept, which objective has to be to enable a high extraction ratio. Some deposit losses for the benefit of the control of rock pressure are in most situations unavoidable. However, these deposit losses should be minimized. Solely reducing the extraction ratio to improve the rock mechanics situation is not considered an appropriate or advanced stress management.

- Profitability: Regarding the profitability of extraction it can be highlighted that rather complex and sophisticated measures may not be implementable practically due to for example high cost, low productivity or low production rates. These instances are further discussed in the next section.

At the end, it can be concluded that the applicability from a rock mechanics perspective is obviously strongly connected to the first point, the controllability of rock pressure problems.

5.1.3 Applicability from a production perspective

Besides the effectivity and applicability of rock pressure control measures from a rock mechanics perspective the applicability of these measures must also be possible from a production and operational perspective. A critical circumstance is that the implementation of stress control measures requires often additional steps or processes. Hence, the productivity and efficiency may be reduced. For this reason, measures, which do not need complex and difficult implementation steps, layouts or sequences, are mostly superior. Ideally, stress control measures should, where possible, be implemented hand-in-hand with the ongoing production; for example mined-out stopes control the stress and energy release situation. Another considerable advantage of relatively simple measures is that such measures are usually associated with a larger flexibility.

Besides the safety, which must be ensured always and throughout, the production and operational considerations have a significant impact on the additional costs for stress management and thus on the profitability of mineral extraction. Concluding, if additional mining costs for the utilization of the stress management concept are unacceptably high, the concept is not applicable in practice and alternative stress management concepts, which can achieve the desired results, need to be investigated. If such concepts cannot be found, it may mean the end of extraction.

5.1.4 Adaptability to different mining environments and production requirements

Individual mining environments and production requirements are typically associated with specific features and peculiarities. Normally, they differ from site to site or at least from mining region to mining region. Amongst others differences comprise:

- Deposit size, shape and grade distribution
- Geological conditions
- Primary stress state
- Rock and rock mass properties
- Certainty regarding natural parameters
- Surface considerations
- Production target and corresponding quality control
- Subsequent production processes and production steps
- Available technologies
- Available skills and experience of personnel

Overall, the stress management concept must provide sufficient flexibility to be adaptable to local mining conditions and production and operational requirements.

5.1.5 Flexibility during implementation to react on uncertainties

Flexibility of the stress management concept is required for following reasons:

- Applicability of the active stress control approach
- Adaptability to the local mining environment and production requirements

The applicability of the active stress control approach is central, because the proposed stress management concept is based on it. The active approach calls for a proper rock engineering mine planning, wherefore knowledge and understanding of the behavior of rock mass and structural elements as well as of the spatial distribution of natural parameters are crucial. However, there are inherent uncertainties associated with these points. Principally, these uncertainties are addressed best by:

- Continuous observation and monitoring to improve the knowledge and understanding of the prevailing conditions and to gain experience with the utilized mine layout and mining sequence.
- Subsequent adaptions and optimizations of the mine layout and mining sequences based on monitoring and observation.

In order to implement changes timely, a certain degree of flexibility is required. Flexibility is especially critical for key issues, which have a substantial effect on the operation, and on aspects, which are associated with a relatively high degree of uncertainty. Mine layouts and mining sequences with a larger degree of flexibility are principally preferable.

Concluding, the stress management concept must be rather flexible for and during its implementation. Otherwise, it may not be possible to design mine layouts and mining sequences, which enable an appropriate reaction on uncertainties, on changes in the prevailing mining environment or on changes of production requirements.

5.2 Elements and element functions

The proposed stress management concept is based on several elements, which are further grouped into main and auxiliary elements. The main elements are central for the implementation of the stress management concept, whereas the auxiliary elements have an assisting task for the main elements.

- Main elements
    - Excavation
    - Pillar
    - Loading system
    - Time
- Auxiliary elements
    - Support and reinforcement
    - Monitoring and observation

The prevailing mining environment is comprised of the so-called natural parameters (compare section 3.4) and forms the framework of the concept. The elements are created, established, installed or utilized within the prevailing mining environment and they have a physical effect, which depends on the element properties and characteristics, on the prevailing mining environment. Accordingly, the physical effect of an element gives an element a specific function. The physical effects of several elements may have to be combined for certain functions as well. Following functions are distinguished:

- Access function
- Extraction function
- Stress blocking function
- Regional stress transfer function
- Stress distribution function
- Protection function
- Strength enhancing function
- Data and experience collection function

The elements and their functions are then utilized for the implementation of the proposed stress management concept. A specific combination of the available elements and their functions is therefore necessary. Furthermore, the elements and their functions represent the parameters, which can be influenced; compare section 3.4. Hence, the elements and their functions enable to adapt the stress management concept to the prevailing natural parameters, the local conditions, the rock mechanics requirements and the production requirements.

Figure 43 provides a conceptual overview of the stress management concept, the elements and the element functions.

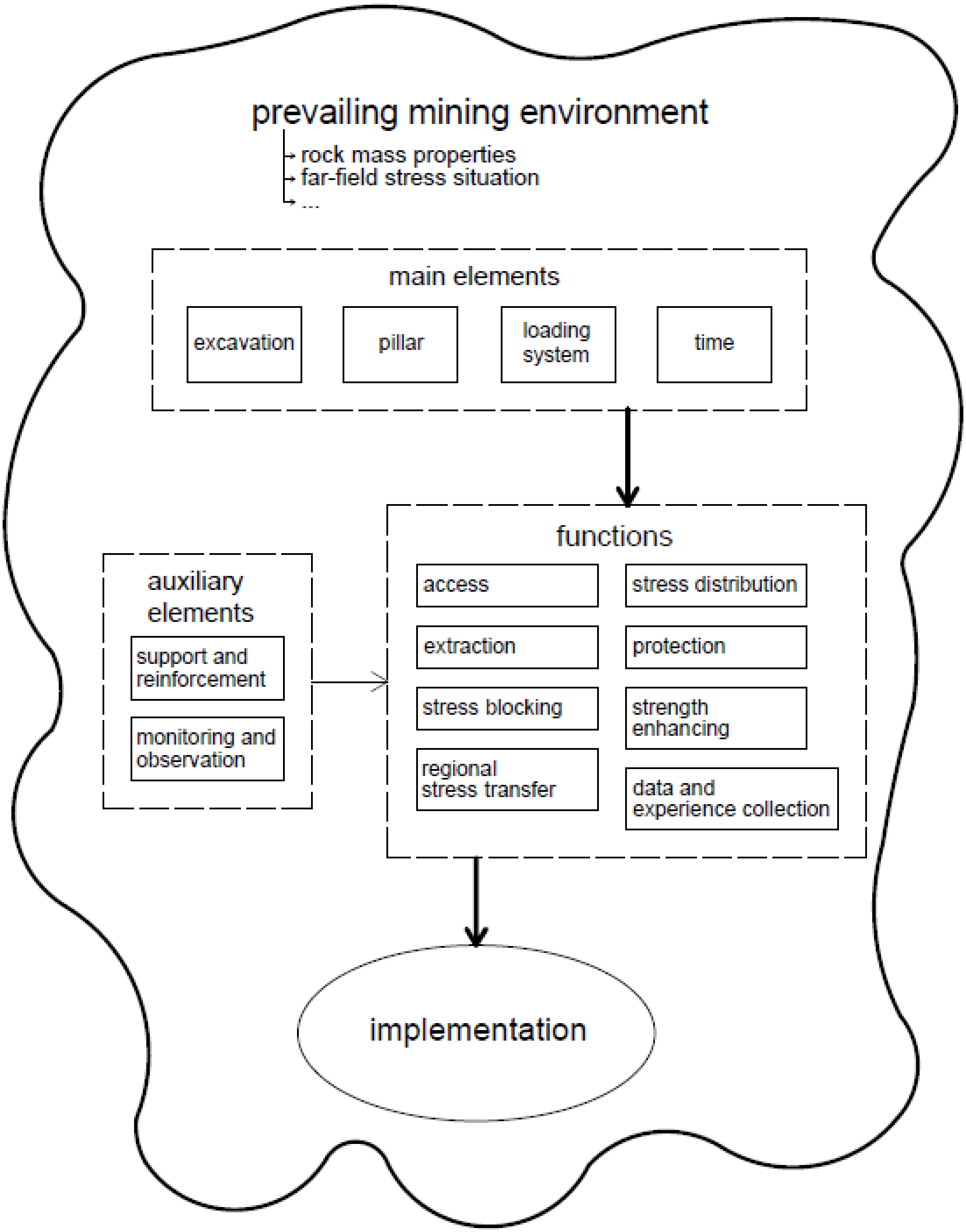


Figure 43: Conceptual overview of the proposed stress management concept. The prevailing mining environment forms the framework of the concept. The main and auxiliary elements, their functions and the combination of their functions are utilized for the implementation of the concept.

6 Elements of the stress management concept

In this chapter the individual elements and their physical effects on the prevailing mining environment are outlined and discussed. For this discussion main elements and auxiliary elements are distinguished.

- Main elements constitute the central elements of the stress management concept and their physical effects are decisive for the individual functions. Accordingly, the main elements are essential for the implementation of the stress management concept. Main elements can be used without auxiliary elements.
- Auxiliary elements have a supporting role for main elements. Accordingly, auxiliary elements assist main elements to fulfill a certain function. Auxiliary elements can only be utilized in combination with main elements, because they do not provide stand-alone functions.

The importance of main elements is the reason why this chapter concentrates on main elements and their physical effects. Main elements are discussed in detail, whereas auxiliary elements are only outlined briefly.

6.1 Main elements

6.1.1 Excavation

An excavation is a void of defined dimensions, shape and orientation, which is created in the rock mass. An excavation has following physical effects on the prevailing mining environment:

1. Creating a void
2. Causing stress changes and deformations
3. Causing fracture and failure in the nearby rock mass

The first effect, creating a void, is straightforward and does not require further explanations. However, the void introduces a stress disequilibrium and triggers therefore stress changes and deformations. These stress changes and deformations are of paramount importance for the stress management concept and are described in subsequent sections. Fracturing and failure in the surrounding rock mass may occur as a result of the stress changes. Consequently, additional stress changes and deformations occur in the fractured and failed rock mass portion and its vicinity.

Finally, it is noted that excavations are completely independent main elements, because they do not require any other main elements to be created for their establishment and because their physical effects are in general mostly independent of other main elements.

6.1.1.1 Stress changes resulting from excavations

The resultant stresses near excavations are of interest for several functions of the stress management concept. The stress changes and deformations resulting from an excavation were outlined and discussed on basis of a conceptual model in section 3.3.2.1 and Figure 25. Furthermore, the effect of excavation shape, orientation and dimensions and of the primary stress state on the resultant stresses near excavations were highlighted in sections 2.2.2 and 3.3.2.2 briefly. Due to their importance the resultant stresses near excavations are discussed further in subsequent sections on basis of typical, idealized excavation geometries. Different primary stress states, excavation sizes and excavation orientations are considered.

6.1.1.1.1 Influence of the excavation size and shape and the primary stress state

The effect of the primary stress state and the excavation size and shape is investigated with a number of idealized geometries in two dimensions. Table 4 outlines the considered geometries and their dimensions. All considered excavations are flat-lying. For rectangular, square and elliptical excavations their width (W_e) is their extension in horizontal direction and their height (H_e) is their extension in vertical direction; compare Figure 44. The terms height and width are used for circular excavations as well for simplification and refer to the excavation diameter. The smaller excavation geometries delineate typical infrastructure excavations, whereas the larger excavation geometries delineate mining panels or whole extraction areas.

All geometries represent the cross-section of infinitely long excavations, because the stress changes are calculated for the two-dimensional case. Constraining the analysis to two dimensions is a simplification, but it still outlines the general aspects on the resultant stress distribution. The effect of the third dimension is then highlighted in section 6.1.1.1.3.

Geometry	Width W_e [m]	Height H_e [m]	Aspect ratio W_e/H_e [1]
circular	5	5	1
circular	50	50	1
elliptical	25	5	5
elliptical	50	5	10
elliptical	100	50	2
elliptical	150	50	3
square	5	5	1
square	25	25	1
square	50	50	1
rectangular	25	5	5
rectangular	50	5	10
rectangular	100	5	20
rectangular	150	5	30
rectangular	50	25	2
rectangular	100	25	4
rectangular	150	25	6
rectangular	100	50	2
rectangular	150	50	3

Table 4: Considered excavation geometries in the investigation of the influence of excavation size and shape and primary stress state on the resultant stresses

The calculations of the resultant stress distributions are conducted with FLAC3D (Itasca, 2018). Slice models of the geometries with a thickness of 1 m, which are fixed in their out-of-plane direction, are created to simulate two-dimensional conditions, namely infinitely long excavations. FLAC3D is used so that for the analysis regarding the influence of the third dimension the same code is used. The rock mass has a linear elastic material behavior with a Young's modulus of 40 GPa and a Poisson ratio of 0.25, the primary vertical stresses correspond to a depth of 1000 m and they are 27 MPa. The ratio between primary horizontal to primary vertical stresses is 0.5, 1, 1.5 and 2, respectively. The horizontal stresses in both horizontal directions (in-plane and out-of-plane) are equal. The resultant stresses are shown by means of color plots and along three measurement lines. The position of these lines is displayed in Figure 44 for a rectangular and an elliptical excavation. All lines start at the excavation boundary, which also remarks the point zero for the distance along the line. Line 1, and 2 are vertical and situated below the excavation. Line 1 is in the middle of the excavation at half width and line 2 is at the horizontal end of the excavation. Line 3 is horizontal and situated in the middle of the excavation at half height.

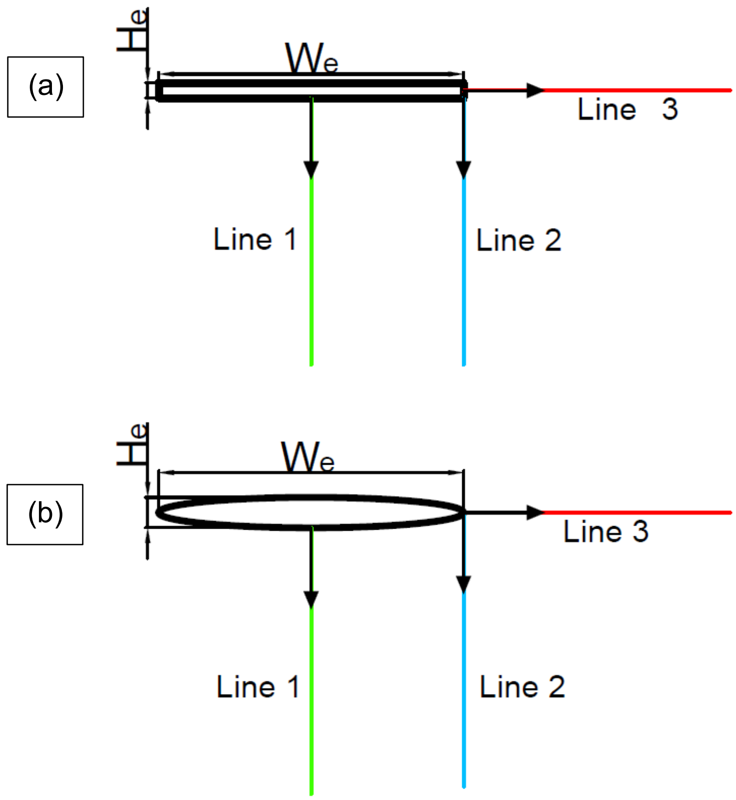


Figure 44: Position and orientation of measurement lines for (a) a rectangular and (b) an elliptical excavation

Of the resultant stresses the principal stresses as well as the normal and shear stresses in certain direction are of interest. A difficulty associated with principal stresses is that their orientation varies and that it is therefore difficult to outline the effect of an excavation on the normal stresses in a certain direction by means of showing principal stresses. In order to overcome this issue, the normal stresses in direction of the excavation axes are considered. These normal stresses represent the normal stress tangential and perpendicular, respectively, on the excavation wall. In case of the prevailing flat-lying excavation geometries, these are the vertical and in-plane horizontal stresses. The shear stresses are of interest, because they can cause shear failure along geological structures or shear failure of rock mass. The magnitude of shear stresses in a certain direction depends on the magnitude and orientation of the principal stresses and must be calculated for each direction separately. In order to overcome this issue, the maximum possible shear stress magnitude (T_{max}), which is calculated after Equation 11, is used in the analyses.

$$T_{max} = absolute\left(\frac{\sigma_1 - \sigma_3}{2}\right)$$

Equation 11

The general characteristics of the resultant stress distribution are outlined for the case of an elongated rectangular excavation with a width of 100 m and a height of 5 m. The ratio of the primary horizontal to primary vertical stresses is 0.5. Figure 45 to Figure 50 display the resultant vertical, horizontal and principal stresses as well as the resultant maximum shear stresses. All resultant stresses show that they correspond to the primary stresses at some distance from the excavation wall. However, in the surrounding of the excavation the stress state is significantly influenced. The zone, where the excavation alters the stress state is referred to as its zone of influence. Following observations are made:

- The vertical stresses (Figure 45) are significantly influenced. The excavation generates a de-stressed zone above and below of it. Within in this de-stressed zone, the resultant vertical stresses are lower than the primary vertical stresses. The de-stressing effect is most pronounced at half width of the excavation and diminishes with increasing distance from the excavation wall. Furthermore, zones of high resultant vertical stresses develop near the sidewalls of the excavation, which are referred to as the abutment areas. The high resultant vertical stresses diminish with distance.
- The in-plane horizontal stresses (Figure 46) are not as significantly influenced as the vertical stresses, because the excavation height is comparatively small and hence the disturbance of the far-field in-plane horizontal stresses is smaller. In the abutments resultant in-plane horizontal stresses rise, whereas they decrease above and below the excavation. Above and below of the excavation the resultant in-plane horizontal stresses are even tensile in the vicinity of the excavation. This circumstance is a result of the linear elastic material behavior. In-situ these tensile stresses will most likely not develop because of the low tensile strength of the rock mass.
- The out-of-plane horizontal stresses (Figure 47) are not as significantly influenced as the vertical stresses, because the excavation height is comparatively small and the hence the disturbance of the far-field out-of-plane horizontal stresses is smaller. The out-of-plane horizontal stress magnitudes increase in the abutment areas and they decrease above and below the excavation.
- The principal stresses (Figure 48 and Figure 49) show as well that the abutment areas highly stressed and that the areas above and below the excavation are de-stressed or even associated with tensile stresses. The influence of the excavation on the resultant principal stresses diminishes with increasing distance from the excavation. Overall, the distribution of the resultant major and minor principal stresses is in general relatively similar to the resultant vertical and in-plane horizontal stresses, respectively. However, differences between the vertical and in-plane horizontal stresses and the principal stress are caused by the rotation of the principal stress directions.
- The maximum shear stresses (Figure 50) have a considerable magnitude in the abutment areas. They diminish with distance from the abutments. In the de-stressed zone the maximum shear stress magnitudes are lower than the primary maximum shear stress magnitudes.

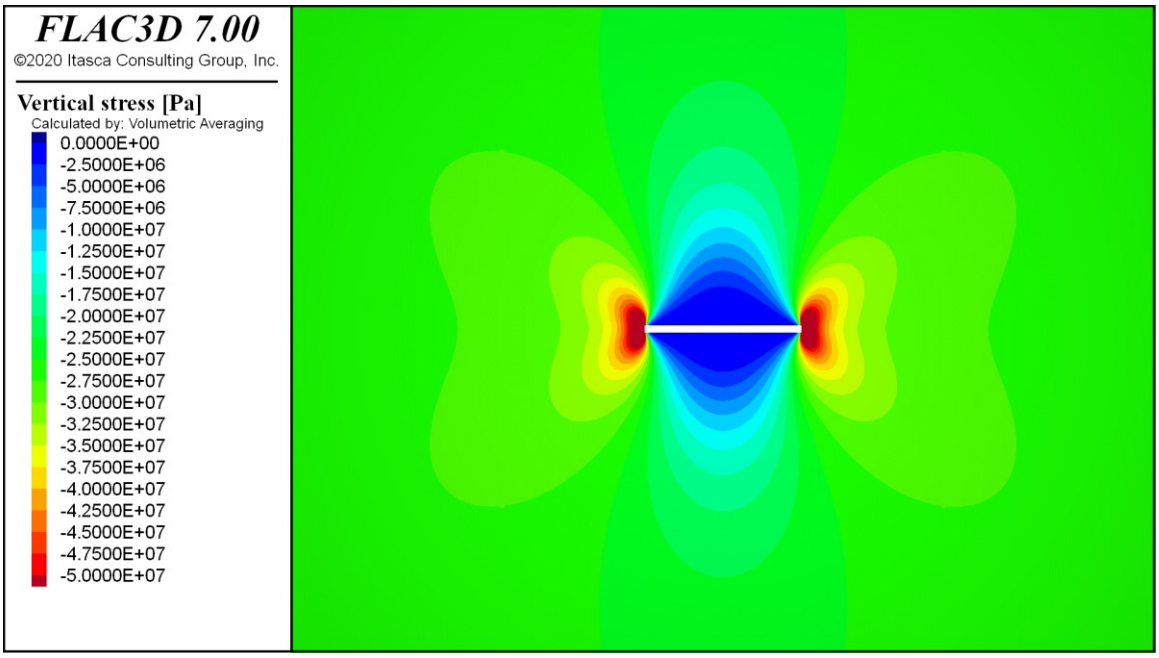


Figure 45: Resultant vertical stresses near an elongated rectangular excavation with a width of 100 m and a height of 5 m; compressive stresses are negative.

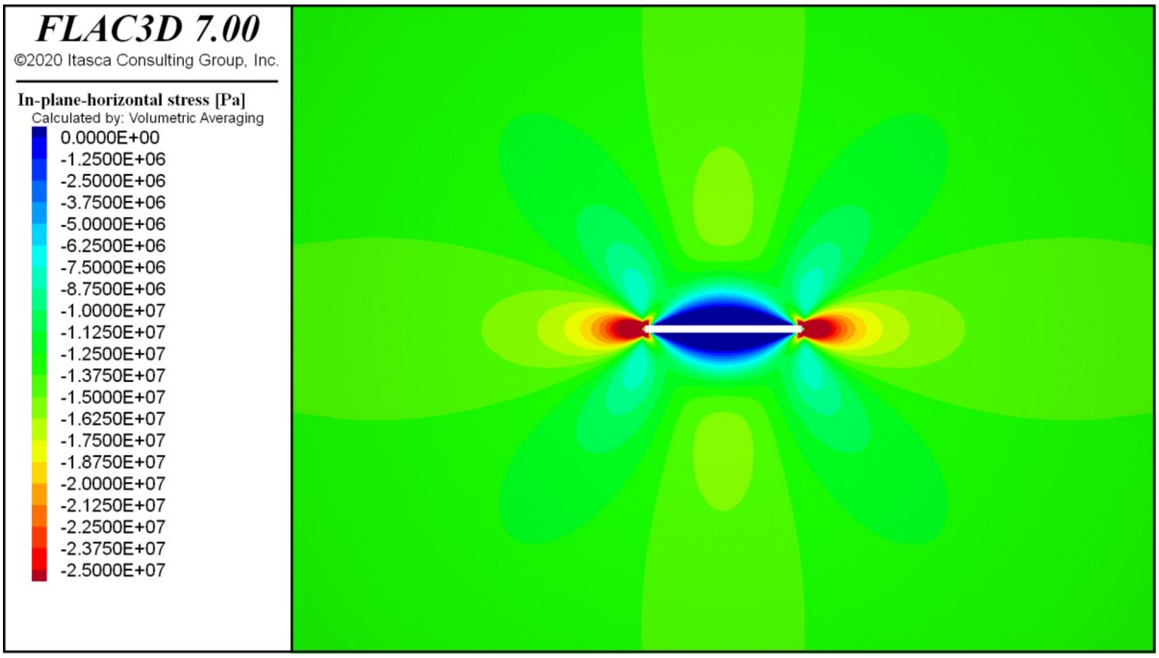


Figure 46: Resultant in-plane horizontal stresses near an elongated rectangular excavation with a width of 100 m and a height of 5 m; compressive stresses are negative.

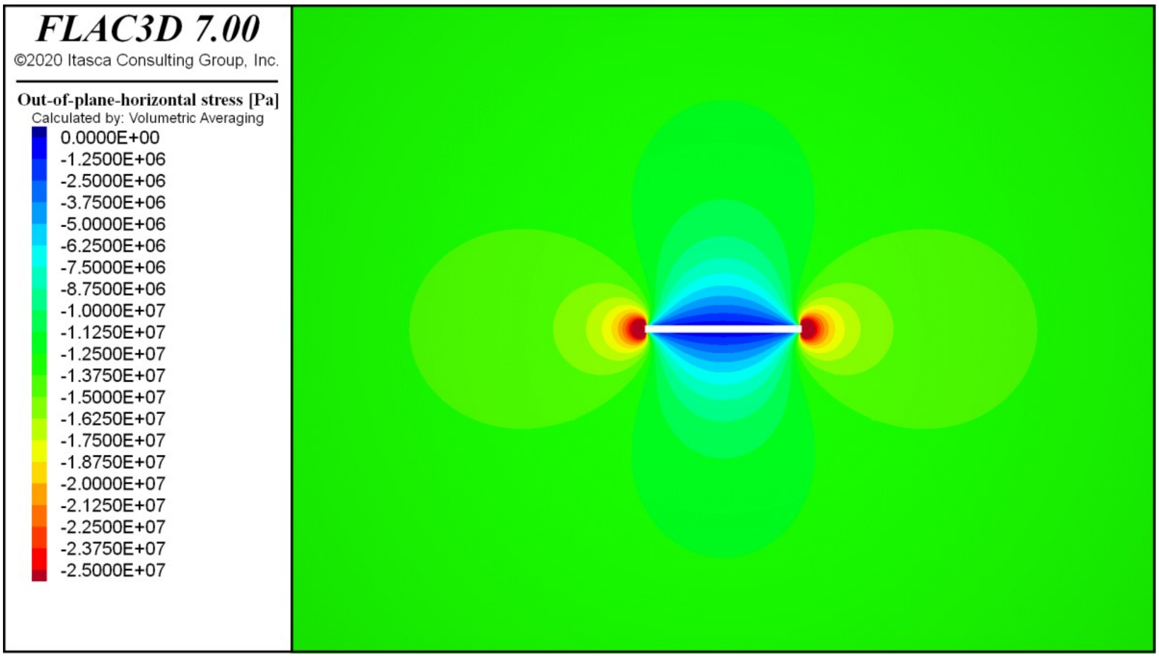


Figure 47: Resultant out-of-plane horizontal stresses near an elongated rectangular excavation with a width of 100 m and a height of 5 m; compressive stresses are negative.

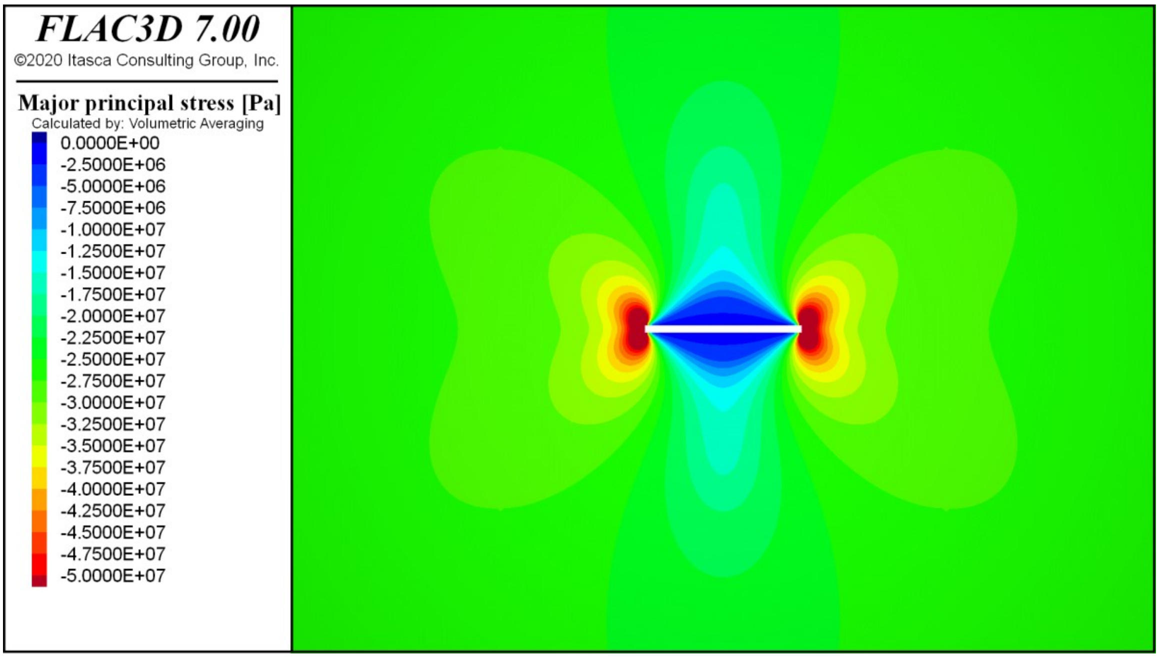


Figure 48: Resultant major principal stresses near an elongated rectangular excavation with a width of 100 m and a height of 5 m; compressive stresses are negative.

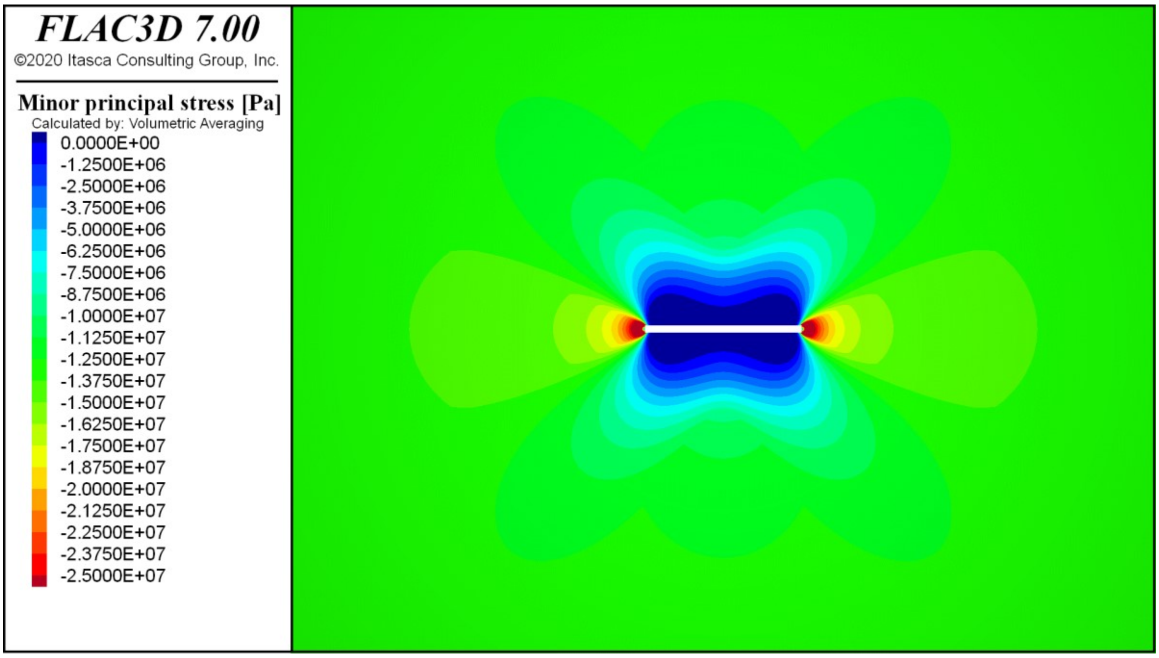


Figure 49: **Resultant minor principal stresses near an elongated rectangular excavation with a width of 100 m and a height of 5 m; compressive stresses are negative.**

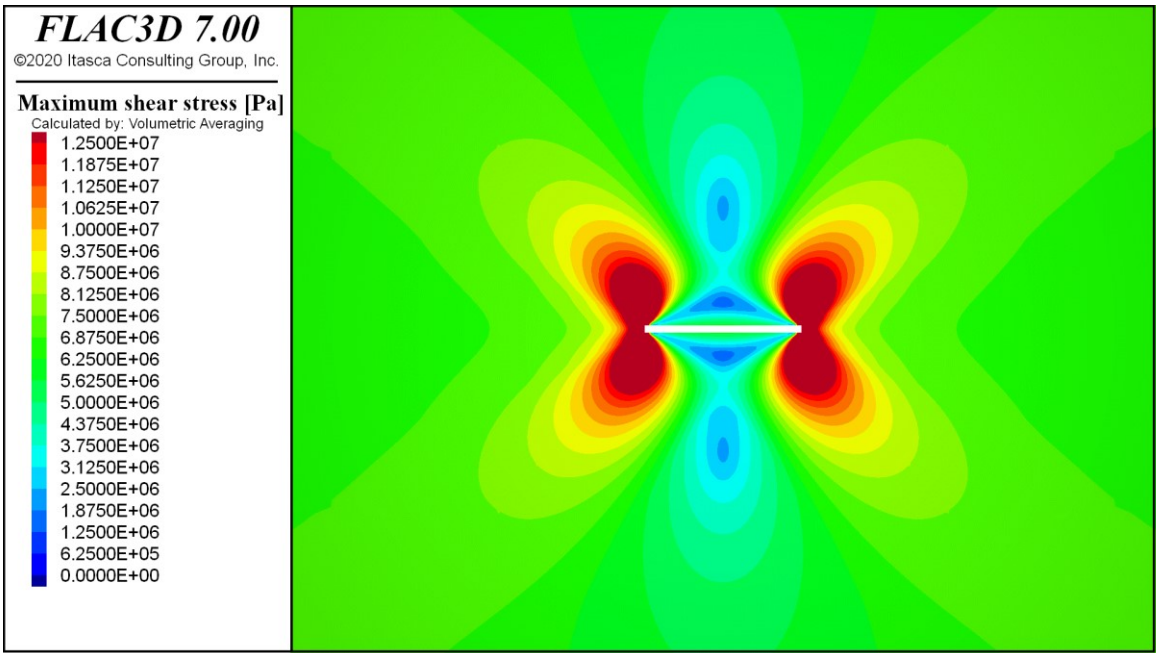


Figure 50: **Resultant maximum shear stresses near an elongated rectangular excavation with a width of 100 m and a height of 5 m**

The effect of the excavation size and shape is discussed on basis of rectangular and square excavations. Therefore, the normalized resultant vertical and in-plane horizontal stresses are shown along line 1 and 3 and the normalized resultant maximum shear stresses along line 2. The lines and displayed stresses along these lines are chosen such that they outline relevant aspects for the stress management concept. The ratio of primary horizontal to primary vertical stresses is constant at 0.5. Figure 51 to Figure 55 display the considered stresses along the measurement lines. Full lines represent thereby the stresses for excavations with a height of 5 m, dashed lines for excavations with a height of 25 m and dot dashed lines for excavations with a height of 50 m. The colors for excavations of the same width are equal. Following are made:

- The resultant vertical stresses along line 1 (Figure 51) show that the stress magnitudes decrease significantly compared to the primary stress state. At the excavation boundary the stresses are zero and the stresses increase with distance from the boundary. Accordingly, a de-stressed zone develops. The magnitude and spatial extent of stress reduction increase considerably with increasing excavation width. The excavation height does not have a mentionable influence.
- The resultant in-plane horizontal stresses along line 1 (Figure 52) show as well that the stress magnitudes drop in the vicinity of the excavation, but also that the stress magnitudes exceed the primary stress magnitudes at some distance from the excavation. Again, the excavation width has a prominent influence. The larger the excavation width is, the larger is the stress drop and the larger is the spatial extent of the stress drop. At a certain excavation width the in-plane horizontal stresses in the vicinity of the excavation become even tensile. However, these tensile stresses do usually not develop in-situ because of the diminishing tensile strength of rock mass. The excavation height has a minor influence on the resultant in-plane horizontal stresses along line 1. In general, an increasing excavation height reduces the magnitude and the spatial extent of the stress reduction.
- The resultant vertical stresses along line 3 (Figure 53) show the development of a highly stressed zone in the vicinity of the excavation. This highly stressed zone, in which the stress magnitudes are up to several times higher than the primary stress magnitude, is usually referred to as abutment area and the vertical stresses, which are tangent to the excavation wall in this area, are referred to as abutment stresses. For a given excavation height the stress magnitudes increase strongly with increasing excavation width. An increasing excavation height at a fixed excavation width decreases the stress magnitudes significantly. The spatial extent of the abutment area depends mainly on the excavation width. In general, the high stress magnitudes drop relatively quickly with increasing distance from the excavation boundary.
- The resultant in-plane horizontal stresses along line 3 (Figure 54) are different compared to the resultant vertical stresses along line 3. At the excavation boundary the resultant in-plane horizontal stresses are zero and they increase with distance from the excavation boundary. The excavation height has a prominent influence. At low excavation heights, the stress magnitudes rise above the primary stress magnitudes. This effect decreases with increasing excavation height. Furthermore, the excavation width has an influence. The wider the excavation, the larger is the zone, in which the in-plane horizontal stress distribution is affected, and the more rapid is the stress increase with distance from the excavation boundary.
- The resultant maximum shear stresses along line 2 (Figure 55) show that high maximum shear stresses develop near the excavation and that the maximum shear stresses decrease with distance from the excavation. This zone of elevated maximum shear stresses is usually also referred to as abutment area. The maximum shear stress magnitudes at the excavation boundary are considerable and

principally independent of the excavation size. However, the excavation width has a major influence on the spatial extent of high maximum shear stresses, whereas the excavation height has only a minor influence on the spatial extent of high maximum shear stresses.

Based on the observations following relevant conclusions for the stress management concept are drawn:

- A stress shadow develops below (and above) of an excavation; compare stresses along line 1 (Figure 51 and Figure 52). The width of the excavation is critical. A larger excavation width results in a larger spatial extent of the stress shadow and a more pronounced stress drop. The excavation height has only a minor influence on the stress shadow.
- Abutment areas develop near the sidewalls of an excavation; compare stresses along line 3 (Figure 53 to Figure 55). For the vertical and in-plane horizontal stresses in the sidewall both the excavation width and excavation height have a noticeable influence. Stress magnitudes increase with increasing excavation width or decreasing excavation height significantly. For small excavation heights the abutment stress magnitudes are relatively high, but the in-plane horizontal stresses reach close to excavation considerable magnitudes. Hence, the in-plane horizontal stresses provide a good confinement in the rock mass, which instance normally constrains potential rock mass fracture and failure resulting from the high abutment stresses to the vicinity of the sidewalls. Contrary, for larger excavation heights the abutment stress magnitudes are significantly lower, but also the confinement is reduced considerably, which instance can result in a larger spatial extent of potential fracture and failure zones in the abutments.
- High maximum shear stresses are present in the abutment areas as well; compare stresses along line 2 (Figure 55). The excavation width is critical for the spatial extent of high shear stresses, whereas the excavation height has only a minor influence.
- Excavations with an elongated rectangular cross-section (a large aspect ratio) are particularly suited for the creation of stress shadows, because the stress shadows, which are generated by these excavations, are of considerable extent. Furthermore, the significant confinement in the abutment areas can be advantageous for the control of high abutment stress magnitudes. Moreover, the maximum shear stress magnitudes and the spatial extent of high maximum shear stresses in the abutment areas are not significantly influenced by the excavation height, which aspect does not impose a disadvantage for an excavation with an elongated rectangular cross-section for the creation of stress shadows.
- Excavations of larger heights still generate a considerably sized stress shadow, presupposed their width is sufficiently large. However, the abutment stress situation may be more difficult to manage because of the lost confinement.

At this point it is important to note that these conclusions are drawn for a number of flat-lying excavation shapes and different excavation sizes. Further parameters have not been varied so far. However, despite these simplifications the considered excavation geometries highlight the development of de-stressed zones and abutment areas as well as the noticeable influence of the excavation geometry well. The influence of further parameters, such as the primary stress state or the excavation orientation, on the de-stressed zones and abutment areas are outlined in the following.

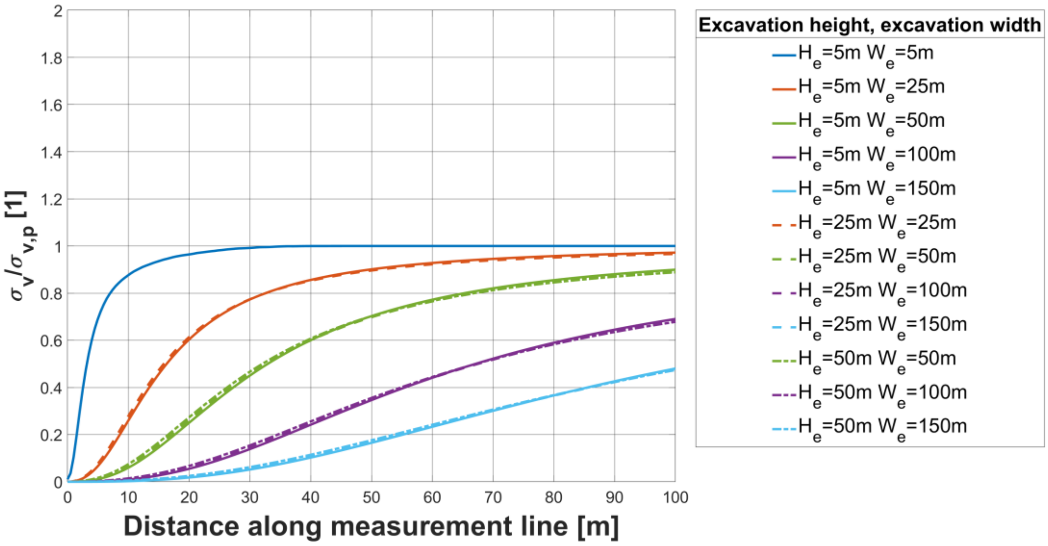


Figure 51: Effect of excavation size and shape for square and rectangular excavations on the resultant vertical stresses along line 1.

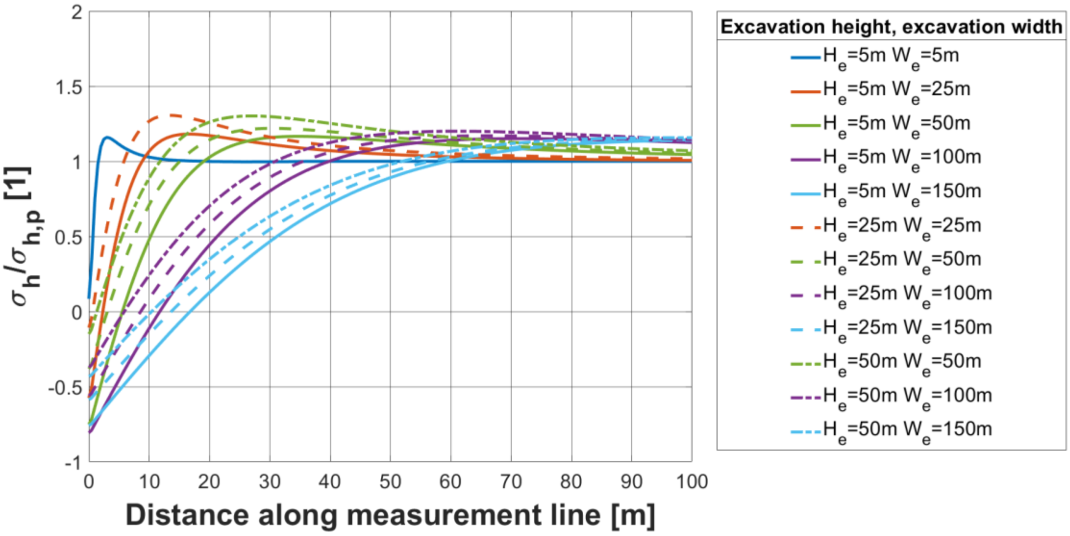


Figure 52: Effect of excavation size and shape for square and rectangular excavations on the resultant in-plane horizontal stresses along line 1.

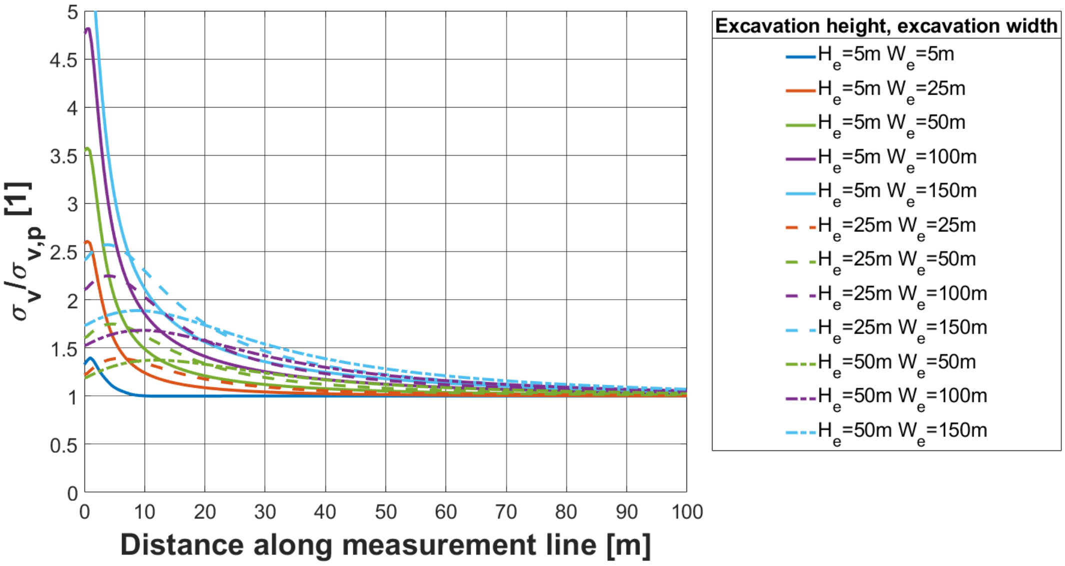


Figure 53: Effect of excavation size and shape for square and rectangular excavations on the resultant vertical stresses along line 3.

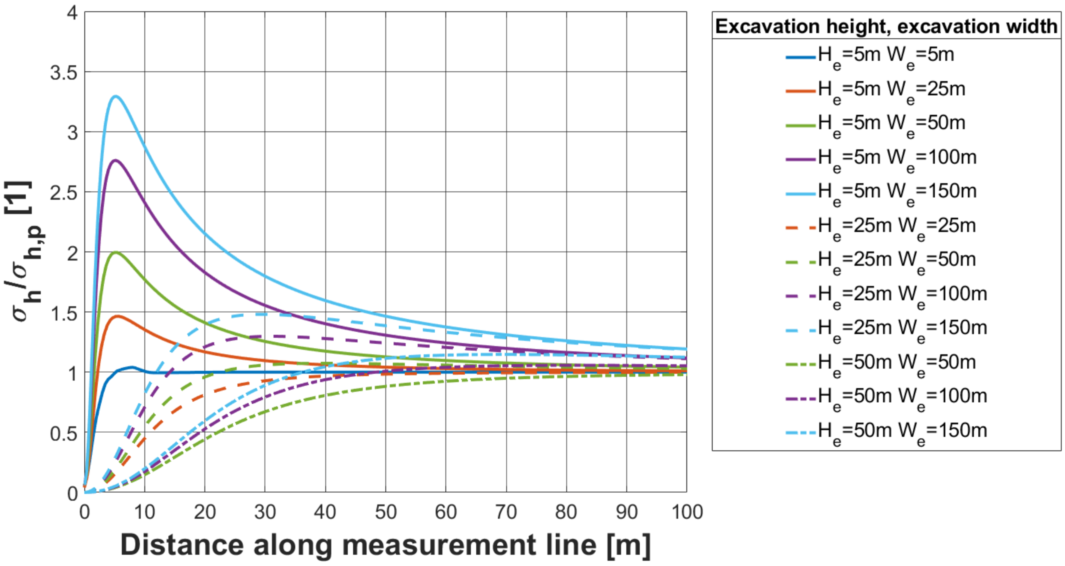


Figure 54: Effect of excavation size and shape for square and rectangular excavations on the resultant in-plane horizontal stresses along line 3.

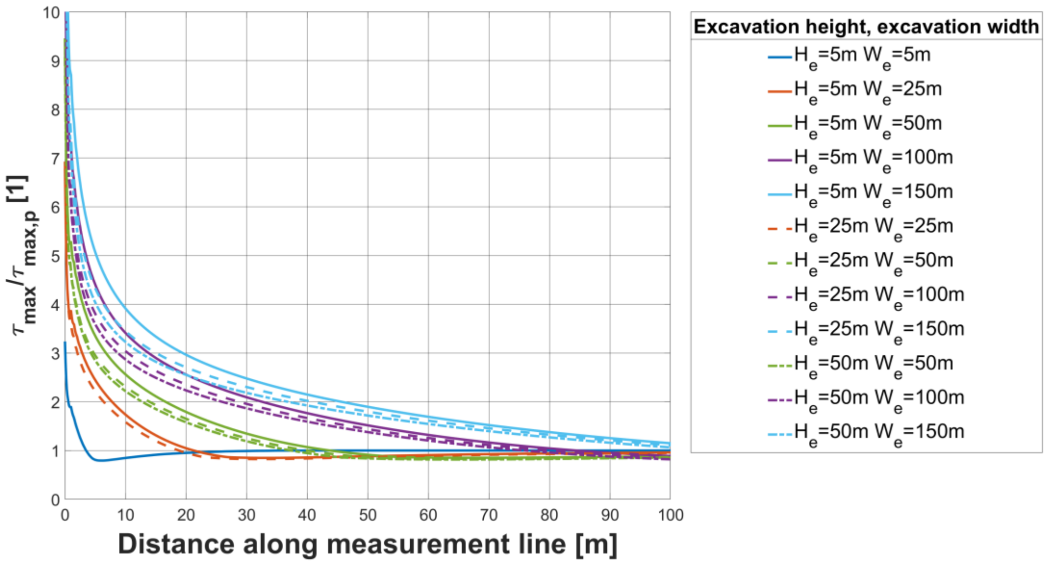


Figure 55: Effect of excavation size and shape for square and rectangular excavations on the resultant maximum shear stresses along line 2.

The analysis of the influence of the excavation size and shape showed the principal stress distribution in the vicinity of an excavation of varying size and shape. The influence of the ratio of primary horizontal to primary vertical stresses (k) on the resultant stresses has not been investigated. Hence, its influence is exemplary shown for square and rectangular excavations with a height of 5 m and variable widths. The excavations with 5 m height are chosen, because foregoing analysis showed that elongated rectangular excavations are well suited for the generation of stress shadows. Lines 1 and 3 are used therefore and the normalized resultant vertical and in-plane horizontal stresses are shown in Figure 56 to Figure 59. The lines and displayed stresses along these lines are chosen such that they outline relevant aspects for the stress management concept. The ratio of primary horizontal to vertical stresses of 0.5 is shown as full line, a ratio of 1 as dashed line, a ratio of 1.5 as dot dashed line and a ratio of 2 as dotted line. The colors for excavations of the same width are equal. Following observations are made:

- The resultant vertical stresses along line 1, which is situated in the de-stressed zone, (Figure 56) and along line 3, which is situated in the abutment area, (Figure 58) are altered only minimal by varying primary stress ratios. The identified trends and dependencies of the excavation size and shape remain the same.
- The resultant in-plane horizontal stresses along line 1 (Figure 57) and along line 3 (Figure 59) show the same characteristics, which were described in the analysis of the influence of the excavation size and shape. However, the magnitude of the resultant in-plane horizontal stresses depends strongly on the ratio of primary horizontal to primary vertical stresses. The higher the primary horizontal stresses are, the higher are the resultant in-plane horizontal stress magnitudes. The resultant in-plane horizontal stresses can be of considerable magnitude. Consequently,

mining-induced fractures may be generated because of these high horizontal stress magnitudes.

- The analysis of the maximum shear stress magnitudes in the abutment area shows as well the same trends and characteristics, which were described in the analysis of the influence of the excavation size and shape. For all considered primary stress ratios the maximum shear stresses in the abutment area are relatively high at the excavation boundary, but they decrease with distance from the boundary. In contrast, the maximum shear stress magnitudes in the de-stressed zone increase significantly with an increasing ratio of primary horizontal to primary vertical stresses. The reason for this is that the vertical stresses in the stress shadow are reduced considerably, whereas the drop of the stress magnitude of the horizontal stresses is not as pronounced, which instance results in comparably high horizontal stress magnitudes in the stress shadow.

Based on these observations it can be concluded that the ratio of primary horizontal to primary vertical stresses does not alter the general characteristics of the resultant stress situation in the de-stressed zone and the abutment area. However, the magnitude of resultant in-plane horizontal stresses can be significantly affected, which instance can be of importance in the de-stressed zone, particularly if the ratio of primary horizontal to primary vertical stresses is large. In this case a situation emerges, where the in-plane horizontal stress magnitudes are considerably larger than the vertical stress magnitudes in the de-stressed zone. This is a situation, which can affect the stability of excavations despite the de-stressing effect adversely. An important further aspect regarding the influence of the ratio of primary stresses on the de-stressed zone and the abutment area is the excavation orientation, which influence is highlighted in section 6.1.1.1.2.

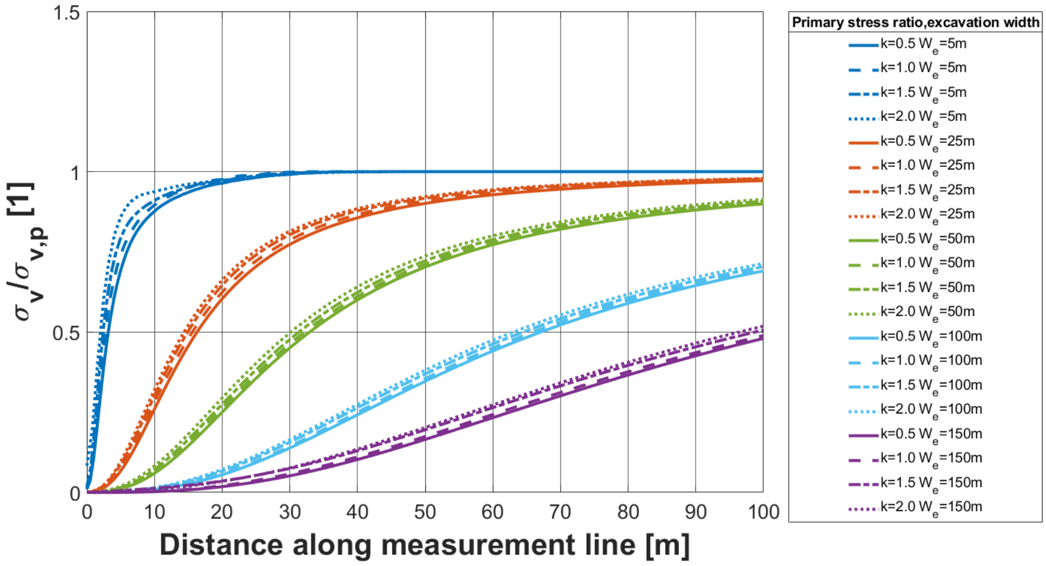


Figure 56: Effect of the primary stress state for square and rectangular excavations on the resultant vertical stresses along line 1.

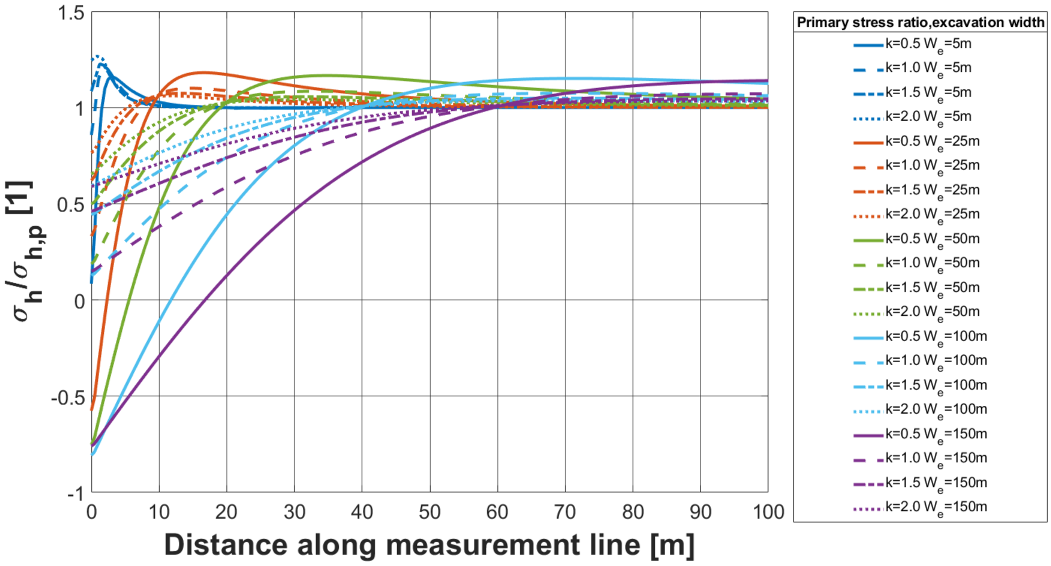


Figure 57: Effect of the primary stress state for square and rectangular excavations on the resultant in-plane horizontal stresses along line 1.

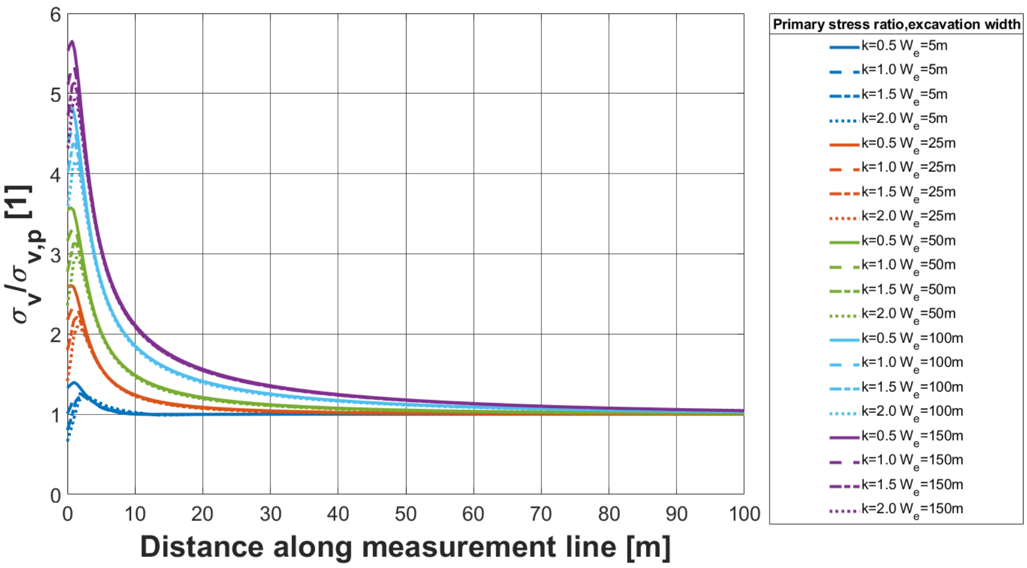


Figure 58: Effect of the primary stress state for square and rectangular excavations on the resultant vertical stresses along line 3.

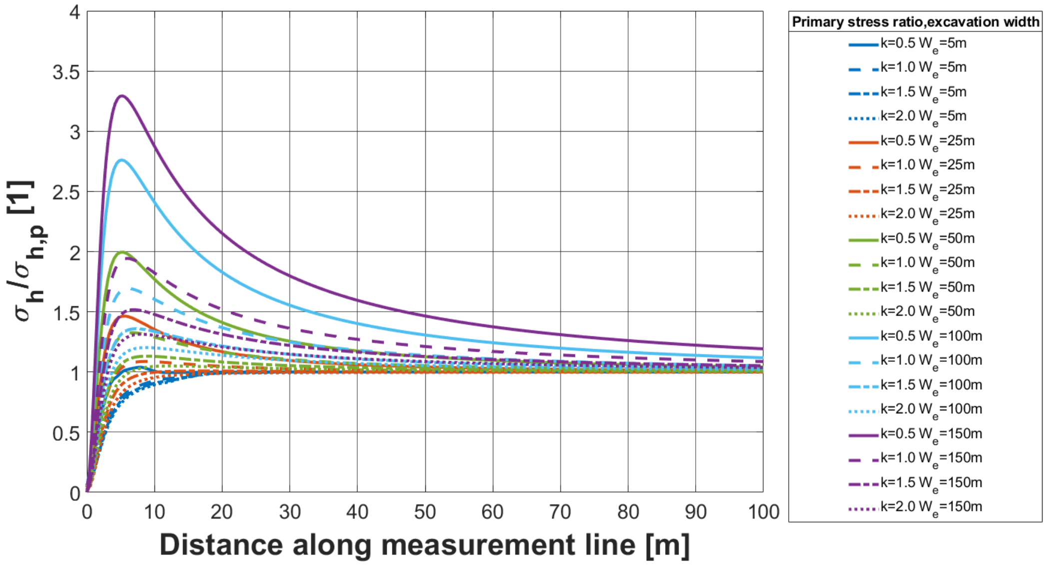


Figure 59: Effect of the primary stress state for square and rectangular excavations on the resultant in-plane horizontal stresses along line 3.

So far only square and rectangular shaped excavations were investigated. The differences between them and circular and elliptical excavations are outlined in Figure 60 to Figure 64. This comparison comprises excavations with a height of 5 m and 50 m and a ratio of primary horizontal to primary vertical stresses of 0.5. The normalized resultant vertical and in-plane horizontal stresses are plotted along line 1 and 3 and the resultant maximum shear stresses along line 2. The lines and displayed stresses along these lines are chosen such that they outline relevant aspects for the stress management concept. The square and rectangular shaped excavations with a height of 5 m and 50 m are shown as full and dashed lines, respectively, and the circular and elliptical shaped excavations with a height of 5 m and 50 m as dot dashed and dotted lines, respectively. The colors for excavations of the same width are equal. Following observations are made:

- The resultant vertical stresses along line 1 (Figure 60) show that the de-stressing effect of elliptical and circular excavation is principally comparable to the de-stressing effect of rectangular and square excavations of the same size. However, the de-stressing effect decreases in spatial extent, if the excavation geometry becomes less elliptical and hence more circular.
- The resultant in-plane horizontal stresses along line 1 (Figure 61) show that the resultant in-plane horizontal stresses of circular and elliptical excavations are to a large extent comparable to those of square and rectangular excavations of the same size. Differences arise though near the boundary of circular excavations or of excavations, which become more circular (lower aspect ratio). In this case the drop of stress magnitudes near the excavation is smaller or even not present.
- The resultant vertical stresses along line 3 (Figure 62) show that high abutment stresses develop for circular and elliptical excavations as well and that these abutment stresses decrease with distance from the excavation. In contrast, to square and rectangular excavations of the same size, the abutment stress

magnitudes for circular and elliptical excavations are considerably higher in the vicinity of the excavation.

- The resultant in-plane horizontal stresses along line 3 (Figure 63) for circular and elliptical excavations show the same general trend as for square and rectangular excavation of the same size. However, the stress increase and hence the generation of confinement in the abutment areas is considerably larger for circular and elliptical excavations. This effect is thereby more prominent, the more elliptical (the larger the aspect ratio of) an excavation is.
- The resultant maximum shear stresses along line 2 (Figure 64) show principally that high maximum shear stress magnitudes are present in the abutment area of circular and elliptical excavations as well and that they decrease with distance from the excavation. In contrast to square and rectangular excavations of the same size the magnitude of maximum shear stresses becomes significantly smaller for circular and elliptical excavations, the more circular (the lower the aspect ratio of) such an excavation is.

The similarities of the resultant stress distribution near a square and circular excavation are further outlined in Figure 65. The shown resultant major and minor principal stress contours show that at a certain distance from the excavation the stress distribution is very similar. In the vicinity of the excavation the excavation shape has though a significant influence on the stress distribution. The local curvature of the excavation wall affects the stress gradients and the magnitude of the major principal stress. Hence, the corners of the square excavation are characterized by very high stress magnitudes, but also by very high stress gradients so that the stress concentration in the corners is only of local extent. In contrast, the stress gradients and major principal stress magnitudes near the (straight) walls of the square excavation are lower compared with those of the circular excavation at the same position. With distance from the wall of the square excavation the major principal stress magnitudes even increase, before they drop with distance. The point, where this drop of major principal stresses commences, corresponds approximatively to the point, where the major principal stress magnitude near the square excavation equals to the major principal stress magnitude of the circular excavation. Furthermore, the stress gradient of the major principal stress is for both the square and circular excavation from this point on relatively similar. This example shows well that the stress distribution distant from the excavation is very similar for square and circular excavations. This influence of the excavation shape on the stress distribution near the excavation and the similarities distant from the excavation were also outlined on basis of the stresses along the measurement lines (Figure 60 to Figure 64).

Based on these observations the conclusion can be drawn that the resultant stress situation near circular and elliptical shaped excavations is principally comparable to the resultant stress situation near square and rectangular shaped excavations of the same size. Elongated elliptical excavations are especially suited for the generation of stress shadows. As the excavations become more circular, the de-stressing effect starts to diminish. An advantage of circular and elliptical excavations is though that the abutment stress situation can be better controllable particularly because of an increased confinement and reduced maximum shear stress magnitudes.

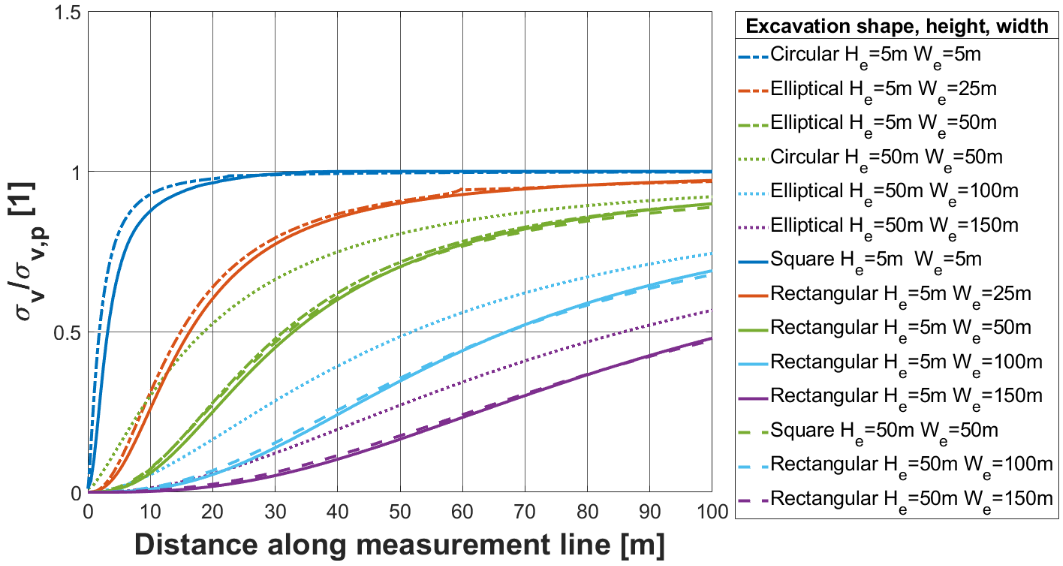


Figure 60: Comparison of the resultant vertical stresses for square and rectangular excavation shapes with circular and elliptical excavation shapes along line 1.

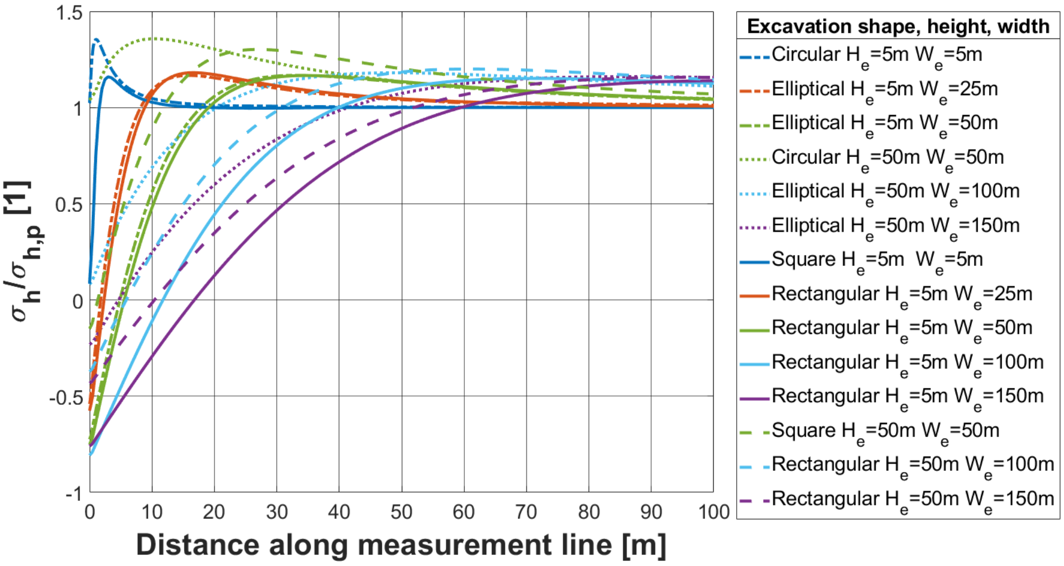


Figure 61: Comparison of the resultant in-plane horizontal stresses for square and rectangular excavation shapes with circular and elliptical excavation shapes along line 1.

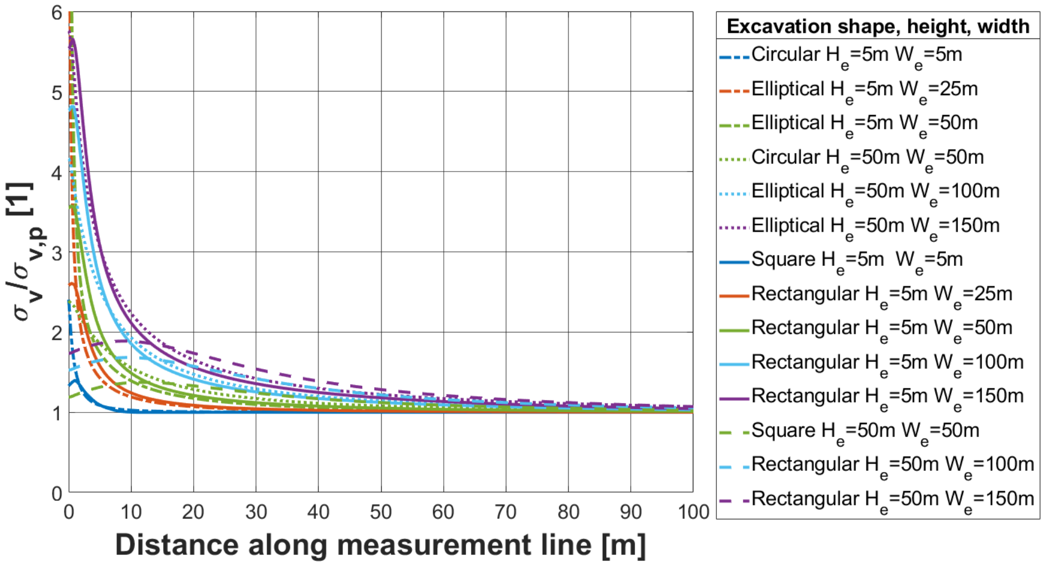


Figure 62: Comparison of the resultant vertical stresses for square and rectangular excavation shapes with circular and elliptical excavation shapes along line 3.

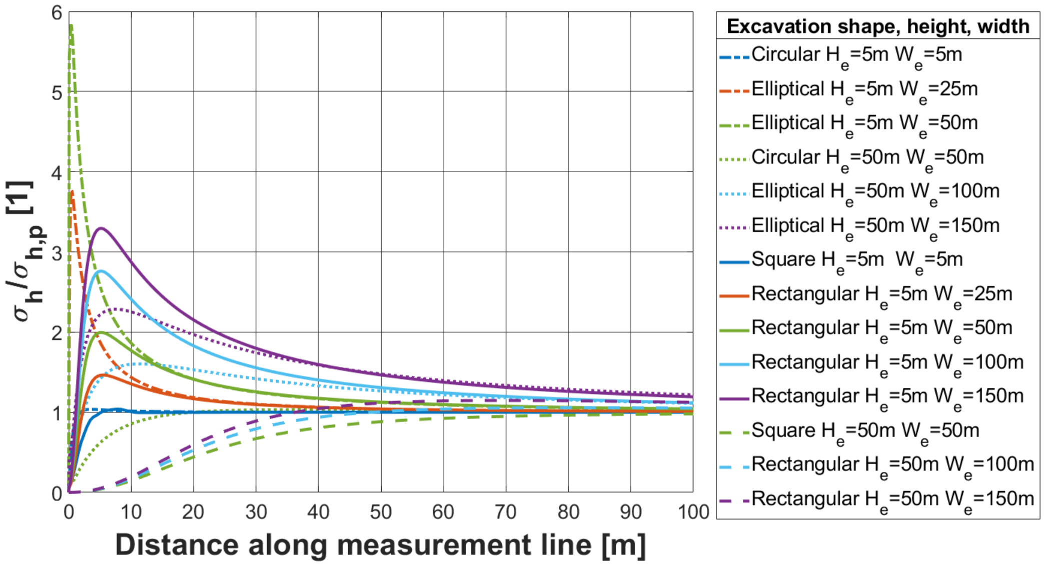


Figure 63: Comparison of the resultant in-plane horizontal stresses for square and rectangular excavation shapes with circular and elliptical excavation shapes along line 3.

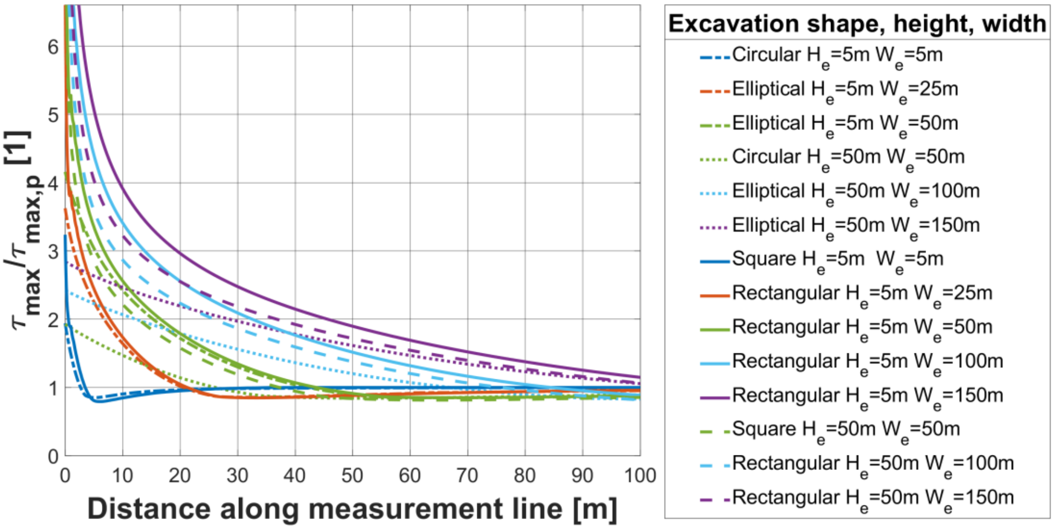


Figure 64: Comparison of the resultant maximum shear stresses for square and rectangular excavation shapes with circular and elliptical excavation shapes along line 2.

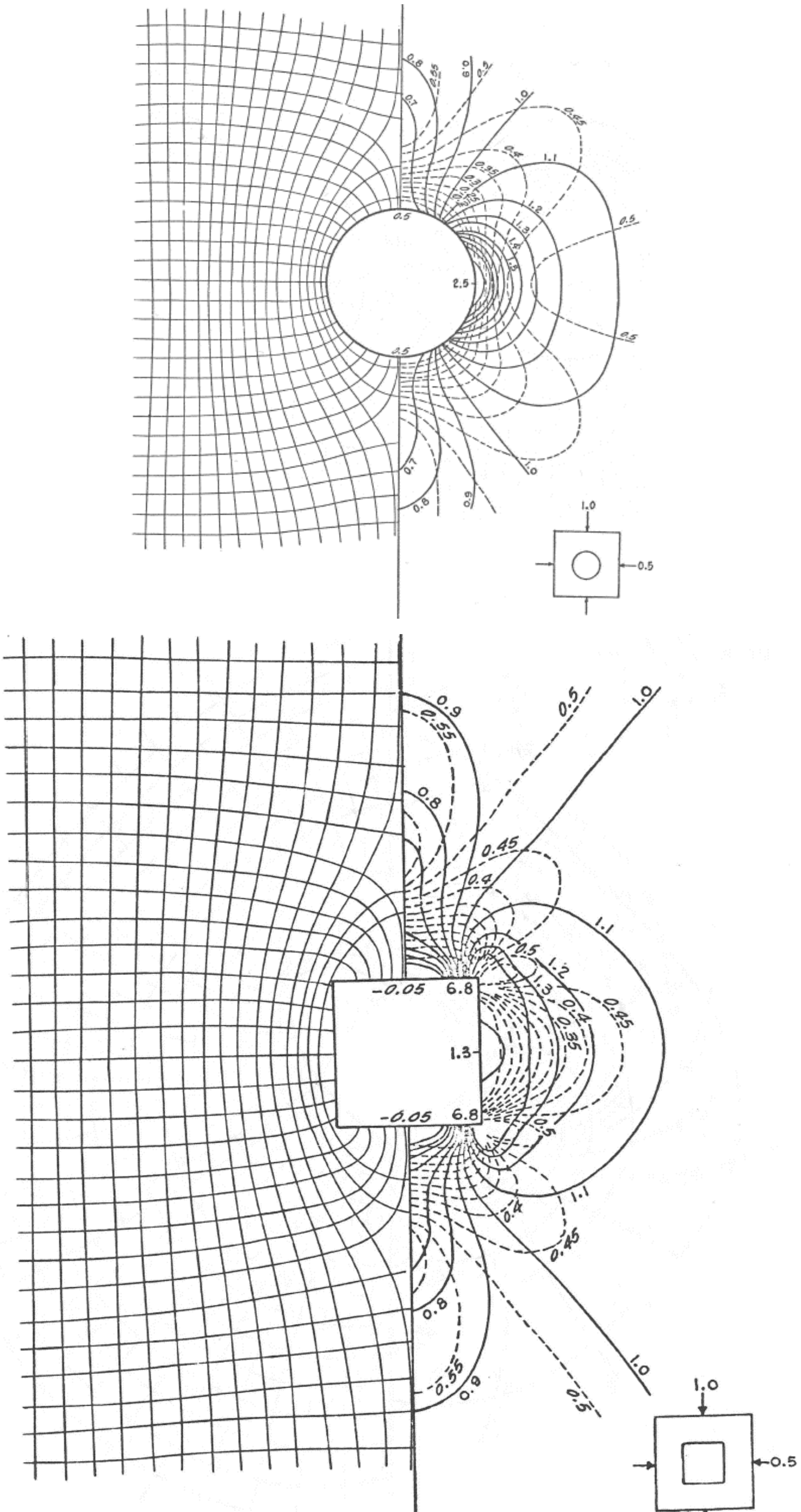


Figure 65: Comparison of the resultant major (full lines) and minor (dashed lines) principal stress near a circular and square excavation, where the diameter of the circular excavation corresponds to the width and height of the square excavation, in the same primary stress field (the ratio of primary horizontal to primary vertical stresses is 0.5); diagrams taken after Hoek and Brown (1980)

6.1.1.1.2 Influence of the excavation orientation

For the conducted investigations regarding the excavation size and shape and the primary stress situation only flat-lying excavations were considered. The influence of the excavation orientation relative to the far-field stresses is outlined in the following. Therefore, a rectangular excavation with a width of 100 m and a height of 5 m is rotated and angles between the horizontal and the larger extension of the excavation of 0 °, 30 °, 60 ° and 90 ° are considered; compare Figure 66. Thereby, the larger extension of the excavation is always referred to as excavation width and the smaller extension of the excavation is referred to as excavation height. Hence, for the excavation, which is oriented at 90 °, the excavation width refers to the extension of the excavation in vertical direction and the excavation height to the extension in horizontal direction. Although this terminology could be confusing, it is kept here to facilitate the discussion and comparison of results with results of foregoing analyses. The same parameters and model setup as for the previous simulations are used. Resultant stresses are displayed as color plots and along three measurement lines. The measurement lines are at the same position as in the previous analyses and the orientation of the measurement lines is adapted according to the orientation of the excavation; compare Figure 66. All measurement lines start at excavation walls.

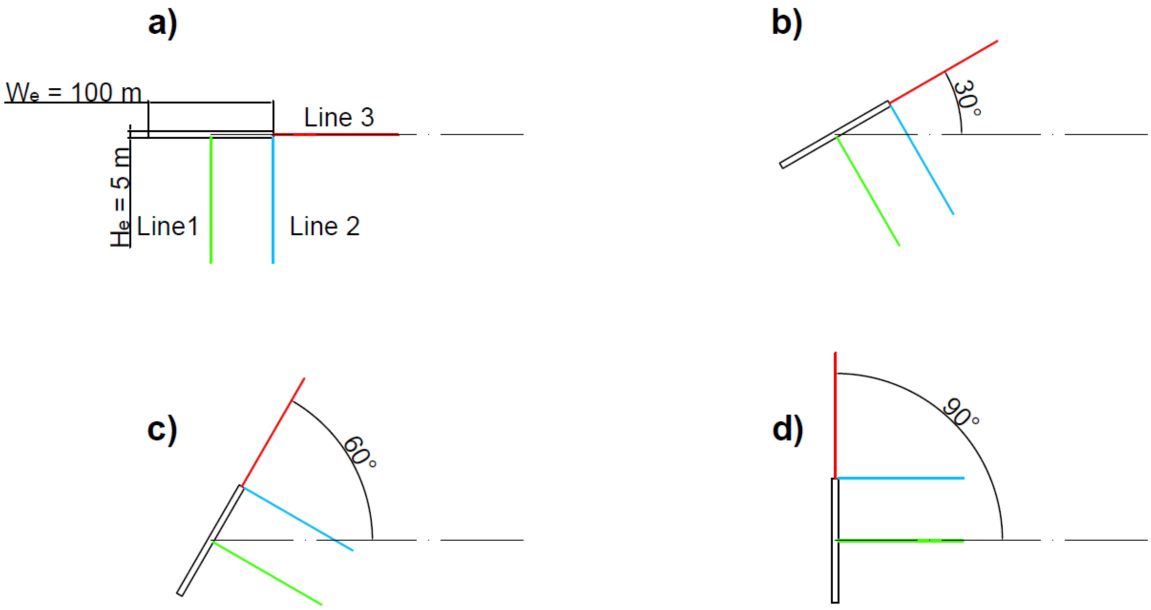


Figure 66: Excavation geometry and considered orientations for outlining the influence of excavation orientation on the resultant stress situation. The positions of considered measurement lines are shown as well.

The resultant stress distribution near an excavation of considered geometry with an orientation of 90 ° and a ratio of primary horizontal to primary vertical stresses of 0.5 is outlined in Figure 67 to Figure 72. The resultant vertical and horizontal stresses, the resultant major and minor principal stresses and the resultant maximum shear stresses are shown. This excavation, which is oriented at 90 °, is referred to as vertical excavation in the subsequent discussion. The excavation geometry and primary stress state are the same as in the plots of the resultant stresses for a flat-lying excavation (Figure 45 to Figure 50), which is referred to as horizontal excavation in the following discussion. Overall, the resultant stress distribution near the vertical excavation shows that their characteristics are principally comparable to the characteristics of the resultant stress distribution near the same horizontal excavation, namely de-stressed zones and highly stressed abutment areas are generated. The difference is that in case of the vertical excavation the primary in-plane horizontal stresses are strongly influenced, whereas the primary vertical stresses are not strongly influenced. Accordingly, the de-stressed zones are near the sidewalls of the vertical excavation and the abutment areas are formed in the roof and floor of the vertical excavation. High resultant maximum shear stresses are present in the abutment areas, but also in the sidewalls and some distance into the sidewalls. The reason for the high maximum shear stresses in sidewall areas is that the in-plane horizontal stresses are reduced in respective area considerably by the vertical excavation, whereas the vertical stresses in respective area are only influenced slightly and thus the vertical stresses are still of comparably high magnitude. Furthermore, the spatial extent of highly stressed abutment areas and stress shadows as well as the prevailing stress magnitudes in the stress shadows and abutment areas for the vertical excavation are different in comparison with the horizontal excavation. The reason for this are the different far-field stress magnitudes relative to the excavation extensions.

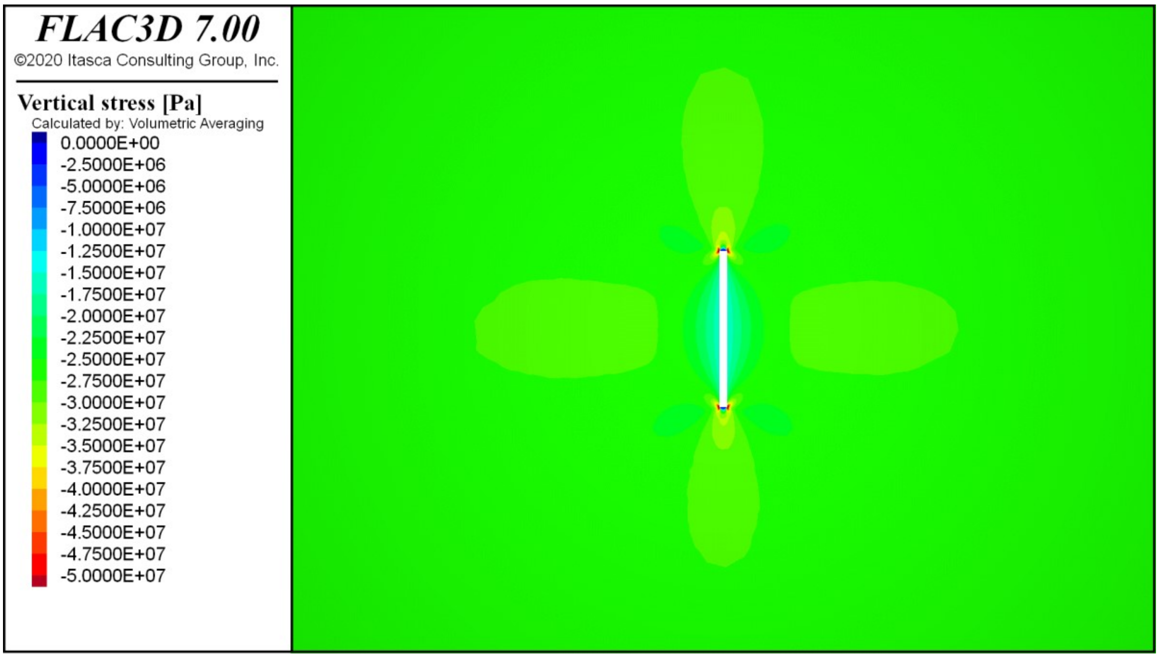


Figure 67: Resultant vertical stresses near an elongated rectangular excavation with a width of 100 m, a height of 5 m and an orientation of 90 °; compressive stresses are negative.

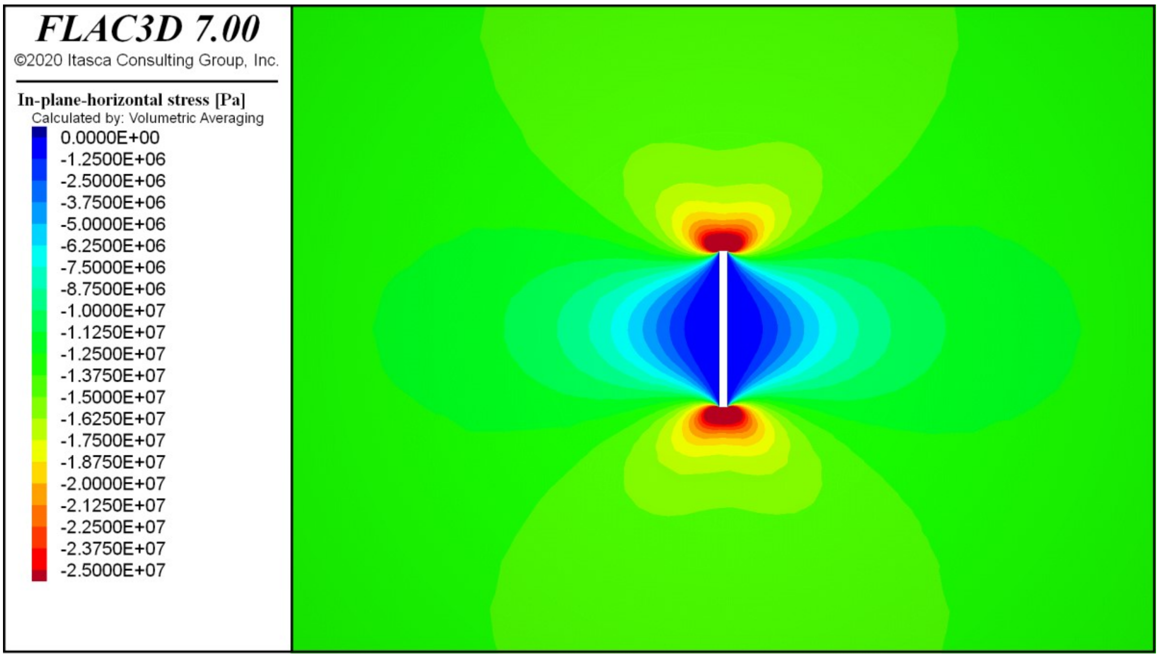


Figure 68: Resultant in-plane horizontal stresses near an elongated rectangular excavation with a width of 100 m, a height of 5 m and an orientation of 90 °; compressive stresses are negative.

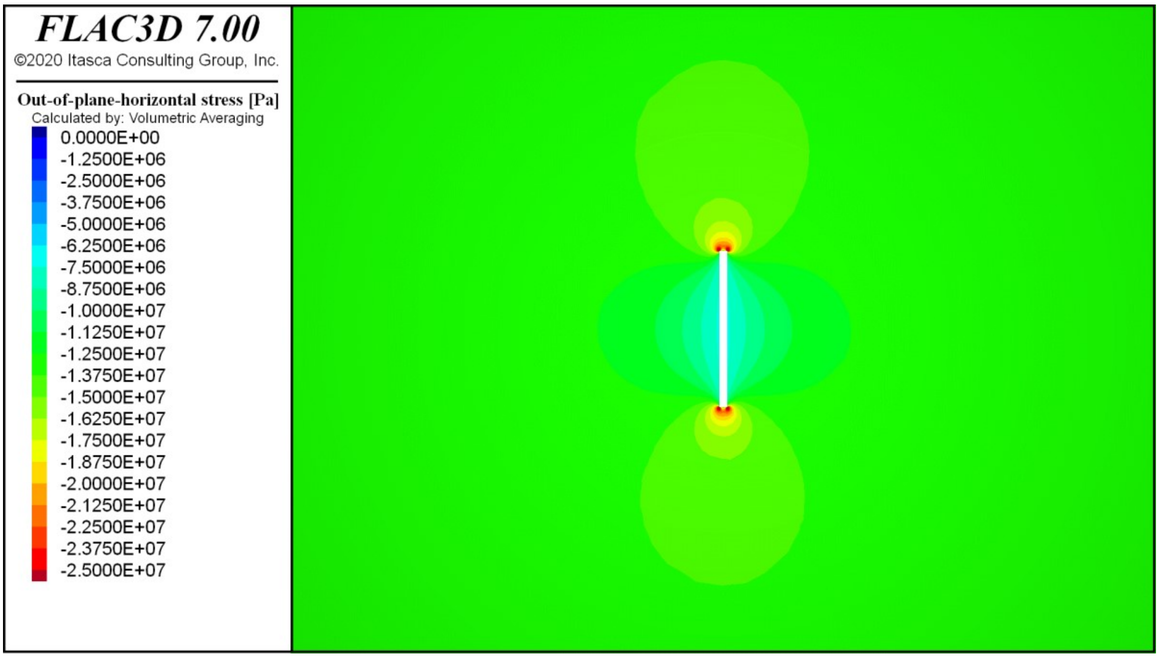


Figure 69: Resultant out-of-plane horizontal stresses near an elongated rectangular excavation with a width of 100 m, a height of 5 m and an orientation of 90 °; compressive stresses are negative.

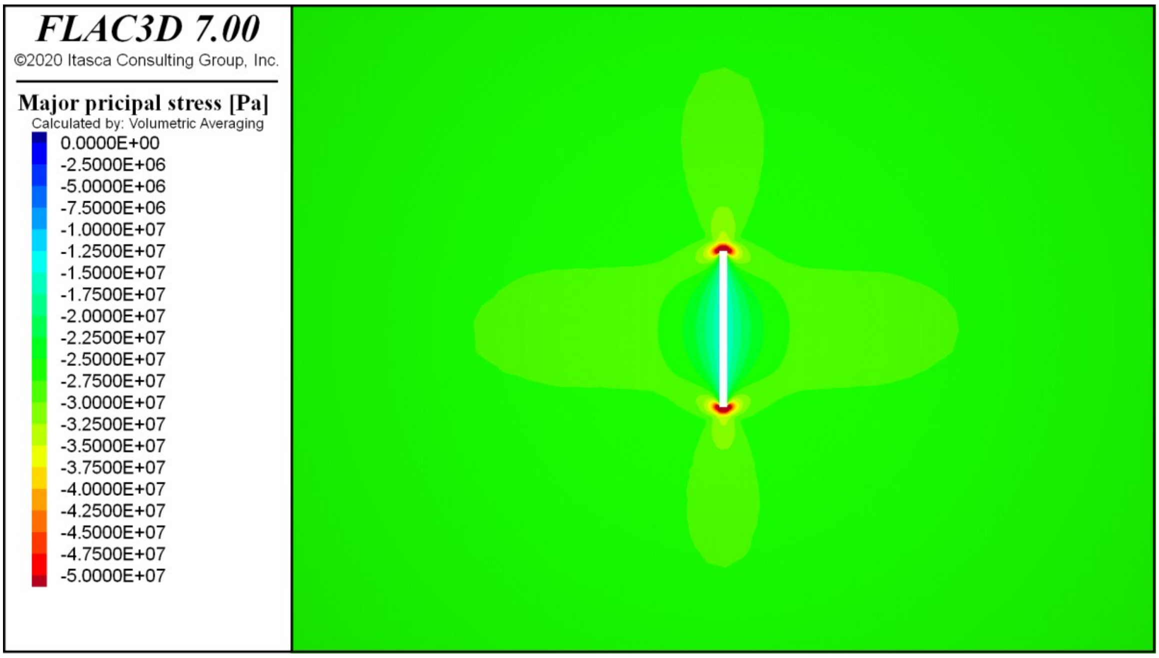


Figure 70: Resultant major principal stresses near an elongated rectangular excavation with a width of 100 m, a height of 5 m and an orientation of 90 °; compressive stresses are negative.

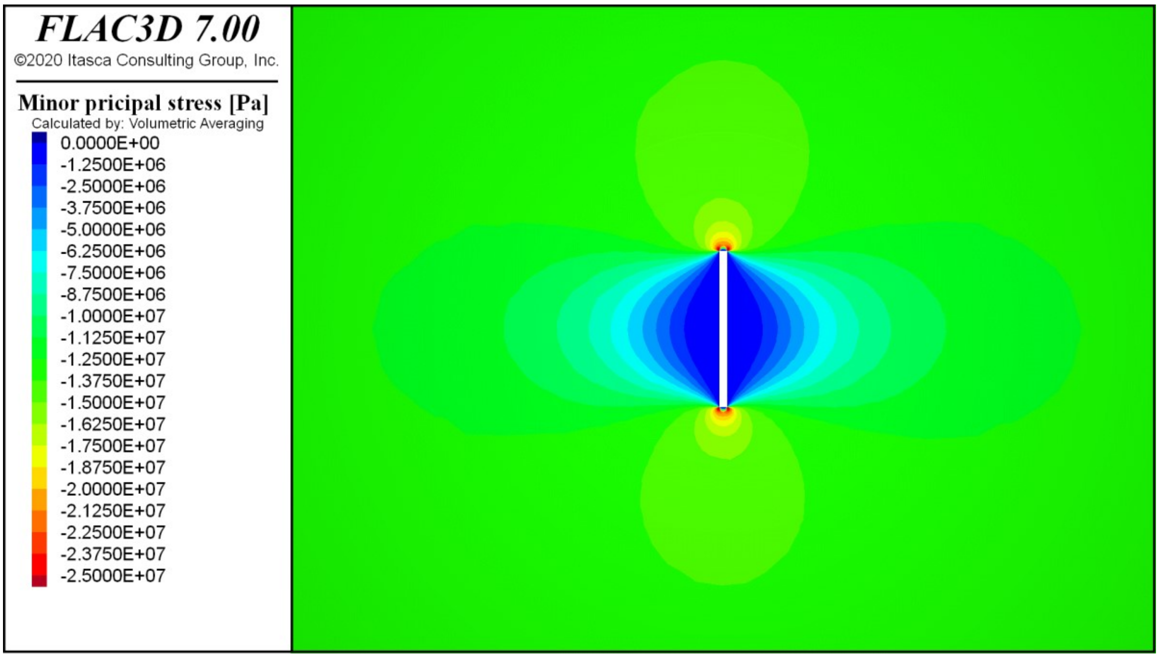


Figure 71: Resultant minor principal stresses near an elongated rectangular excavation with a width of 100 m, a height of 5 m and an orientation of 90 °; compressive stresses are negative.

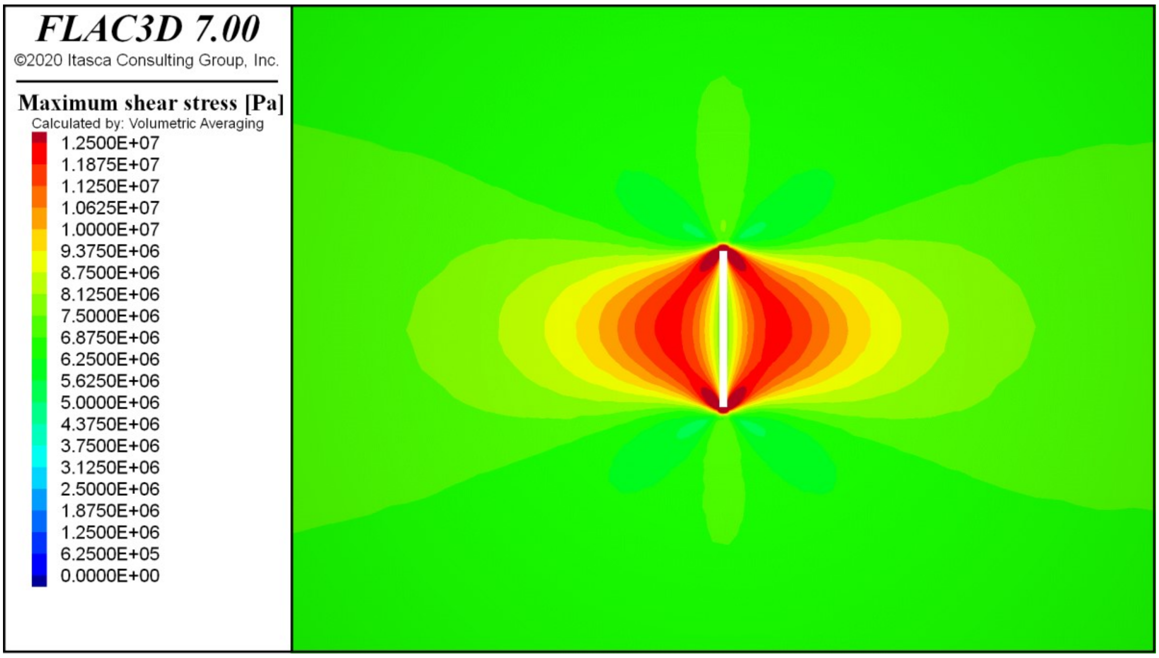


Figure 72: Resultant maximum shear stresses near an elongated rectangular excavation with a width of 100 m, a height of 5 m and an orientation of 90 °

The dependency of the resultant stresses on the orientation of the excavation is further shown along the considered measurement lines in Figure 73 to Figure 76. Ratios of primary horizontal to primary vertical stresses (k) of 0.5, 1 and 1.5 are displayed. Along line 1 and 3 the resultant normal stresses, which are tangential (σ_{tan}) and perpendicular (σ_{per}) on the excavation boundary, are considered. In case of an excavation orientation of 0 ° and 90 ° these stresses correspond to the resultant vertical and in-plane horizontal stresses. All outlined stresses are normalized on the primary stresses in the considered direction ($\sigma_{tan,p}$ and $\sigma_{per,p}$). The lines and displayed stresses along these lines are chosen such that they outline relevant aspects for the stress management concept. The full lines represent an excavation orientation of 0 °, the dot dashed lines an orientation of 30 °, the dotted lines an orientation of 60 ° and the dashed lines an orientation of 90 °. The colors for the same ratio of primary horizontal stresses to primary vertical stresses are equal. Following observations are made:

- The resultant stresses perpendicular and tangential to the excavation boundary along line 1 (Figure 73 and Figure 74) show that a stress shadow is present in this area. In general, the characteristics of the stresses are comparable to those of a flat-lying excavation, which were described and discussed in section 6.1.1.1.1. The actual magnitude of the stress drop in the de-stressed zone depends though significantly on the excavation orientation and the ratio of primary stresses.
- The resultant stresses perpendicular and tangential to the excavation boundary along line 3 (Figure 75 and Figure 76) show the presence of an abutment area. Again, the characteristics of the stress distribution are principally comparable to those of a flat-lying excavation (section 6.1.1.1.1), but the orientation of the

excavation and ratio of the primary stresses have a significant influence particularly on the actual stress magnitudes.

- The analysis of the maximum shear stress magnitudes in the abutment area shows as well the same trends and characteristics, which were described in section 6.1.1.1.1. High maximum shear stress magnitudes are prevailing at the excavation boundary and they decrease with distance from the boundary. The excavation orientation and ratio of primary stresses have an impact on the stress gradients of decreasing maximum shear stresses. Furthermore, the analysis of the maximum shear stress magnitudes in the de-stressed zone shows that they depend noticeably on the excavation orientation and the ratio of primary stresses.
- The excavation orientation does not have an influence on the resultant stress distribution for a ratio of primary horizontal to primary vertical stresses of one, because the far-field stresses in all directions are equal in this case.

Based on these observations it can be concluded that the excavation orientation in combination with the primary stress state have a significant influence on the position and spatial extent of de-stressed zones and abutment areas as well as on the direction, in which stresses are reduced or increased. Overall, the elongated rectangular excavation, which is well suited for the generation of stress shadows, de-stresses the rock mass effectively in the vicinity of its larger extension (its width), whilst abutment areas develop in the vicinity of its smaller extension (its height). Therefore, the excavation decreases the stresses, which are oriented perpendicular to its larger extension (its width), in the stress shadow noticeably, whilst it increases the stresses in the same direction in the abutment areas considerably. Concluding, the orientation of an excavation respective to the prevailing stress state is critical for the resultant stress distribution in its vicinity.

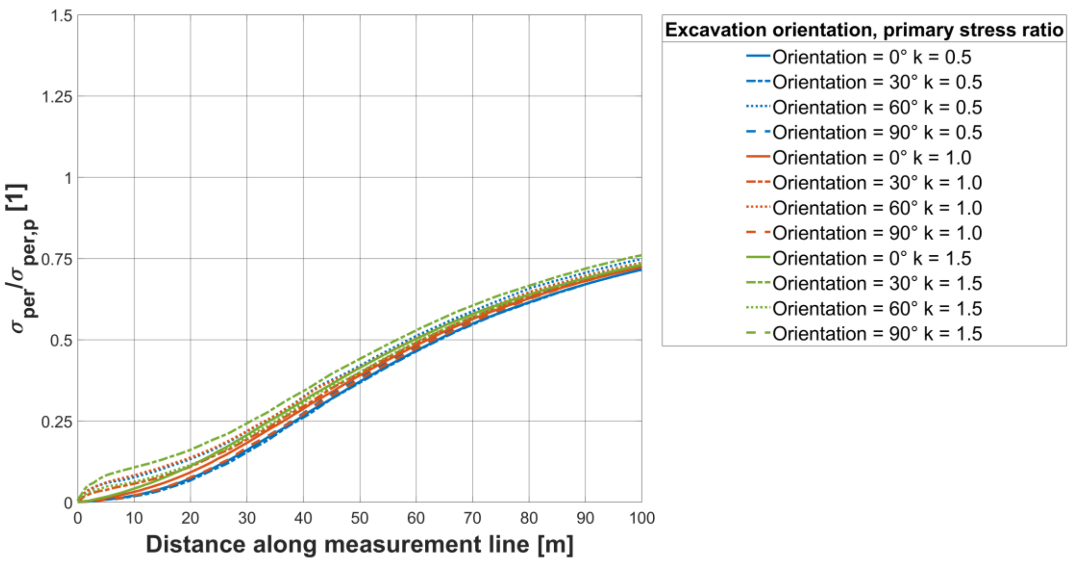


Figure 73: Influence of excavation orientation and ratio of primary horizontal to primary vertical stresses on the resultant normal stresses perpendicular to the excavation boundary along line 1.

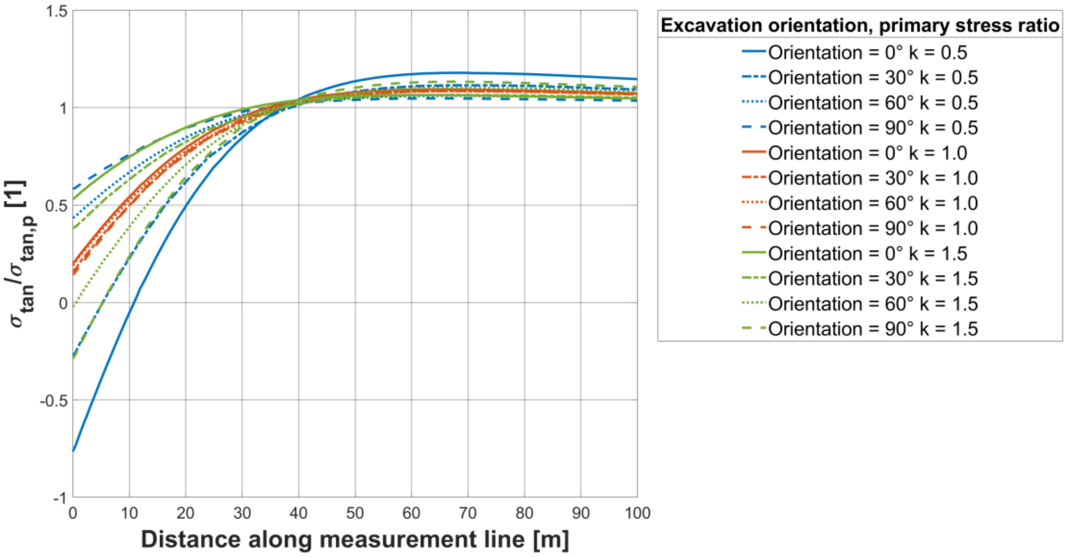


Figure 74: Influence of excavation orientation and ratio of primary horizontal to primary vertical stresses on the resultant normal stresses tangential to the excavation boundary along line 1.

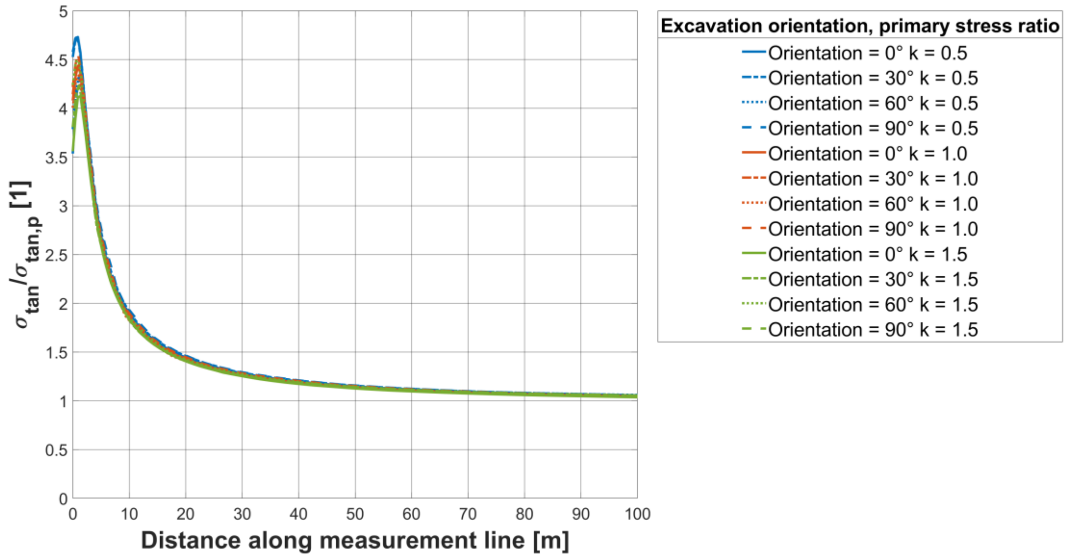


Figure 75: Influence of excavation orientation and ratio of primary horizontal to primary vertical stresses on the resultant normal stresses tangential to the excavation boundary along line 3.

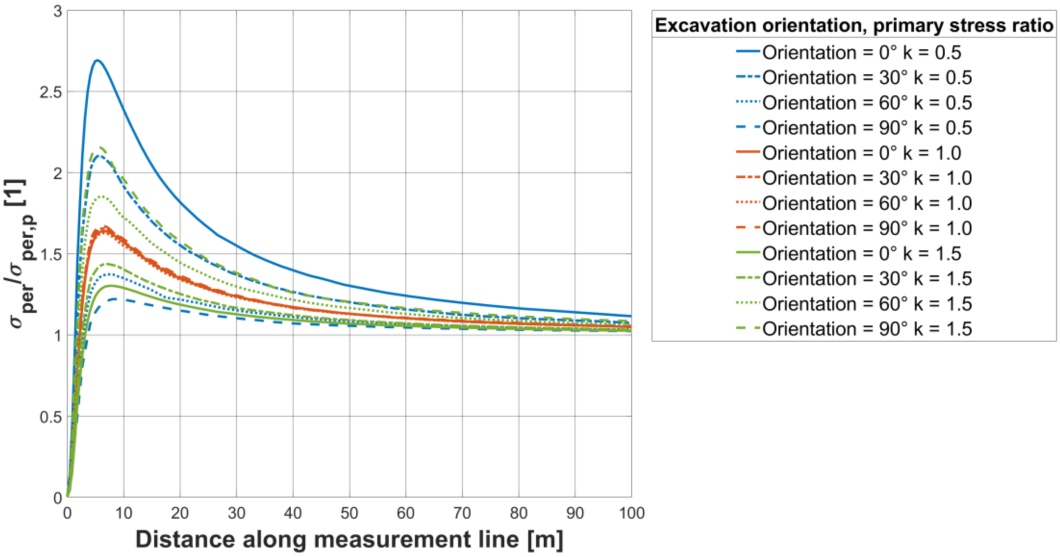


Figure 76: Influence of excavation orientation and ratio of primary horizontal to primary vertical stresses on the resultant normal stresses perpendicular to the excavation boundary along line 3.

6.1.1.1.3 Influence of the third dimension

So far two-dimensional excavations were investigated. A two-dimensional excavation is infinitely long and does not have the additional abutments, which a three-dimensional excavation has. The principal influence of the third excavation dimension is demonstrated on basis of a flat-lying excavation with an elongated, rectangular cross-section. The extension of the excavation in the third dimension is referred to as excavation length (L_e); compare Figure 77. The considered excavation has a height of 5 m and a width of 100 m. The length is varied and it is 50 m, 100 m, 200 m, 400 m. The resultant stress distributions are calculated with FLAC3D. The same input parameter as for the previous simulations are used. The considered ratios of primary horizontal to primary vertical stresses are 0.5 and 1.5. Both primary horizontal stresses are equal in magnitude. The resultant stresses are outlined along four measurement lines; compare Figure 77. The position of lines 1, 2 and 3 are chosen such that these lines are comparable to the positions of lines 1, 2 and 3 in previous simulations. Line 1 is vertical and located in the de-stressed zone at half width and half length. Line 2 and 3 are located in the abutment; line 2 is vertical and located at half length at the excavation corner; line 3 is horizontal, points in direction of the excavation width and is located at half length and half height. Line 4 is horizontal, points in direction of the excavation length, is located in the additional abutment and starts at half width and half height of the excavation. All lines start at the excavation boundary, which also remarks the point zero for the distance along the line.

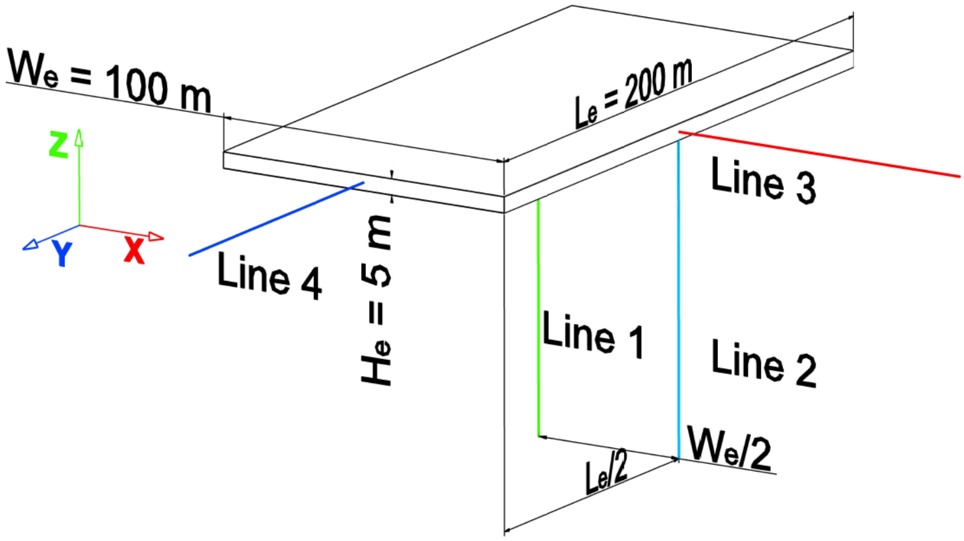


Figure 77: Investigated three-dimensional excavation with a width of 100 m, a height of 5 m and a length of 200 m. The excavation length is varied in the analyses. The positions of the measurement lines are shown as well.

The resultant stress distributions are outlined along lines 1, 2, 3 and 4 in Figure 78 to Figure 84. The lines and displayed stresses along these lines are chosen such that they outline relevant aspects for the stress management concept. All outlined stresses are further normalized with the primary stress magnitudes. The resultant vertical stresses and resultant horizontal stresses in x-direction, which correspond to the resultant in-plane horizontal stresses in the two-dimensional investigations, are shown along line 1 and 3 and the resultant maximum shear stresses along line 2. The outlined stresses along these lines correspond to the outlined stresses of the previous simulations with two-dimensional excavation geometries. For this reason, the resultant stresses of the two-dimensional excavation are shown as well for lines 1, 2 and 3. Moreover, the resultant vertical stresses and resultant horizontal stresses in y-direction are shown along line 4, which is situated in the additional abutment area. The resultant vertical stresses and resultant horizontal stresses along line 3 are also plotted in Figure 83 and Figure 84 so that the stress situation in the two abutment areas can be compared. The resultant stresses for an excavation length of 50 m are shown as dotted lines, for an excavation length of 100 m as dot dashed lines, for an excavation length of 200 m as dashed lines and for an excavation length of 400 m as full lines. The resultant stresses of the two-dimensional simulations, which are shown for comparison, are shown as full lines too. Following observations are made:

- The resultant stresses along lines 1, 2 and 3 (Figure 78 to Figure 82) approach the resultant stresses for the two-dimensional situation, as the excavation length increases. Moreover, the characteristics of the resultant stress distributions remain the same also for excavations with smaller lengths.
- In the de-stressed zone (Figure 78 and Figure 79) the spatial extent of the de-stressed zone as well as the reduction of stress magnitudes are smaller, if the excavation length is small. Hence, the de-stressing effect provided by excavations with a smaller length is reduced compared to an infinitely long excavation. However,

the de-stressing effect is still considerable and it increases relatively rapidly with increasing excavation length.

- In the abutment areas, which are present for an infinitely long excavation, namely line 2 and 3 (Figure 80 to Figure 82), the resultant stress magnitudes are lower for excavations with a smaller length. Furthermore, the spatial extent of increased stress magnitudes is smaller. These lower stress magnitudes in the abutment area enable an improved control of the abutment stress situation. However, the stress magnitudes approach the magnitudes of the infinitely long excavation relatively rapidly with increasing excavation length.
- In the additional abutment area, which is represented by line 4 (Figure 83 and Figure 84), the resultant stress magnitudes are also considerable and they increase with increasing excavation length. However, the stress magnitudes in the additional abutment do not reach the same magnitudes compared to the other abutment (line 3). Furthermore, the spatial extent of the abutment area and its corresponding high stress magnitudes is smaller. Overall, the abutment stress situation at the additional abutment becomes more favorable compared to the other abutments.

In summary, the third dimension increases the complexity of the resultant stress situation, even though the characteristics of the stress distribution of the two-dimensional case are generally remained. Furthermore, the third dimension does not have an adverse effect on the resultant stress situation. In contrast, the third dimension has even a positive effect, because it provides and additional abutment, which reduces the disturbance to the primary stress field. This improvement is particularly visible at the additional abutment, where the abutment stress situation becomes more favorable due to lower abutment stress magnitudes and due to a smaller spatial extent of the abutment area. Accordingly, a two-dimensional approximation of three-dimensional excavations is conservative and reasonable in situations, where the effects in the third abutment are not of interest.

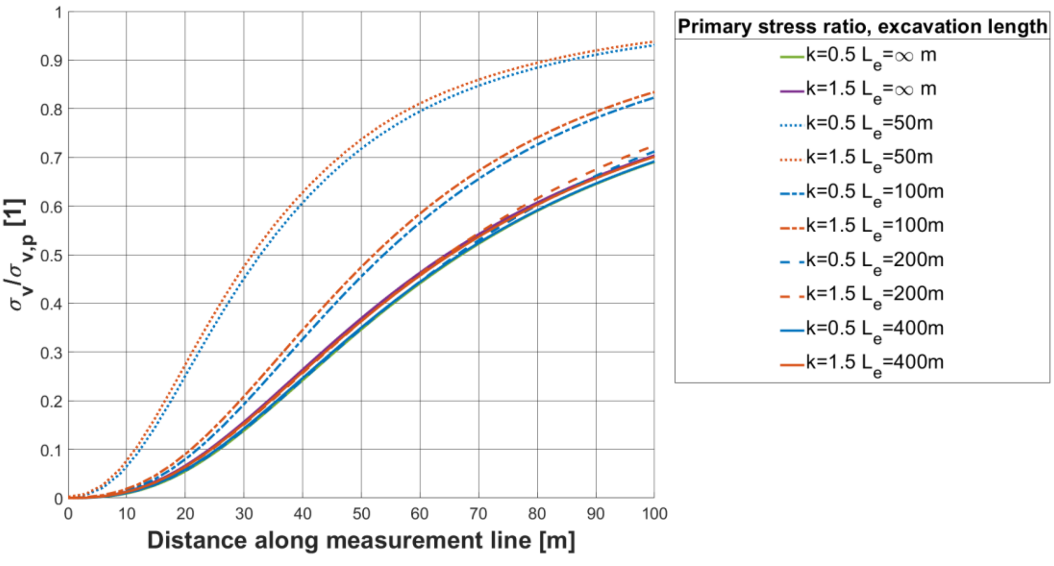


Figure 78: Influence of excavation length on the resultant vertical stresses along line 1.

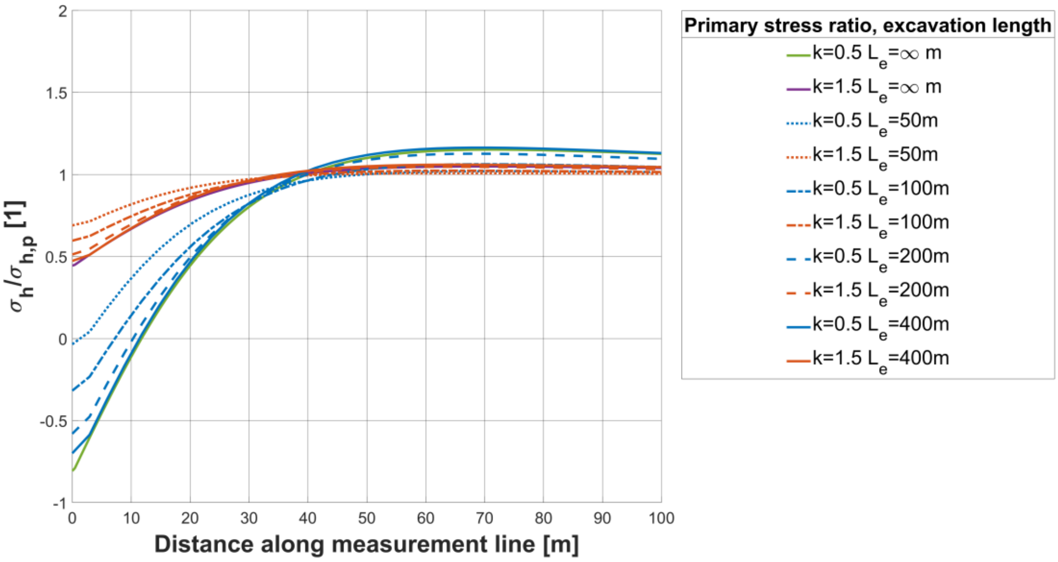


Figure 79: Influence of excavation length on the resultant horizontal stresses in x-direction along line 1.

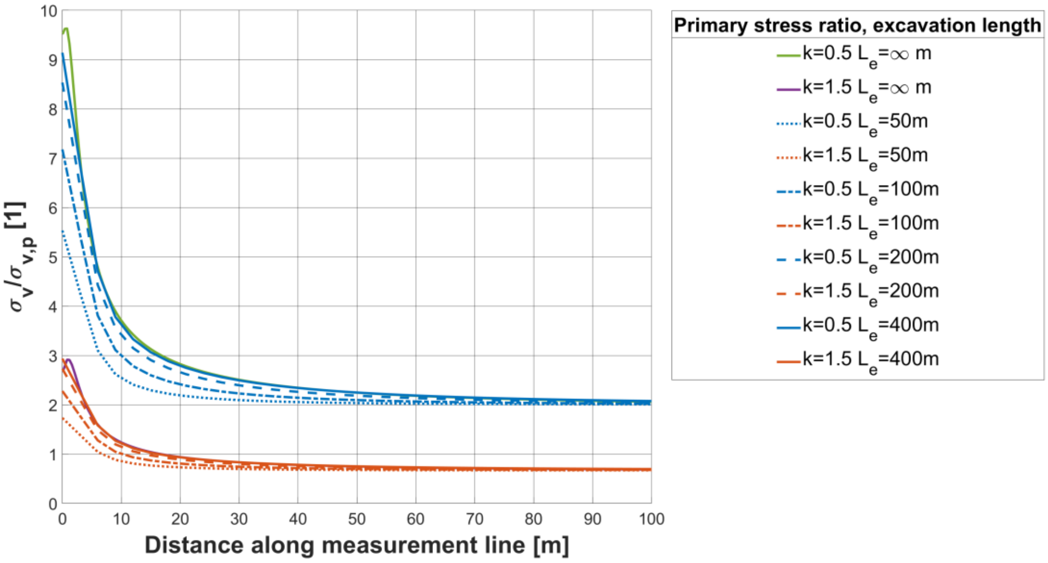


Figure 80: Influence of excavation length on the resultant vertical stresses along line 3.

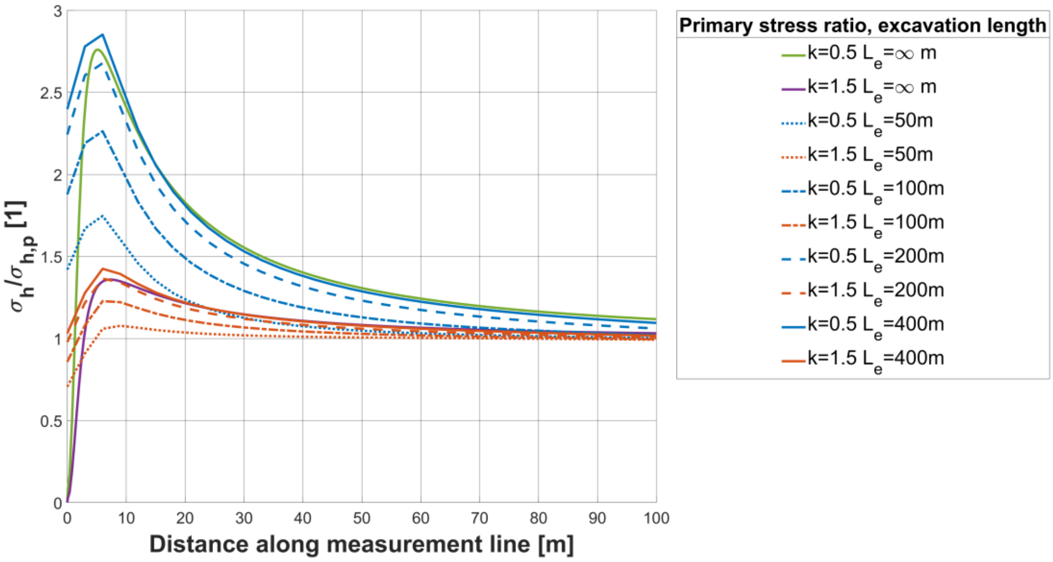


Figure 81: Influence of excavation length on the resultant horizontal stresses in x-direction along line 3.

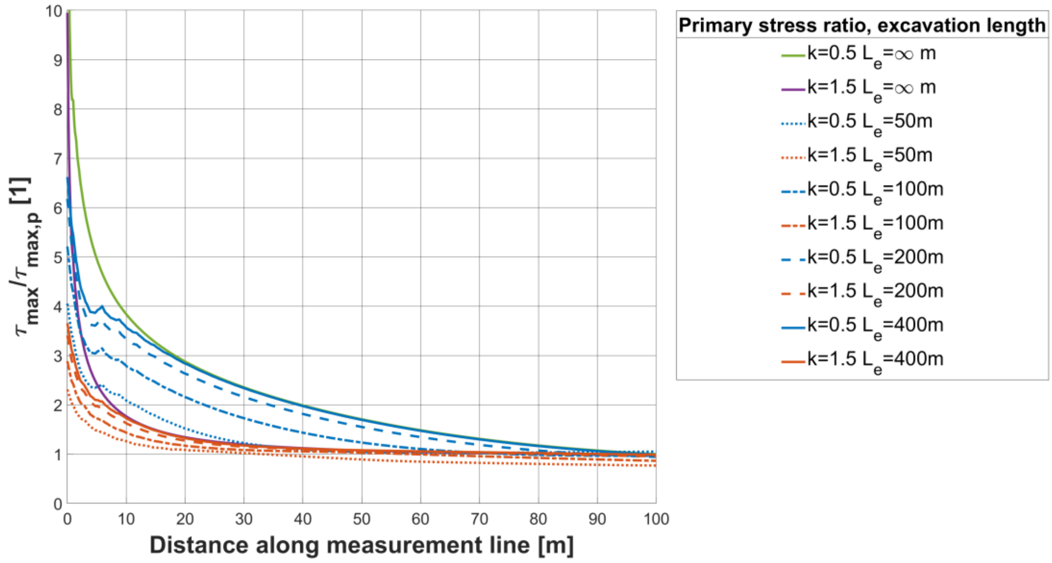


Figure 82: Influence of excavation length on the resultant maximum shear stresses along line 2.

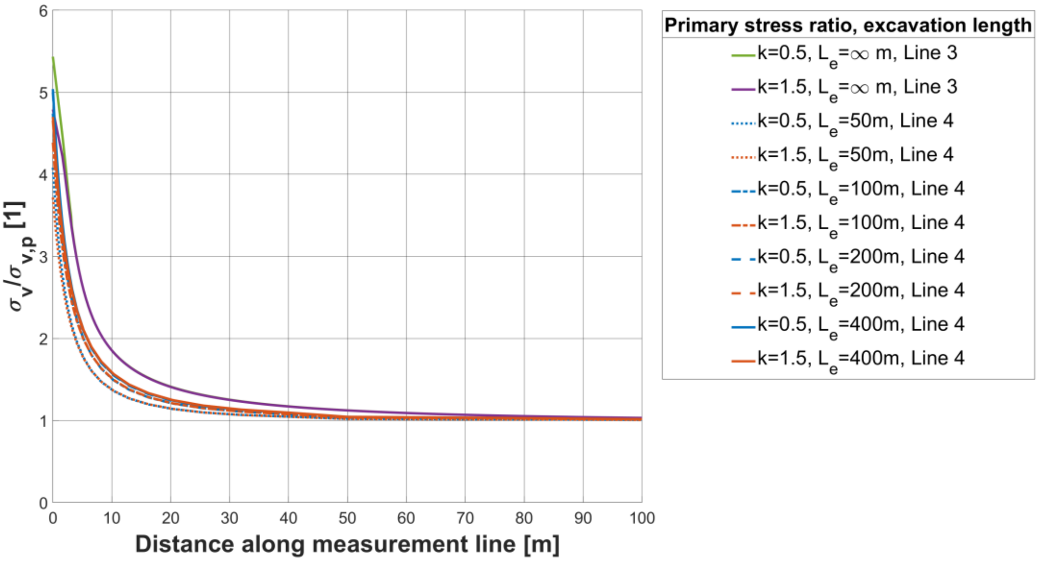


Figure 83: Influence of excavation length on the resultant vertical stresses along line 4. Resultant vertical stresses for an infinitely long excavation along line 3 are shown for comparison.

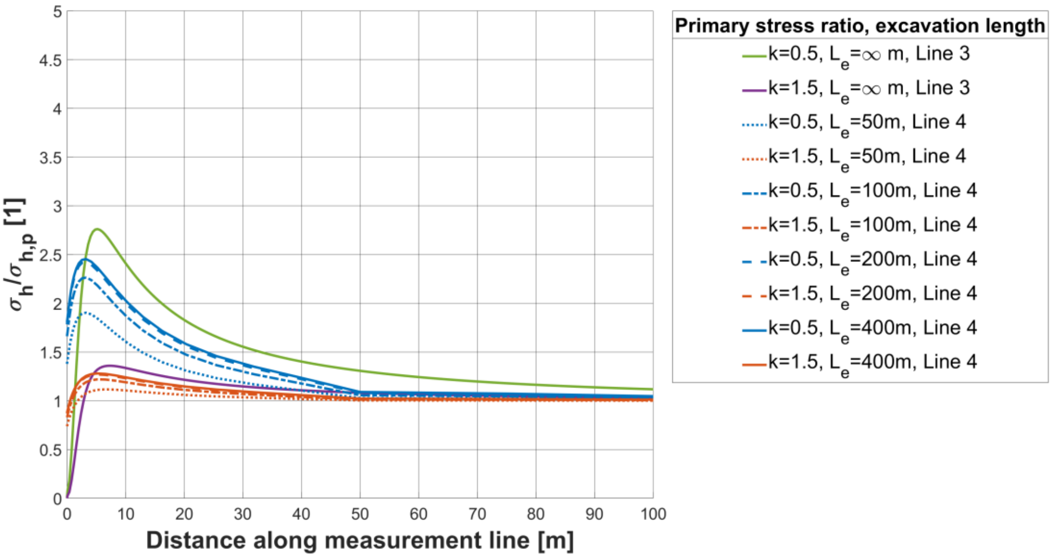


Figure 84: Influence of excavation length on the resultant horizontal stresses in y-direction along line 4. Resultant horizontal stresses in x-direction for an infinitely long excavation along line 3 are shown for comparison.

6.1.1.2 Effect of fracture and failure of the nearby rock mass

The resultant stresses generated by the creation of an excavation may cause rock mass fracture and failure in the vicinity of the excavation. It is reasonable to distinguish between two different situations:

- Detachment of the fractured and failed rock mass: In this case the fractured and failed rock mass detaches and falls into the excavation. Accordingly, the excavation caves and the excavation geometry and size change; compare Figure 85a. The detachment of rock mass is driven by gravity. Accordingly, rock mass can only detach, if the weight of rock mass overcomes resisting forces and if movement of rock mass in direction of gravity (downward direction) is possible. For example, detachment of rock mass from an excavation roof is possible, whereas the detachment of rock mass from an excavation floor is not possible.

- Staying in place of the fractured or failed rock mass: In this case the fractured or failed rock mass does not detach and stays in place. Hence, the geometry and size of the excavation are not altered; compare Figure 85b. However, due to fracture or failure the rock mass can only transfer limited stress magnitudes, which depend on the stress strain behavior of the rock mass and the degree of fracturing or failure. Consequently, the resultant stresses in the fractured or failed zone as well as in the intact rock mass near the fractured or failed zone are altered. A zone of fractured or failed rock mass is also commonly present near zones, where detachment of the rock mass has taken place.

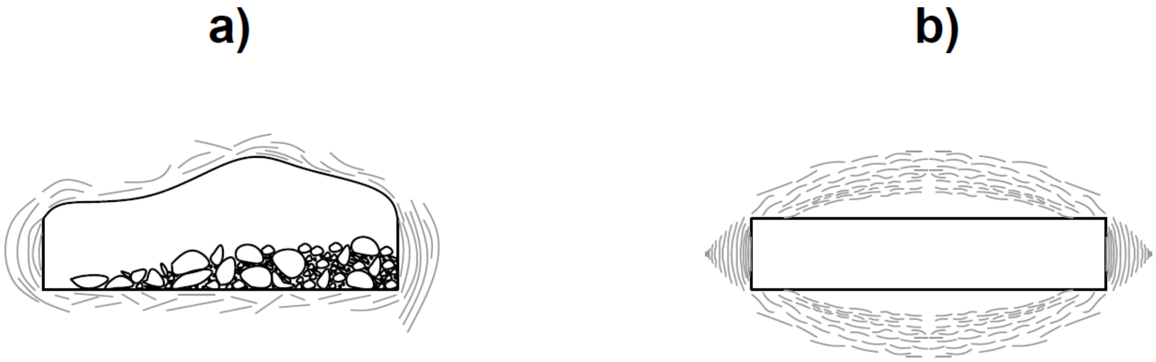


Figure 85: Consequences of rock mass fracture and failure near an excavation; (a) with detachment of rock mass and corresponding change of excavation geometry and size; (b) without detachment of rock mass

The effect of rock mass detachment on the resultant stress situation can be represented by a corresponding adaption of the excavation boundaries. In situations, where caving of large volumes takes place, such as for example in cave mining methods, the weight of the detached rock mass inside the excavation must be considered in the determination of the resultant stress distribution, whereas in the remaining situations the weight of the caved rock mass has usually a negligible effect on the resultant stress distribution.

The general effect of rock mass fracturing or failure, which do not cause detachment, on the resultant stress distribution is outlined by means of an excavation in a rock mass with intermediate strength. The considered excavation has a rectangular cross-section with a height of 5 m and a width of 100 m. The excavation is flat-lying and two-dimensional. The rock mass strength is calculated after Hoek et al. (2002), whereby its uniaxial compressive strength of rock is 150 MPa, its rock material constant m_i is 20 and its GSI is 50. The disturbance factor D is set to zero, because the effect of fracturing and failure at some distance from the excavation boundary, where the influence of blasting practices is not noticeable anymore, is of interest. The Young's modulus of the rock mass is set to 15 GPa and the Poisson ratio to 0.25. The excavation is located at a depth of 1000 m. The primary vertical stresses are 27 MPa and the considered ratio of primary horizontal to primary vertical stresses (k) is 0.5 and 1, respectively. Both primary horizontal stresses are equal.

The resultant stresses are calculated with FLAC3D in 1 m thick slice models. Therefore, the rock mass is modelled with a linear elastic – ideal plastic material behavior and a Hoek-Brown strength criterion. For comparison simulations with a linear elastic rock mass behavior are conducted as well. The excavations are created in a single step. The results are presented as resultant stresses along three lines. The position and number of the lines coincide with the position and number of the lines used in previous simulations of stress distributions near excavations; compare Figure 44. Line 1 represents the area in the rock mass, where a de-stressed zone is present because of the created excavation, and line 3 represents the abutment area of the excavation. The resultant vertical and in-plane horizontal stresses are displayed along lines 1 and 3; compare Figure 86 to Figure 89. All stresses are normalized. The resultant stresses are displayed as full lines for k=0.5 and dashed lines for k=1.

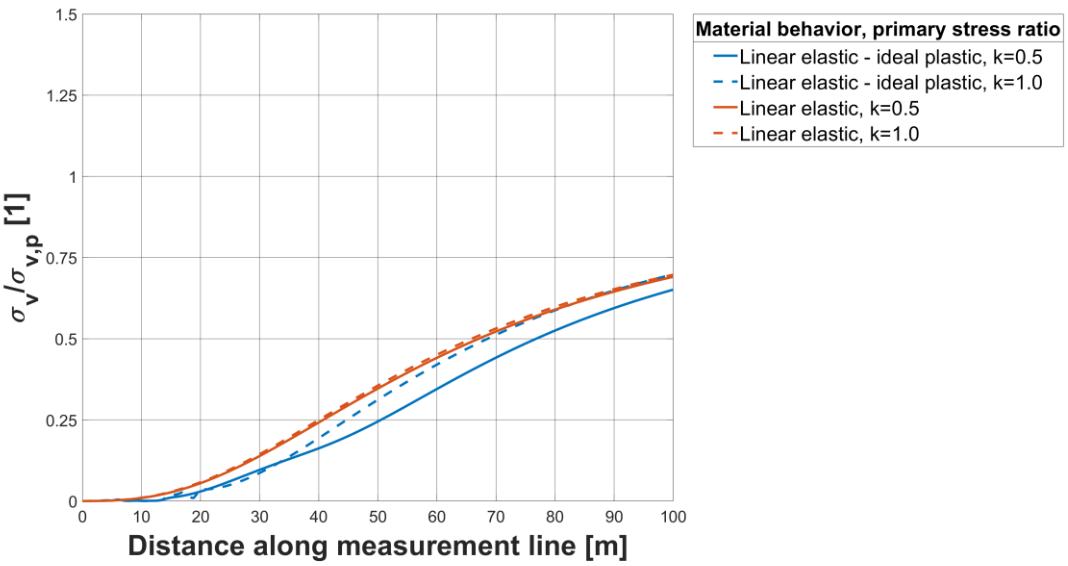


Figure 86: Comparison of the normalized resultant vertical stresses along line 1 for an elastic and a plastic material behavior.

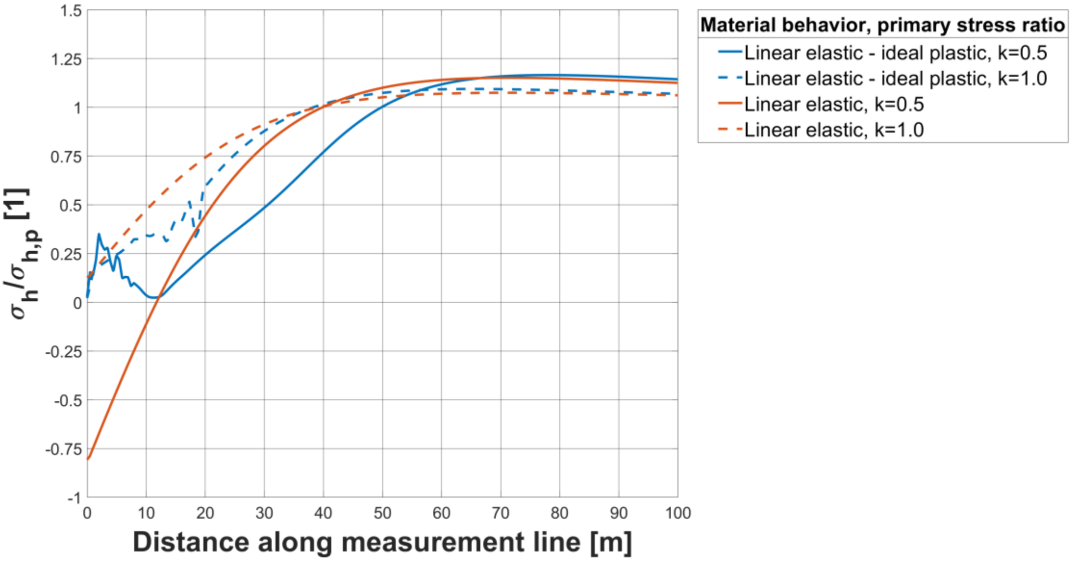


Figure 87: Comparison of the normalized resultant in-plane horizontal stresses along line 1 for an elastic and a plastic material behavior.

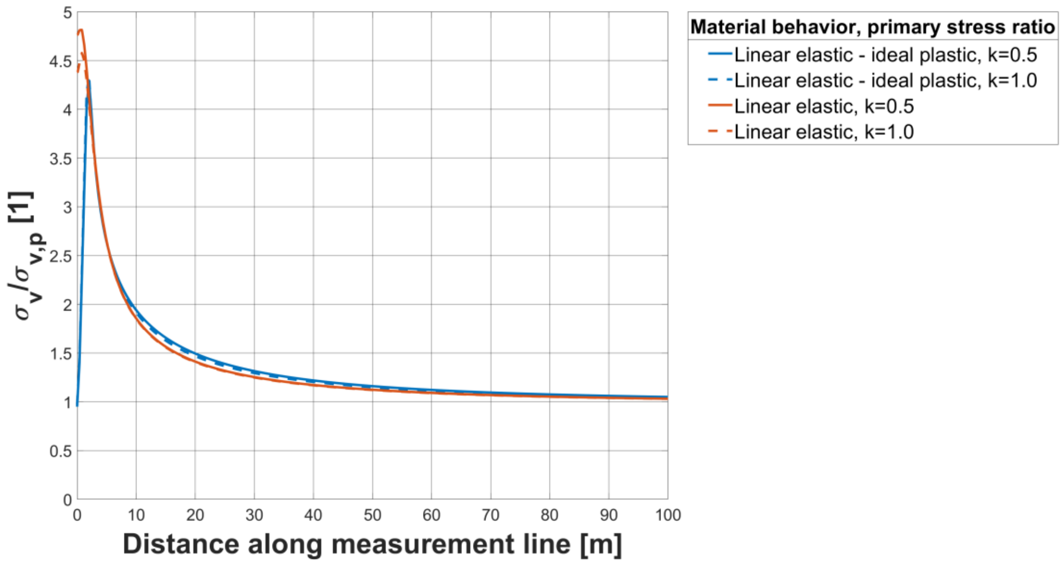


Figure 88: Comparison of the normalized resultant vertical stresses along line 3 for an elastic and a plastic material behavior.

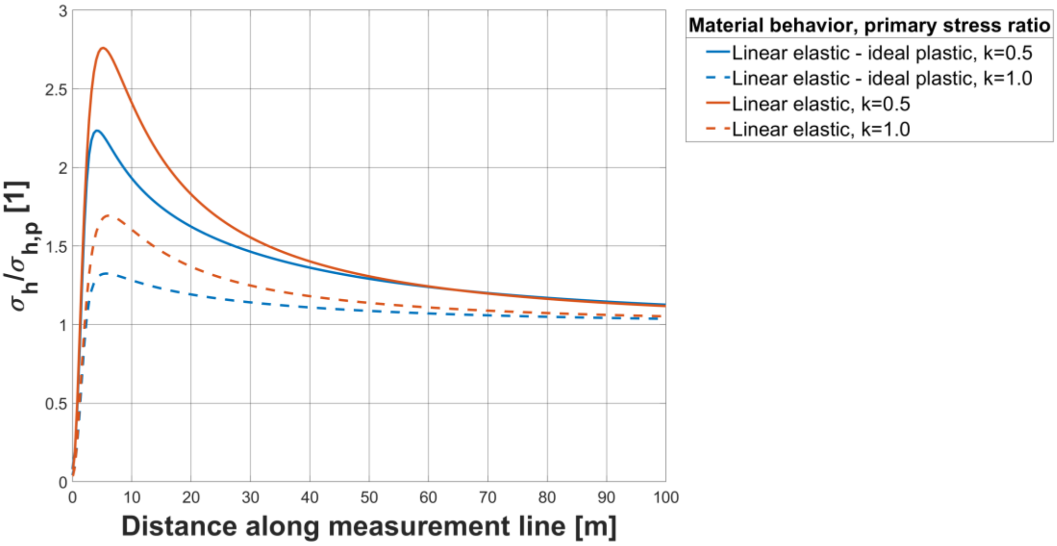


Figure 89: Comparison of the normalized resultant in-plane horizontal stresses along line 3 for an elastic and a plastic material behavior.

Figure 86 to Figure 89 show that rock mass fracture or failure has a significant impact on the resultant stress distribution inside the fractured or failed zone and its immediate vicinity. High stress magnitudes decrease and tensile stresses diminish in the fractured or failed rock mass portions. High stresses are shifted deeper into the rock mass, where the confinement and hence the rock mass strength are higher. This aspect has principally a positive effect on excavation stability, if the fractured or failed rock mass zone can be stabilized. At some distance from the fractured or failed zone the resultant stresses do not deviate significantly from the resultant stresses of linear elastic calculations. Consequently, it is reasonable to apply a (linear) elastic material behavior for the calculation of resultant stresses in many instances. The stress situation distant from excavations is represented sufficiently and in the vicinity of the excavation high stress magnitudes from (linear) elastic modelling indicate that rock mass fracturing and failure may occur. An advantage of (linear) elastic modelling is its lower complexity, its lower number of input parameters and its lower demands on software, hardware and personnel skills. Indeed, plastic modelling is still required in certain situations. For example, an appropriate plastic rock mass representation is necessary, if the actual stresses and deformations in the fracture and failure zone, if the fracture and failure processes, if the interaction between different fracture and failure zones or if the gradual development of the fracture and failure zone and the consequences of this gradual development are of interest. The applicability of (linear) elastic models for many situations as well as its limitations are highlighted amongst others by Andrieux et al. (2007) and Barsanti and Basson (2015).

The actual effect of fracture and failure on the resultant stress distribution depends on a number of site-specific parameters, such as the local rock mass and stress conditions, the mine layout and the mining sequence. For this reason, site-specific analyses are generally necessary to investigate fracture and failure zones and their impact on the resultant stress distribution in detail. Hence, fracture and failure zones and their impact on the resultant stress distribution are not further considered explicitly. Instead, zones, where fracture and failure can take potentially place, such as abutment areas, highly stressed zones, zones of tensile stresses or zones of low confinement, are outlined and the effect of fracture and failure in these zones is discussed on a general basis.

6.1.1.3 Summary of stress changes and the effect of fracture and failure resulting from excavations

The effect of isolated excavations on the resultant stress distributions were highlighted in the foregoing sections. Therein, the emphasis was on relevant aspects for the element functions of the stress management concept. The effect of the excavation size, shape and orientation, of the primary stress state and of rock mass fracture and failure were outlined. Important findings are:

- The alteration of the stress situation in the surrounding (in the zone of influence) of the excavation
- The formation of zones of increased (abutment areas) and decreased (de-stressed zones) resultant stress magnitudes
- The diminishing influence of an excavation on the stress state with increasing distance from the excavation
- The considerable impact of the excavation size, shape and orientation as well as of the primary stress state on the resultant stress magnitudes and the zone of influence
- The effect of fracture and failure on the resultant stress distribution and the zone of influence
- The possibility to represent many situations in two-dimensions
- The possibility to represent many situations with (linear) elastic material behavior

The derived results will be utilized in subsequent chapters, when discussing individual element functions as well as the implementation of the stress management concept in practice.

The deformations near excavations have not been outlined yet. The deformations near excavations are particularly relevant for the loading system element and are discussed in the corresponding section 6.1.3.

6.1.2 Pillar

Pillars are structural elements. A pillar is a piece of rock mass of defined shape, dimension and orientation, which is left in-situ to fulfill a specific purpose and which is situated between adjacent excavations, extraction areas or mines. Furthermore, these excavations, extraction areas or mines must be situated close to each other in their zone of influence so that the pillar has an influence on the overall behavior of these excavations, extraction areas or mines. For this reason, pillars are dependent main elements, because for the formation of a pillar at least two excavations are required on opposite sides of the pillar and hence a loading system element is also created adjacent to the pillar.

Following physical effects of pillars on the prevailing mining environment can be identified:

1. Limiting deformations in the nearby rock mass
2. Transferring of stresses
3. Causing stress changes in the nearby rock mass
4. Causing fracture and failure in the nearby rock mass

The physical effects of a pillar situated between two excavations are shown in Figure 90 schematically. To outline the effects, consider first a large excavation, which is comprised of the two excavations and the pillar between them (Figure 90a). Abutment areas and a de-stressed zone develop and the excavation boundaries deform. The stress changes and the deformations are illustrated in the figure. The red hatched areas indicate high stresses in the abutment area, the blue hatched areas indicate the de-stressed zones and the full lines indicate the deformation of the excavation roof and floor. Initial (undeformed) excavation boundaries are shown as dashed lines. Now consider a pillar, which is positioned in the middle of the large excavation (Figure 90b).

- First, this pillar counteracts the deformations of the roof and floor, which occur in case of a single large excavation. Accordingly, the deformations in the hangingwall and footwall of the two excavations are smaller than in case of a single large excavation.
- Second, the pillar transfers stresses between the hangingwall and footwall. This stress transfer is indicated by the red arrows. Hence, the pillar is highly stressed.
- Third, as the pillar transfers stresses and as the pillar limits deformations, the resultant stress distribution near the two excavations separated by the pillar is altered in comparison to the stress distribution near a single large excavation. The pillar and the rock mass above and below the pillar, the so-called pillar foundations, are more highly stressed. These high stress magnitudes diminish with distance from the pillar. As the pillar transfers stresses, the abutment stress magnitudes decrease. Furthermore, the spatial extent of the de-stressed zones decreases because of the smaller excavation dimensions; compare section 6.1.1.1.1.
- Fourth, rock mass fracture and failure may take place in the pillar or pillar foundations because of the increased stress magnitudes. Rock mass fracture and failure in the pillar or pillar foundations alter the stress situation further.

The actual physical effects of a pillar are a function of the prevailing mining environment, the pillar properties, particularly pillar strength and pillar behavior, the nearby excavations and the loading system properties. Furthermore, the excavations, extraction areas or mines forming the pillar and their size, geometry, orientation and relative position to each other have a significant influence. The subsequent sections discuss these aspects in respect to the physical effects of pillars.

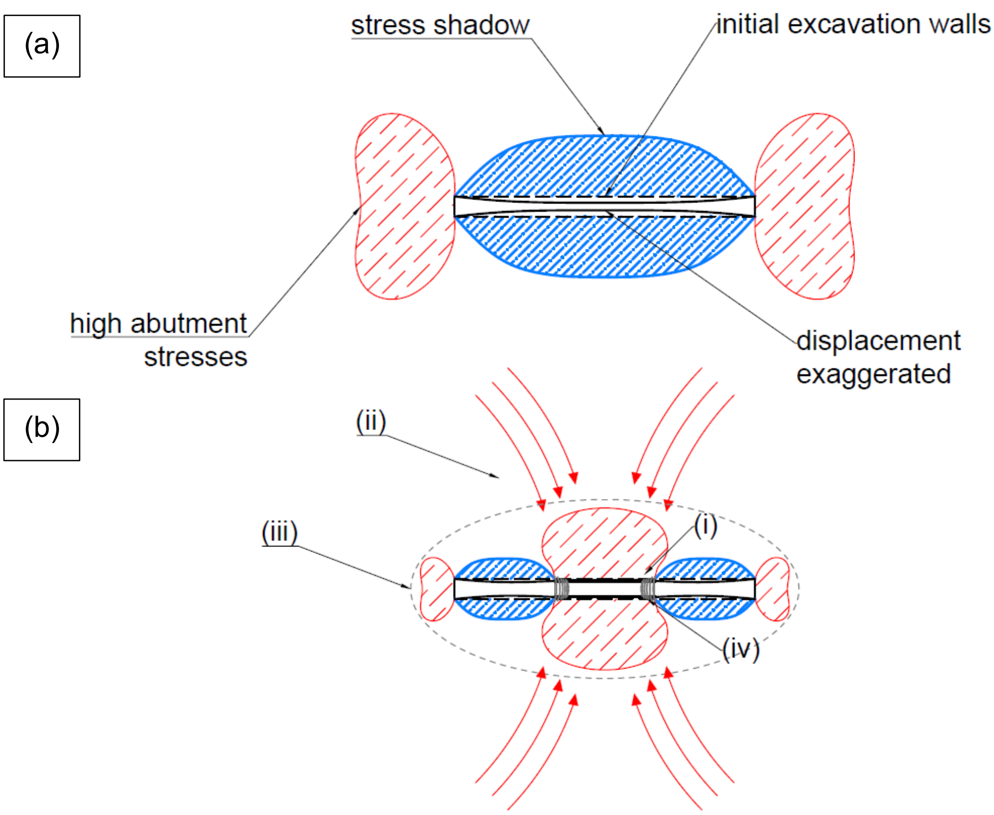


Figure 90: Schematic model of physical effects of a pillar; (a) single large excavation without a pillar; (b) two neighboring excavations with a pillar between them; (i) limiting deformations, (ii), transferring of stresses, (iii) altering the resultant stress distribution in nearby rock mass, (iv) causing fracture and failure in the pillar

6.1.2.1 Stress changes in the vicinity of pillars

Before discussing the pillar strength and stress strain behavior, the effect of a pillar on the resultant stress situation in its vicinity is outlined. Two different situations, which are of relevance for pillars in the stress management concept, are investigated. The emphasis is thereby on pillars, which are utilized to transfer loads on a local and regional scale, such as panel, barrier or stabilizing pillars, and not on pillars, which are utilized to protect infrastructure or large, discrete structures inside the pillar, such as shaft or protective pillars.

- Situation 1 – A pillar of constant average pillar stress but variable pillar width: The purpose of this situation is to outline the influence of the pillar width on the resultant stress situation in the vicinity of the pillar. The average pillar stress is kept constant therefore so that the influence of the pillar width can be compared better. However, it has to be noted that the stress distribution inside the pillar is not constant and that it differs for pillars of different width.
- Situation 2 – A pillar of constant pillar width but variable average pillar stress: The purpose of this situation is to outline the effect of the stress magnitudes inside the pillar on the resultant stress situation in the vicinity of the pillar. The pillar width is kept constant to improve the comparability.

The resultant stress distributions are calculated for a two-dimensional pillar with numerical simulations, wherefore slice models with a thickness of 1 m and the code FLAC3D are used.

The model is fixed in the out-of-plane direction to simulate infinitely long (two-dimensional) pillars and excavations. Figure 91 displays the geometry. The model comprises two flat-lying, rectangular shaped excavations with width (W_e) and height (H_e) and a pillar between the excavations of width (W_p) and height (H_p). The pillar is in the center of the model and on each side of the pillar is an excavation of half width. The extraction ratio of this excavation pillar model can be derived after Equation 12. All boundaries of the model are fixed in their normal direction to represent planes of symmetry. In each model run the primary stress state is implemented and solved to equilibrium. Then both excavations are mined-out at the same time and the model is run to equilibrium again.

$$e = \frac{W_e}{W_e + W_p}$$

Equation 12

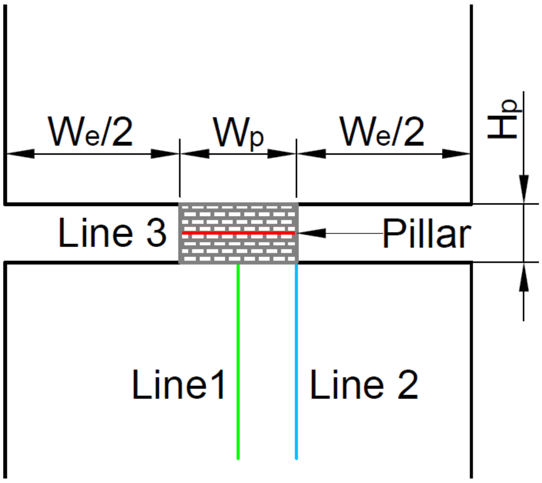


Figure 91: Geometry for investigating the effect of a pillar on the resultant stress situation. The positions and orientations of measurement lines are shown as well.

All calculations are conducted with a linear elastic rock mass behavior. The Young's modulus is 40 GPa and the Poisson ratio 0.25. The primary vertical stress is considered at a depth of 1000 m and corresponds to 27 MPa. The ratio of primary horizontal to primary vertical stresses (k) is set to 0.5 and 1.5 and both primary horizontal stresses are equal. The excavation height and pillar height are kept constant at 5 m. Due to the flat-lying excavations the vertical stresses are relevant. Thus, the average pillar stress corresponds to the average resultant vertical stress along a horizontal line at half height of the pillar; compare line 3 in Figure 91. The model setup represents a load-controlled situation, which enables to calculate the average pillar stress (σ_{avpil}) according to the tributary area theory by means of the primary vertical stress (σ_{vp}) and the extraction ratio (e); compare Equation 13. As the average pillar stress in the model is determined by the primary vertical stress and the extraction ratio, the extraction ratio can be utilized to control the average pillar stress. Therefore, the pillar width and excavation width are varied. The considered excavation and pillar widths for the situation of constant average pillar stress are shown in Table 5 and those for the situation of constant pillar width in Table 6. For the situation of constant average pillar stress the extraction ratio is constant at 75 % and for the situation of constant pillar width the pillar width is constant at 10 m.

$$\sigma_{avpil} = \frac{\sigma_{vp}}{1 - e}$$

Equation 13

Excavation width We [m]	Pillar width Wp [m]	Extraction ratio e [%]
15	5	75
30	10	75
75	25	75
150	50	75

Table 5: Considered excavation widths, pillar widths and extraction ratios for the situation of constant average pillar stress

Excavation width We [m]	Pillar width Wp [m]	Extraction ratio e [%]
12.2	10	55
18.5	10	65
30	10	75
57	10	85

Table 6: Considered excavation widths, pillar widths and extraction ratios for the situation of constant pillar width

The resultant stress distributions for different average pillar stresses and pillar dimensions (geometries according to Table 5 and Table 6) are compared along two measurement lines, which are referred to as line 1 and 2, which start the at the contact of the pillar with the surrounding rock mass. Furthermore, the average pillar stress is calculated along another measurement line, which is referred to as line 3. The position and orientation of the measurement lines are chosen such that they show relevant points for the stress management concept and they are shown in Figure 91. Line 1 is vertical, is located at half width of the pillar and starts at the elevation of the excavation floor. Line 2 is vertical, is located at the pillar corner and starts at the elevation of the excavation floor. Line 3 is horizontal and is located at half height of the pillar.

6.1.2.1.1 General characteristics of the resultant stress distribution in the vicinity of a pillar

The characteristics of the resultant stress distributions in the vicinity of a pillar with a width of 10 m, an extraction ratio of 75 % and a ratio of primary horizontal to primary vertical stresses (k) of 0.5 are shown in Figure 92 to Figure 97. The resultant stress distributions show:

- The resultant vertical stress magnitudes (Figure 92) in the pillar and in the pillar foundation areas increase substantially. The stress magnitudes decrease with distance from the pillar.
- The resultant in-plane horizontal stress magnitudes (Figure 93) increase inside the pillar, particularly the pillar core, significantly. Contrary, the resultant in-plane horizontal stresses are relatively low some distance into the foundation. Distant from

the pillar the resultant in-plane horizontal stresses correspond to the primary horizontal stresses.

- The resultant out-of-plane horizontal stress magnitudes (Figure 94) increase inside the pillar as well as in the pillar foundations. With distance from the pillar the resultant out-of-plane horizontal stress magnitudes diminish and reach primary stress magnitudes distant from the pillar. Regarding the out-of-plane horizontal stress magnitudes must be considered that the shown pillar is infinitely long.
- The resultant major principal stress magnitudes (Figure 95) show as well that the pillar and the pillar foundations are highly stressed. The high stress magnitudes diminish with distance from the pillar.
- The resultant minor principal stress magnitudes (Figure 96) are elevated inside the pillar, but in the pillar foundations the minor principal stress is relatively low. Distant from the pillar the far-field stress magnitudes are reached again.
- The resultant maximum shear stresses (Figure 97) are of considerable magnitude in the pillar and pillar foundations. With distance from the pillar the resultant maximum shear stress magnitudes diminish.

In summary, the pillar and its surroundings are highly stressed. Accordingly, the pillar acts as a stress raiser. Indeed, it is noted that the characteristics of the stress distribution are outlined for an infinitely strong pillar and a linear elastic rock mass behavior. Pillar fracturing and failure have a considerable influence on the stress raising effect of the pillar. If a pillar fails and crushes, the resultant stress magnitudes inside the pillar and its surroundings are reduced. Pillar strength and stress strain behavior are further outlined in section 6.1.2.2.

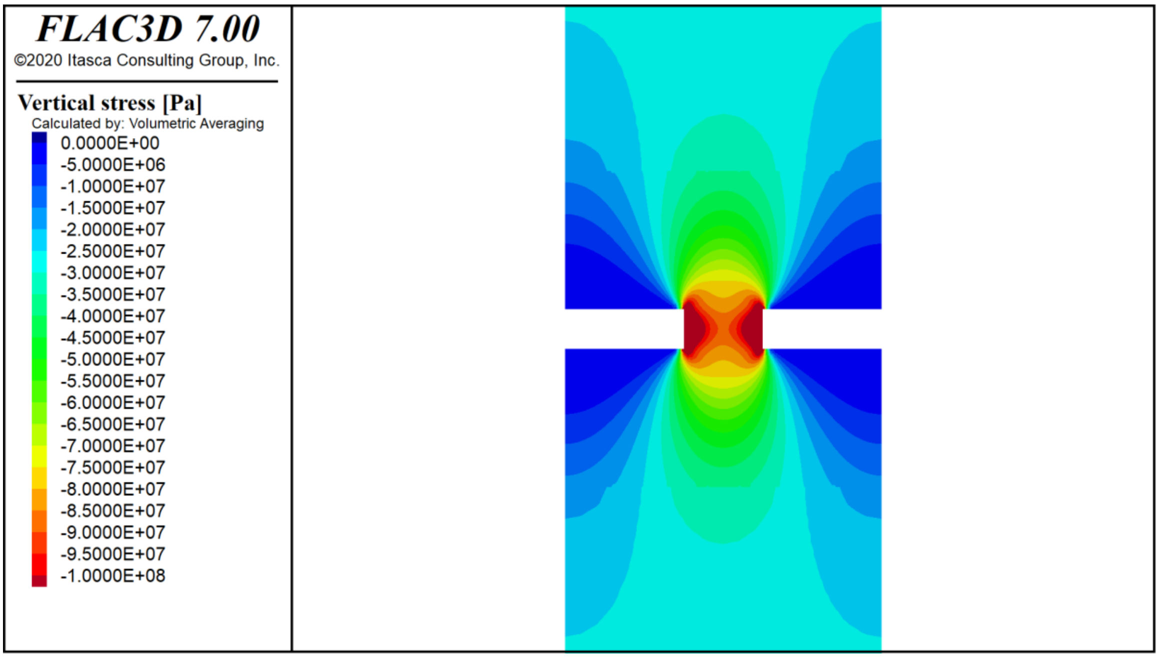


Figure 92: Resultant vertical stress distribution for a pillar with a width of 10 m, an extraction ratio of 75 % and k=0.5; compressive stresses are negative.

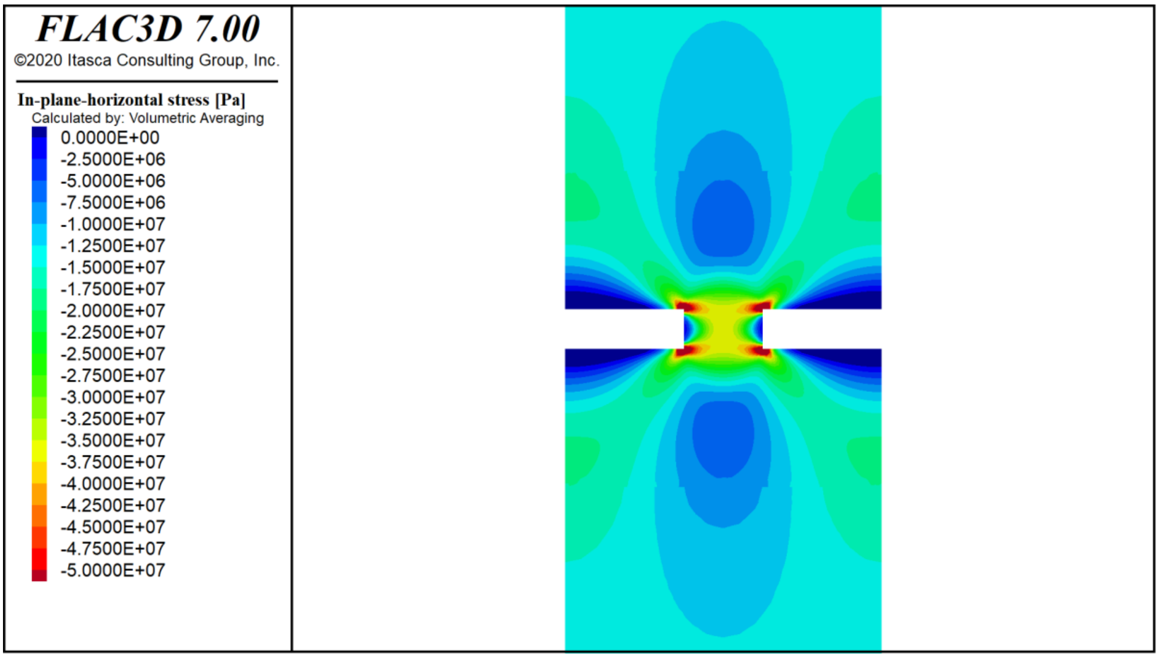


Figure 93: Resultant in-plane horizontal stress distribution for a pillar with a width of 10 m, an extraction ratio of 75 % and k=0.5; compressive stresses are negative.

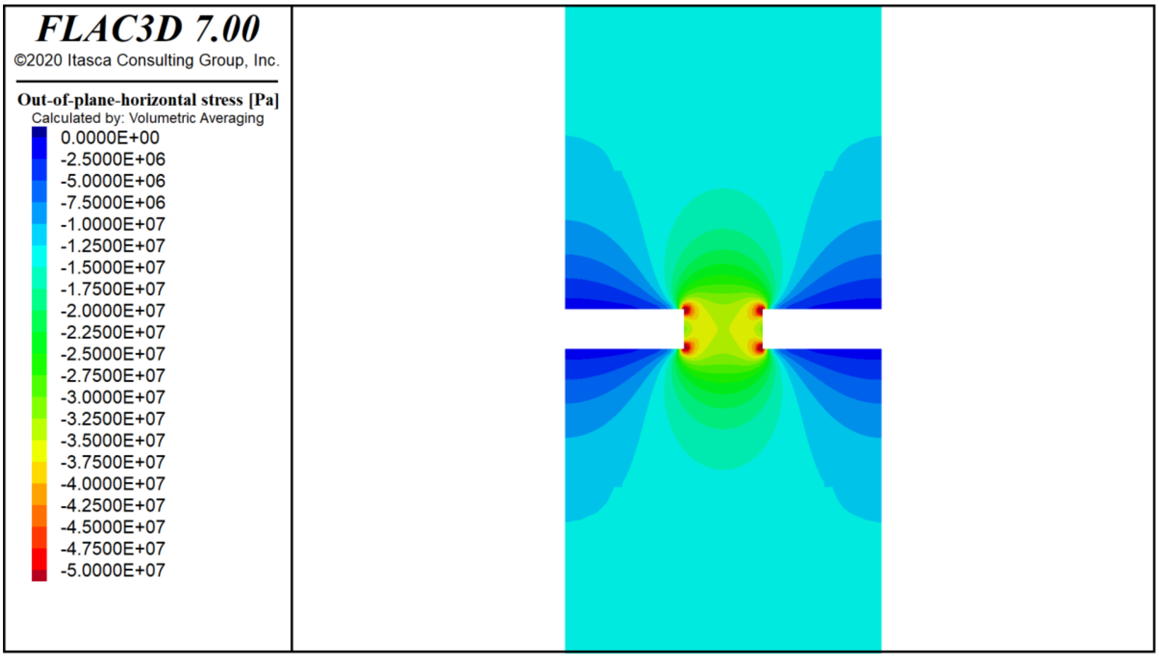


Figure 94: Resultant out-of-plane horizontal stress distribution for a pillar with a width of 10 m, an extraction ratio of 75 % and k=0.5; compressive stresses are negative.

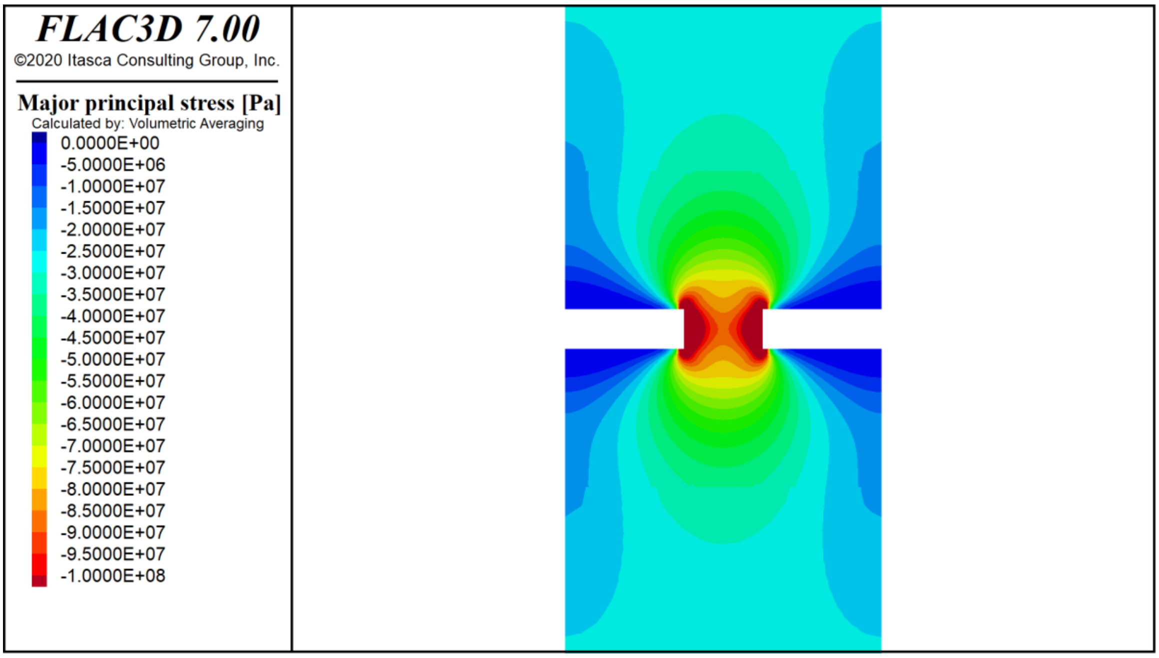


Figure 95: Resultant major principal stress distribution for a pillar with a width of 10 m, an extraction ratio of 75 % and k=0.5; compressive stresses are negative.

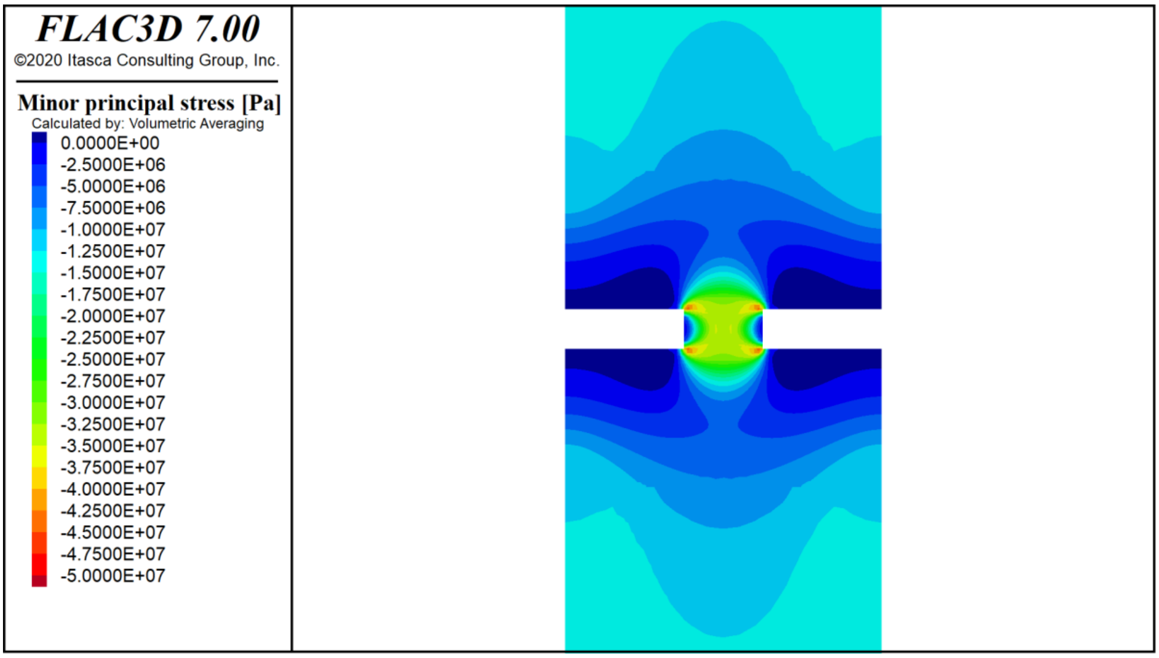


Figure 96: Resultant minor principal stress distribution for a pillar with a width of 10 m, an extraction ratio of 75 % and k=0.5; compressive stresses are negative.

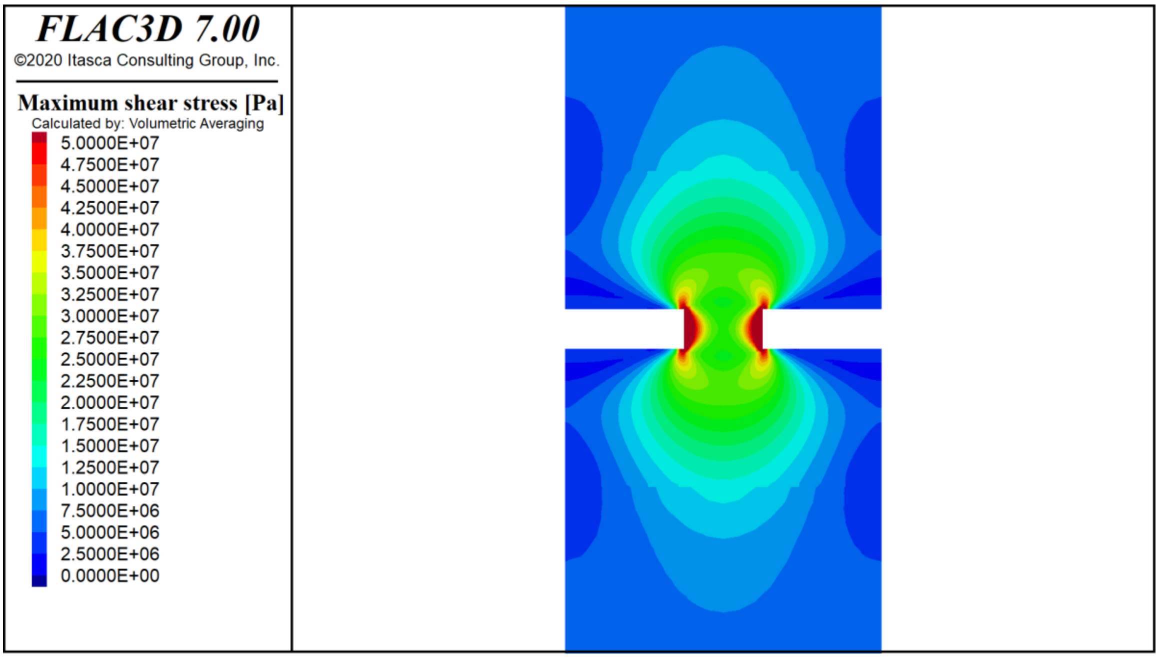


Figure 97: Resultant maximum shear stress distribution for a pillar with a width of 10 m, an extraction ratio of 75 % and k=0.5.

6.1.2.1.2 Resultant stress distributions for the situation of constant average pillar stress

The resultant stress magnitudes along the considered measurement lines for the situation of constant average pillar stress but variable pillar width (geometries of Table 5) are shown in Figure 98 to Figure 100. The resultant stresses for k=0.5 are shown as full lines and those for k=1.5 as dashed lines. Following observation can be made:

- The rock mass in the vicinity of the pillar is highly stressed, which can be seen by the increased stress magnitudes along line 1 and line 2. The stress magnitudes decrease with increasing distance from the pillar and reach finally primary stress magnitudes distant from the pillar.
- The stress magnitudes in the vicinity of the pillar and the stress gradient depend on the pillar width and the ratio of primary horizontal to vertical stresses. The wider the pillar, the slower is the decrease of stresses with distance from the pillar and hence the larger is the zone, in which the resultant stress situation is influenced by the pillar.
- The stress magnitudes along line 2, which represents the rock mass in the vicinity of the pillar and near the boundary of the pillar, are close to the pillar principally higher than the stress magnitudes along line 1, which represents the rock mass in the vicinity of the pillar and near the center of the pillar. However, with distance the stress magnitudes drop more rapidly along line 2 than along line 1.

Based on these observations the relevant conclusion for the stress management concept can be drawn that the pillar acts as a stress raiser. The rock mass in the vicinity of the pillar is highly stressed and the stress magnitudes decrease with distance from the pillar. Particularly important is the pillar width, which has a strong impact on the spatial extent of elevated stresses. The wider the pillar is, the larger is its spatial impact on the resultant stress distribution.

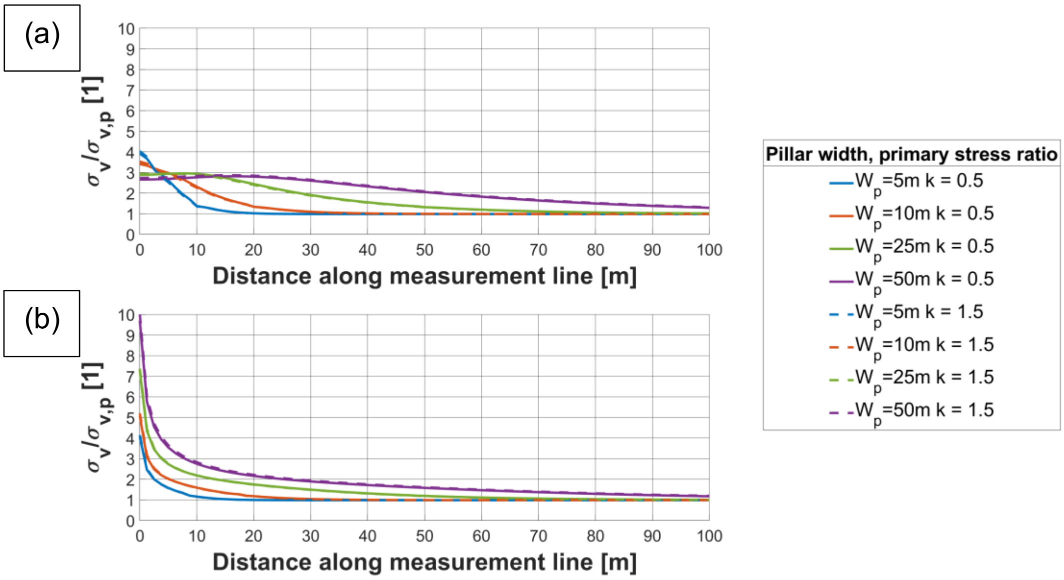


Figure 98: Resultant vertical stresses along (a) line 1 and (b) line 2 for the situation of constant average pillar stress.

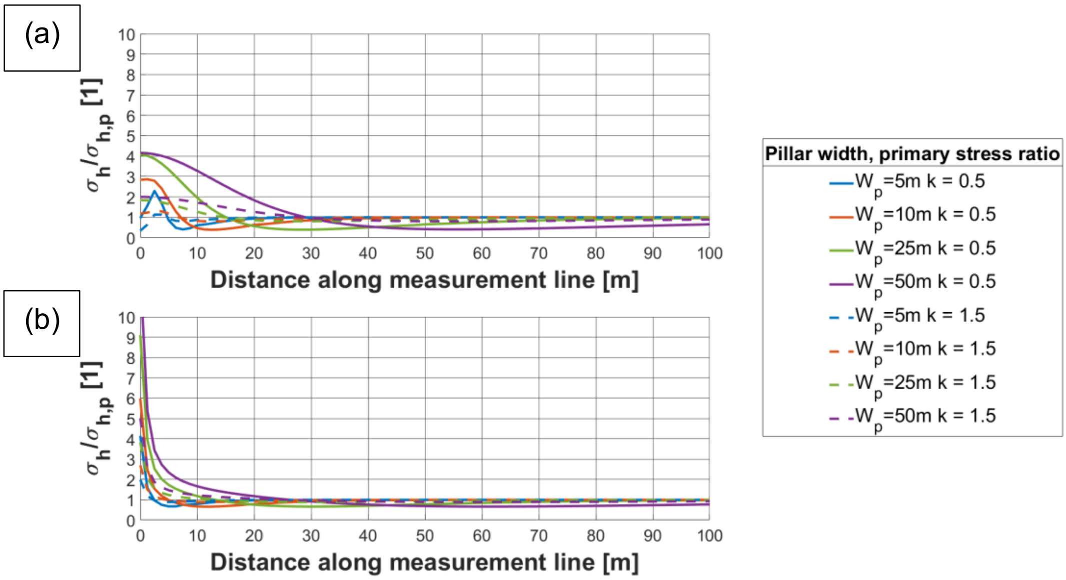


Figure 99: Resultant in-plane horizontal stresses along (a) line 1 and (b) line 2 for the situation of constant average pillar stress.

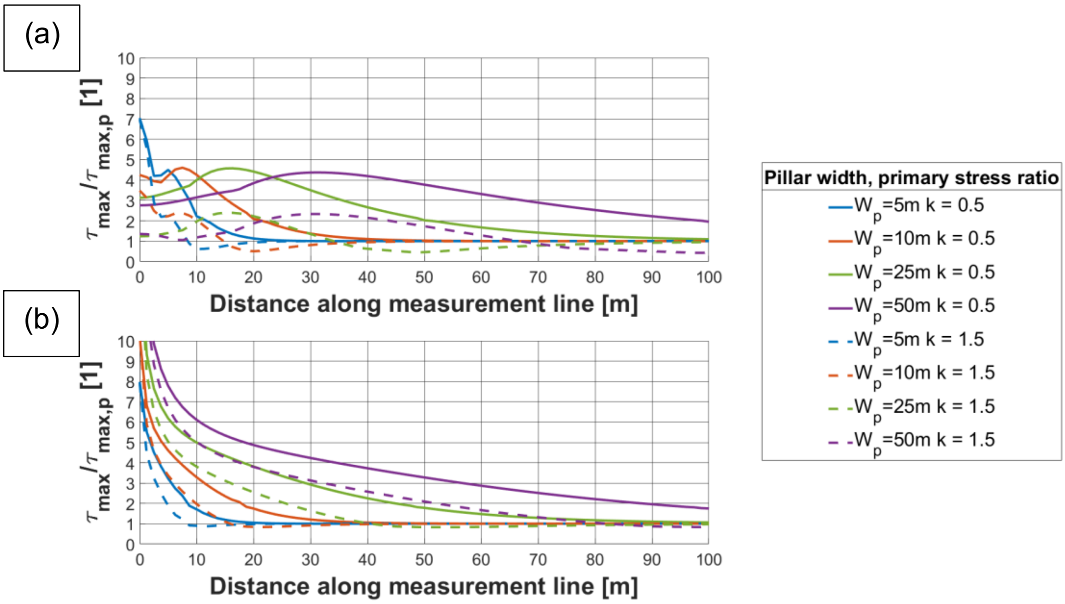


Figure 100: Resultant maximum shear stresses along (a) line 1 and (b) line 2 for the situation of constant average pillar stress.

6.1.2.1.3 Resultant stress distributions for the situation of constant pillar width

The resultant stress magnitudes along the considered measurement lines for the situation of constant pillar width but variable average pillar stress (geometries of Table 6) are shown in Figure 102 to Figure 104. Furthermore, the average pillar stress is shown in Figure 101. The resultant stresses for k=0.5 are shown as full lines and those for k=1.5 as dashed lines.

The results show that the average pillar stress increases with an increasing extraction ratio. The ratio of primary horizontal to primary vertical stresses has thereby not an influence, because the primary vertical stress is critical for the average pillar stress because of the pillar orientation. The stresses along line 1 and line 2 show principally the same. The stress magnitudes increase with increasing extraction ratio. Moreover, the stresses increase in a larger zone in the rock mass for higher extraction ratios. For the stress management concept of relevance is that the stresses in the pillar and in the vicinity of the pillar increase with increasing extraction ratio and that the spatial influence of pillars on the resultant stress distribution increases with increasing extraction ratio.

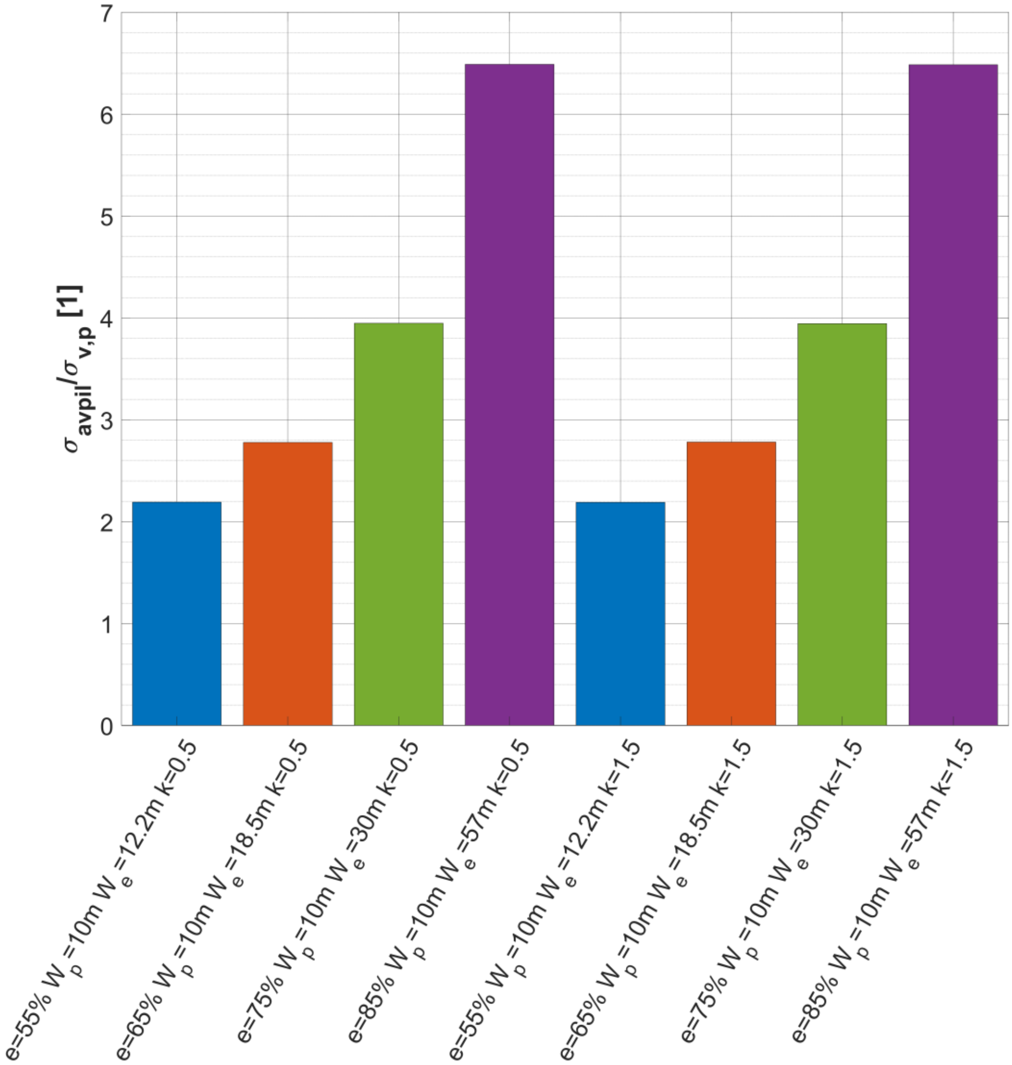


Figure 101: Average vertical pillar stress for the situation of constant pillar width.

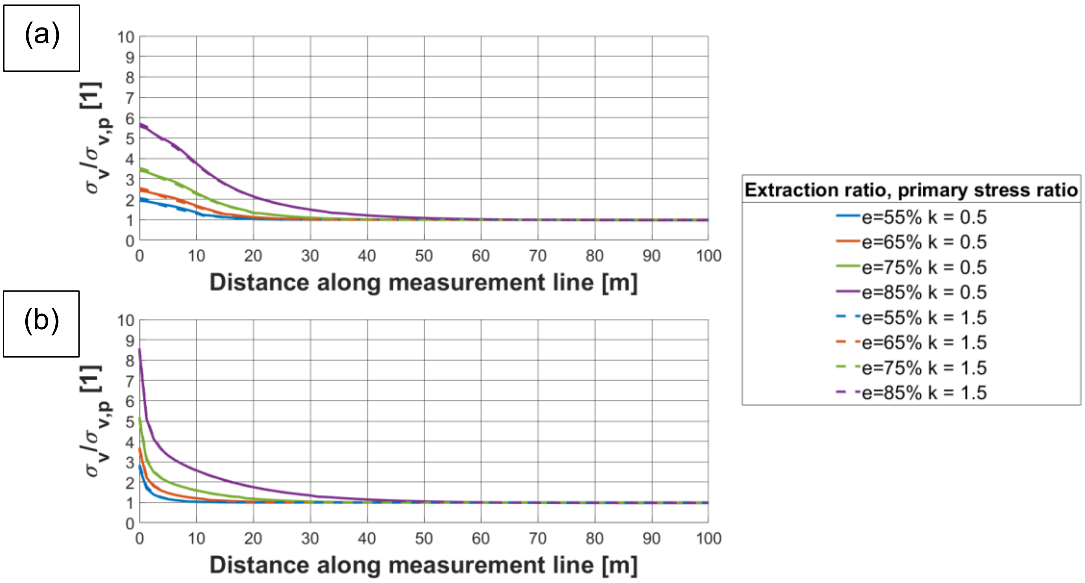


Figure 102: Resultant vertical stresses along (a) line 1 and (b) line 2 for the situation of constant pillar width.

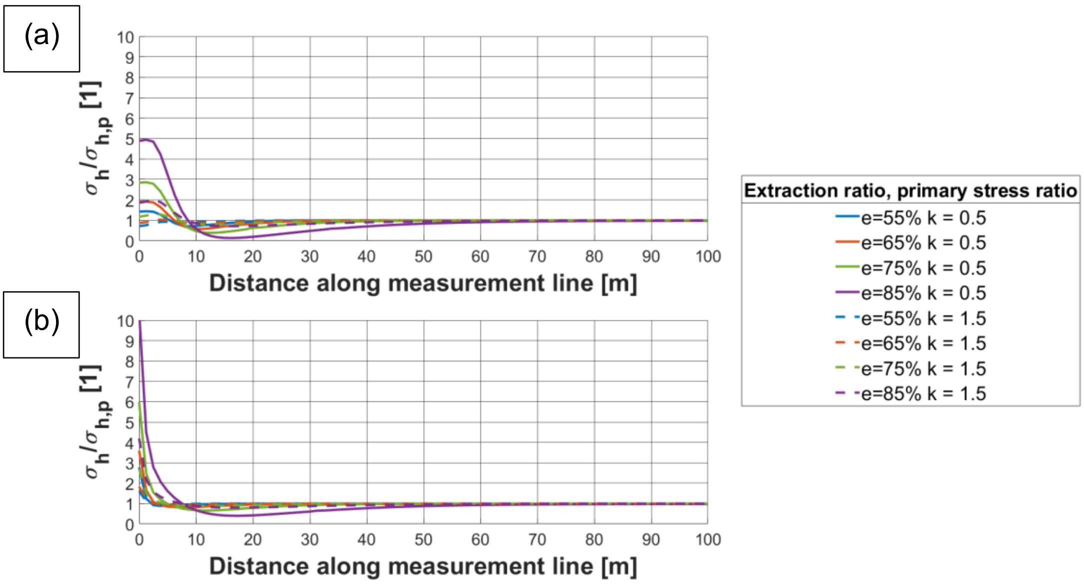


Figure 103: Resultant in-plane horizontal stresses along (a) line 1 and (b) line 2 for the situation of constant pillar width.

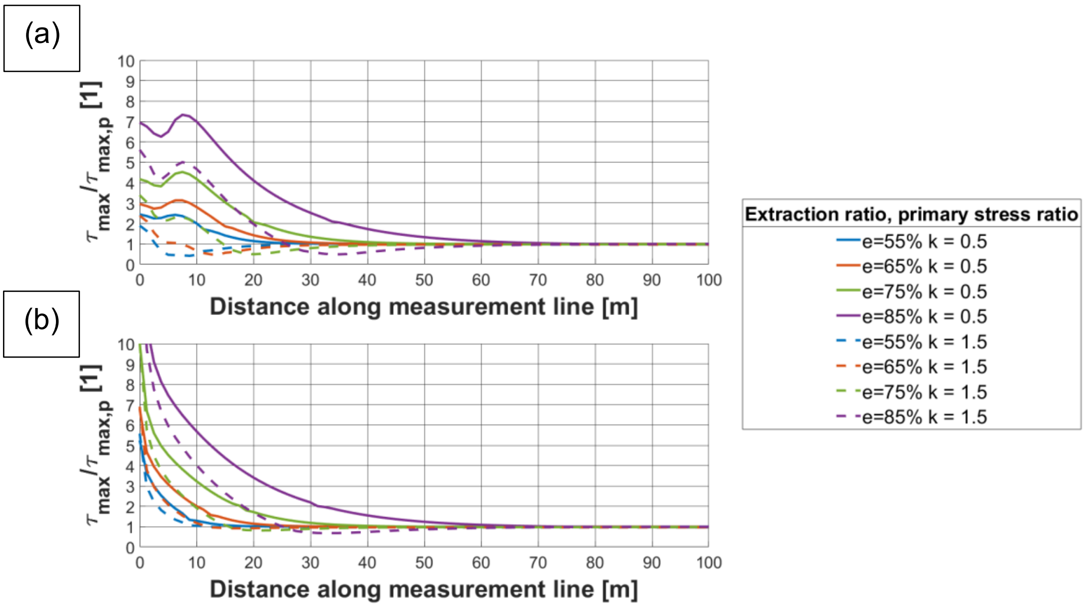


Figure 104: Resultant maximum shear stresses along (a) line 1 and (b) line 2 for the situation of constant pillar width.

6.1.2.1.4 Concluding remarks related to stress changes in the vicinity of pillars

The conducted analyses show that pillars are highly stressed and that pillars act as stress raisers, namely they increase the resultant stress magnitudes in their surroundings considerably. The influence of a pillar on the resultant stress state diminishes with distance from the pillar. The pillar width and average pillar stress have a considerable impact on the stress raising effect of pillars.

The analyses were made for horizontal and infinitely strong pillars. Furthermore, the prevailing average pillar stress was determined by the model setup. In-situ these aspects are not that idealized and they have an impact on the stress magnitudes inside the pillar and hence the stress raising effect of the pillar.

- The influence of the pillar orientation on the resultant stress situation is comparable to the influence of excavation orientation on the resultant stress situation. In comparison to the investigated horizontal pillar, in which high vertical stress magnitudes are present and for which the stress raising effect is strongest in vertical direction, a pillar, which is oriented in vertical direction, is highly stressed in the horizontal direction and its stress raising effect is strongest in horizontal direction. In general, the pillar is highly stressed perpendicular to the pillar – rock mass contacts and the stress raising effect of the pillar is strongest in perpendicular direction to the pillar – rock mass contacts.
- The strength and stress strain behavior of pillars have a considerable impact on the stress magnitudes inside the pillar and hence also on the stress raising effect of the pillar. In general, the pillar strength and stress strain behavior restrict the stress magnitudes inside the pillar and in its surroundings. Pillar strength and stress strain

behavior are principally important for pillars and their functions and they are further discussed in section 6.1.2.2.

- The actual load acting on a pillar and hence the stresses inside a pillar are a function of the pillar properties and the loading system of the pillar. The influence and role of the loading system are discussed briefly in section 6.1.3. Detailed investigations are normally required to determine the stress state inside pillars.

6.1.2.2 Pillar strength and pillar stress strain behavior

The pillar strength and the pillar stress strain behavior have a significant influence on the physical effects of pillars and thus on their functions in the stress management concept. Therefore, the current knowledge related to pillar strength and pillar stress strain behavior is reviewed. This review emphasizes on the requirements of the stress management concept.

Since the development of the coal pillar strength equation of Salamon and Munro (1967) considerable research effort has been put into improving the understanding of pillars. It is widely accepted that pillar strength increases with increasing pillar width-to-height ratio and with increasing strength of the rock mass. Various pillar strength equations consider these aspects; see for example Hedley and Grant (1972), Wagner and Madden (1984), Bieniawski (1992), Sjöberg (1992) Lunder and Pakalnis (1997), Esterhuizen et al. (2011). The pillar post-peak strain softening rate is expected to decrease and eventually to transform to a strain hardening behavior with increasing pillar width-to-height ratio; see Wagner (1974), Ozbay (1989), Zipf (1999). Moreover, it was found that discontinuities intersecting a pillar affect its strength significantly especially for a slender pillar with a low width-to-height ratio. (e.g. Esterhuizen (1997), Iannacchione (1999), Esterhuizen (2007), Esterhuizen et al. (2011)) The contacts of pillars with surrounding rock mass, weak surrounding strata and the presence of weak layers in the pillar are further found to be critical, whereby weak and slippery contacts or layers inside the pillar can decrease pillar strength significantly. (e.g. Gale (1999), Esterhuizen and Ellenberger (2007), Tesarik et al. (2013), Murphy et al. (2016)) However, the actual quantity of these effects as well as the pillar strength in general are largely unknown especially for hard rock pillars and pillars with large width-to-height ratios; compare for example Ozbay et al. (1995), Mark (1999), Salamon et al. (2006), Malan and Napier (2011). The reasons behind are manifold. However, some of the major points seem to be the limited (or unavailable) possibility to conduct full-scale pillar strength tests, the limited amount of monitoring and observation data related to pillar behavior and the limited knowledge related to the strength and stress strain behavior of rock mass.

As pillars are a main element of the stress management concept and as the functions of pillars are central for the stress management concept, pillar strength and stress strain behavior are discussed in more detail. The emphasis is on hard rock pillars, which are of interest for following investigations on the implementation of the stress management concept in practice and which are compared to coal pillars understood less well.

6.1.2.2.1 <u>Knowledge related to hard rock pillar strength</u>

6.1.2.2.1.1 In-situ observations, measurements and back analyses related to pillar strength

In-situ investigations and measurements related to pillar strength are an appropriate starting point for the following discussion. Such in-situ investigations allow observing pillar stress strain behavior and pillar fracturing and failure in real conditions and do not suffer from simplifications and assumptions. A drawback from in-situ pillar investigations is though that it is rather difficult or even impossible to measure pillar strain and particularly pillar stress. Consequently, indirect methods for pillar stress determination, such as for example dead-weight overburden loading (e.g. Salamon and Munro (1967), Hedley and Grant (1972), Mark (1992)), numerical simulations (e.g. Potvin et al. (1989), Watson et al. (2008b)) or stress measurements at some distance from the pillar (e.g. Cassie et al. (1999), Watson et al. (2007), Watson et al. (2009), Watson et al. (2014)), are commonly applied.

Probably, the largest amount of in-situ pillar observations has been made for the establishment of pillar strength equations by means of back analysis. (e.g. Salamon and Munro (1967), Hedley and Grant (1972), Salamon et al. (1996), Lunder and Pakalnis (1997), van der Merwe (2003), Esterhuizen et al. (2011)) The principle of this approach for the determination of such pillar strength equations is based on in-situ observations of pillars or mining panels comprised of equally designed pillars followed by a classification of pillars or mining panels into stable, unstable or failed and a determination of the pillar stresses. Afterwards different statistical methods are applied to derive a pillar strength equation. Generally, these pillar strength equations consider the rock mass strength and the impact of pillar width-to-height ratio, where a square pillar cross-section is usually assumed. Additionally, the general form of pillar strength equations is occasionally extended to account for further effects, such as for example elongated pillar cross-sections (e.g. Wagner (1980), Esterhuizen et al. (2011)) or the effect of discontinuities intersecting the pillar (e.g. Esterhuizen et al. (2011)). The application range and reliability of pillar strength equations are of main interest for the present discussion. The main limitations are posed by the geometrical range of investigated pillars, the number of back analyzed cases, the number of failed pillars, the local mining conditions and the investigation methods.

In case of coal pillars, databases do generally not cover a lot of (failed) cases beyond width-to-height ratios of four to five. Experience and site observations have indicated though that coal pillar strength increases quite rapidly beyond these width-to-height ratios. (e.g. Wagner and Madden (1984), Mark (1999)) These observations led finally to extension or adaption of certain coal pillar strength equations; for example the squat-pillar formula after Wagner and Madden (1984). Moreover, large-scale, in-situ coal pillar strength tests were conducted; see for example Bieniawski (1968), Wagner (1974), van Heerden (1975). For these reasons, it can be concluded that the strength of coal pillars for a relatively large width-to-height ratio range seems to be reasonably understood particularly in comparison with hard rock pillar strength. Further advantages of coal pillar strength equations are that the mining environments in coal mining are relatively similar within mining regions or even within mining regions of different continents and that pillar databases and experience for coal pillars are comparatively large. Accordingly, coal pillar strength equations are usually applicable with a certain degree of confidence and reliability. However, for coal pillars with width-to-height ratios larger than five, there is still considerable uncertainty regarding pillar strength. The considerable scatter in the predicted pillar strength of different strength equations is an indicator therefore; compare Figure 105.

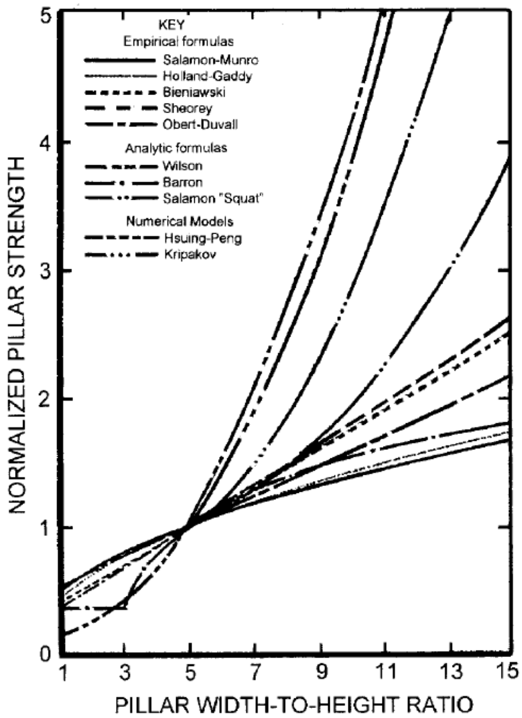


Figure 105: Predicted coal pillar strength of different pillar strength equations (Mark, 1999)

The situation is principally different for hard rock pillars. There are some pillar strength equations around, but it is well recognized that these pillar strength equations and the corresponding databases suffer from drawbacks; see for example Malan and Napier (2011). Limitations comprise often a rather small number of investigated pillars, a rather small number of unstable or failed pillars and a rather small pillar width-to-height ratio range, which is mostly below two to three. Moreover, rock mechanics conditions in hard rock mining vary usually from mine to mine and in many instances even within the same mining area or mine. For this reason, applying hard rock pillar strength equations in other mines or conditions compared to those, in which they were developed, is often not appropriate. Accordingly, it can be concluded that hard rock pillar strength is in general insufficiently understood beyond width-to-height ratios of two to three and that pillars in many mining environments have not been investigated at all. Despite these drawbacks the hard rock pillar strength equations are commonly applied.

For hard rock pillars another important point is that pillars themselves with width-to-height ratios beyond 10 to 15 become indestructible, but pillar foundation failure becomes critical. (Salamon and Wagner (1979), Ryder and Ozbay (1990)) Wagner and Schümann (1971) conducted stamp load tests on rock specimen in the laboratory, which showed that the stamp load strength is constant and about two to three times the uniaxial compressive strength, once the stamp diameter is sufficiently large. Based on these stamp load tests Wagner and Schümann (1971) concluded that the foundation strength of pillars corresponds to two to three times the uniaxial compressive strength of the rock forming the pillar foundation.

Figure 106 summarizes mining experience related to hard rock pillar strength schematically and Figure 107 provides a section of Figure 106 at width-to-height ratios smaller than five. The pillar strength is normalized to the uniaxial compressive strength of rock (σ_{UCS}). Following data is included:

- Back analyses of pillars: Individual datapoints in the diagram represent the in-situ pillar observations reported by Lunder and Pakalnis (1997).
- Pillar strength equations: The pillar strength for a pillar height of 5 m according to the pillar strength equations of Hedley and Grant (1972), von Kimmelmann et al. (1984), Krauland and Soder (1987), Potvin et al. (1989), Sjöberg (1992), Lunder and Pakalnis (1997) and Esterhuizen et al. (2011) are outlined. The pillar strength after pillar strength equations (linear formula and power formula) of Watson et al. (2008b) are not shown in Figure 106, because this pillar strength deviates considerably from the pillar strength derived from the other, outlined equations as well as from the pillar case studies, namely it predicts a pillar strength, which is several times higher. Furthermore, the linear formula and power formula of the pillar strength equation of Watson et al. (2008b) are in itself not consistent for the shown pillar height of 5 m, because the power formula gives a pillar strength, which is about 50 % to 70 % higher than the pillar strength from the linear formula. The reason for this deviation and inconsistence could be that Watson et al. (2008b) derived their pillar strength equations from pillars with a comparatively low pillar height between 1.2 m and 2 m. Furthermore, this height range is relatively small and may therefore not represent the influence of the pillar height on the pillar strength appropriately.
- Pillar foundation strength: The pillar foundation strength, which imposes an upper limit of the pillar strength, is shown for pillar foundations comprised of the same rock mass as pillars. According to Wagner and Schümann (1971) the pillar foundation strength corresponds to two to three times of the uniaxial compressive strength of rock.

Overall, Figure 106 and Figure 107 highlight the limited knowledge related to the strength of hard rock pillars well. Some experience in certain mining environments is available for pillars with width-to-height ratios below two to three. However, between these pillars with a relatively low width-to-height ratio and the upper pillar strength limit imposed by the foundation strength the knowledge is limited. The actual pillar strength increase with increasing width-to-height ratio, until the foundation strength is reached, is not known. For this region three possible pillar strength increases are sketched in Figure 106 and Figure 107; namely a fast, an intermediate and a slow increase. The actual pillar strength increase can have a considerable impact on the design of the mine layout and mining sequence.

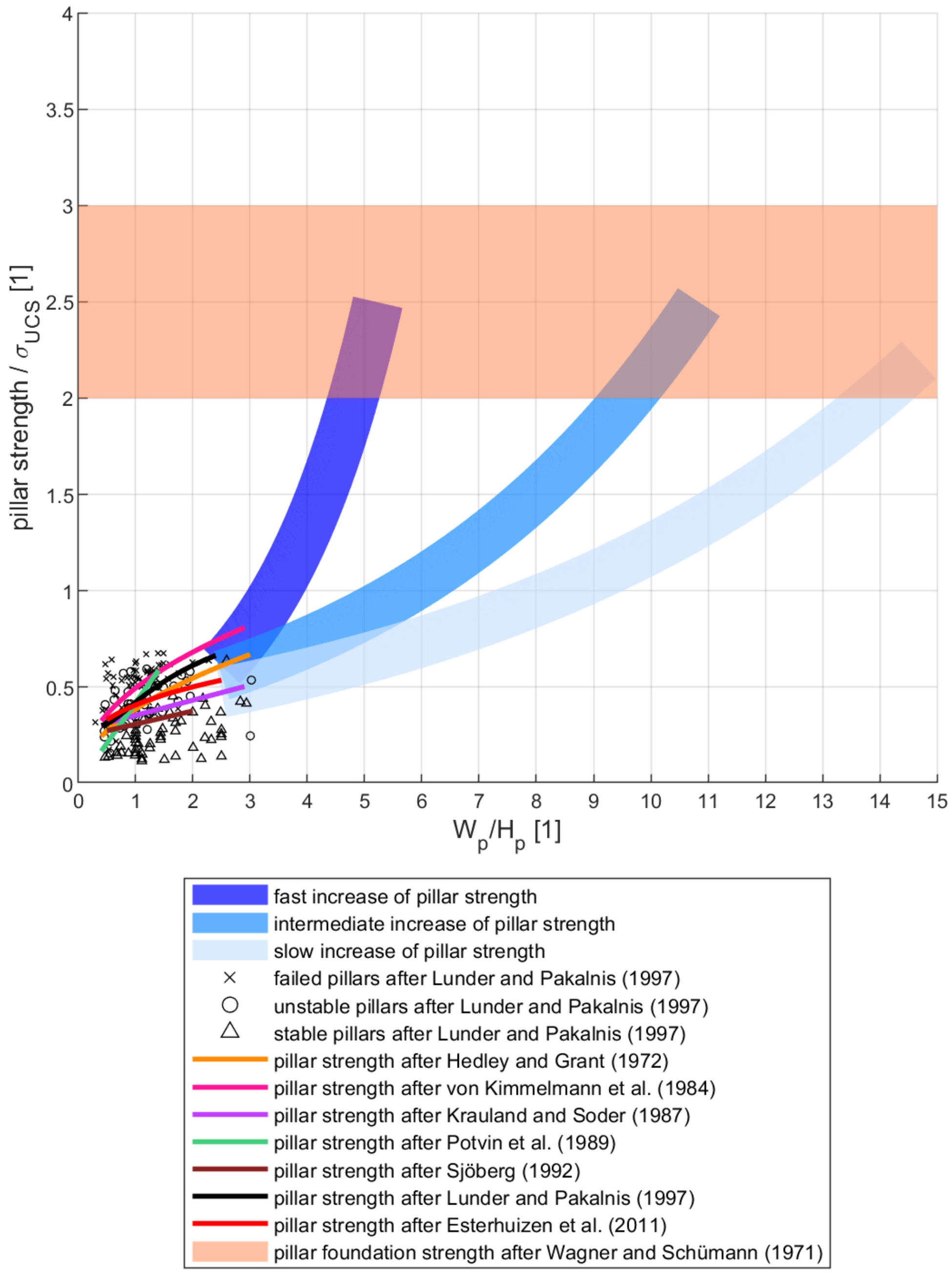


Figure 106: Hard rock pillar strength knowledge based on mining experience

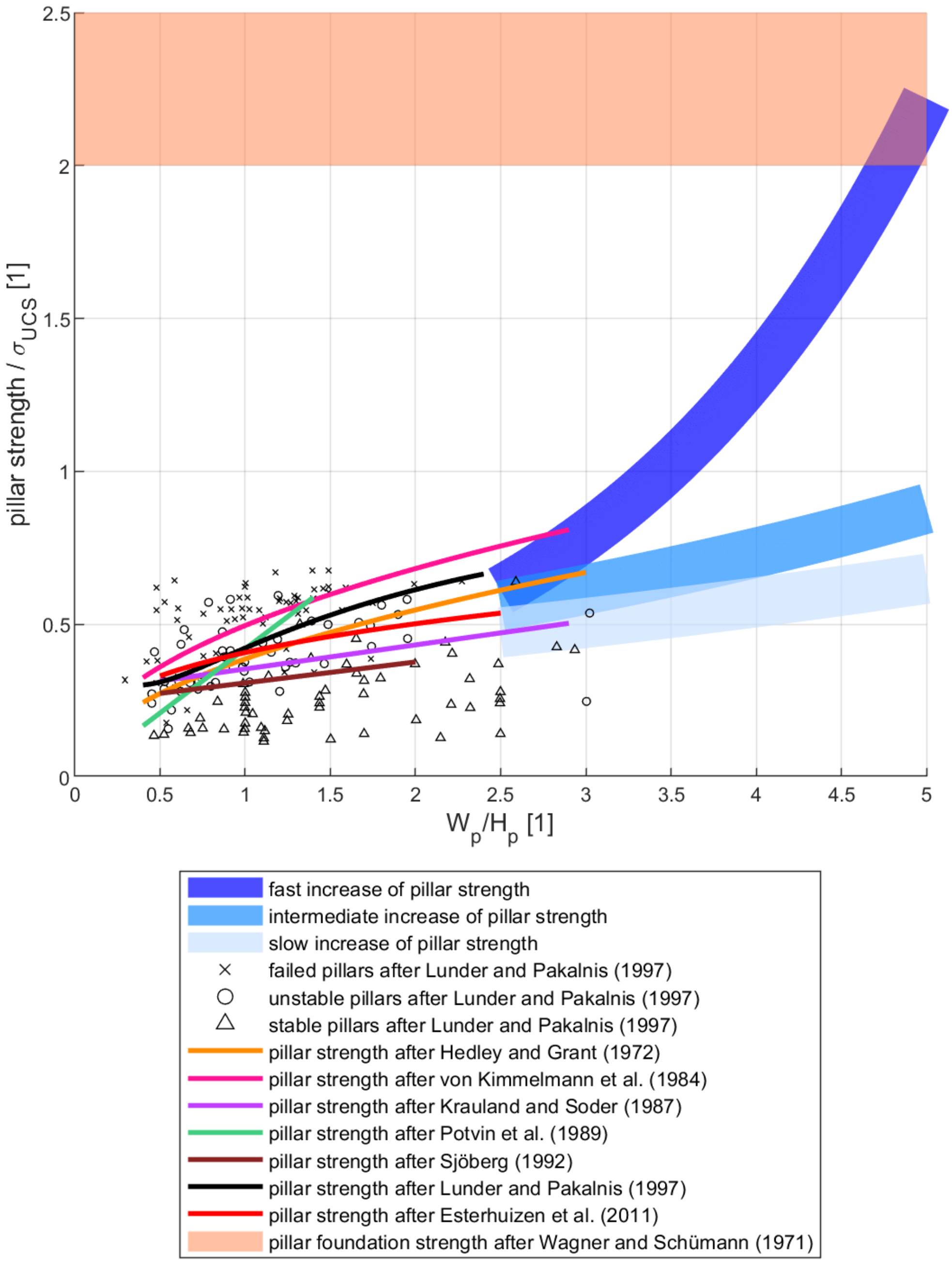


Figure 107: Section of Figure 106 showing hard rock pillar strength knowledge based on mining experience for width-to-height ratio smaller than five.

Different methods and techniques have been applied to overcome the limited knowledge of (hard rock) pillar strength. One of these methods are laboratory pillar tests. Tests have been conducted for different materials, pillar geometries and test setups. (e.g. Starfield and Wawersik (1968), Wagner and Madden (1984), Das (1986)) General conclusions of these tests are that the pillar strength increases with increasing width-to-height ratio and that the pillar fracture, failure and post-peak behavior changes with increasing width-to-height ratio. Typically, the post-peak strain softening rate decreases and the behavior may convert to yielding or strain hardening at a specific width-to-height ratio. Overall, model tests confirm trends of in-situ pillar investigations. However, model tests have some drawbacks. First, it is difficult to replicate rock mass behavior in the laboratory appropriately. Second, it is difficult to replicate and include the pillar foundations and the contacts between pillar and pillar foundations correctly. Third, sample sizes and testable materials are limited due to testing machinery capacities. For these reasons, laboratory model tests are not suited to derive a reliable quantification of pillar strength, pillar stress strain behavior and pillar fracture and failure characteristics. They are rather suited to outline generic trends of pillar behavior.

Besides laboratory model tests in-situ, full scale pillar tests and monitoring campaigns have been conducted. Most noticeable therefore are in-situ coal pillar tests (e.g. Bieniawski (1968), Wagner (1974), van Heerden (1975)) and research conducted on crush pillar behavior in South African mines (e.g. Watson et al. (2007), Watson et al. (2010), Watson (2010), Du Plessis (2015), Du Plessis and Malan (2015a), Du Plessis and Malan (2016)). These tests and monitoring campaigns provide insights into pillar strength, pillar stress strain behavior, pillar fracture and failure characteristics and pillar residual strength.

6.1.2.2.1.2 Fracture and failure propagation inside pillars

In-situ investigations and pillar tests in the laboratory and field allow drawing general conclusions regarding pillar strength. However, the determination of the actual pillar strength, particularly of hard rock pillars, on basis of case studies or pillar tests remains difficult. A possible approach overcoming drawbacks is the application of analytical or numerical models, which incorporate and replicate pillar fracturing and failure appropriately. Various studies (e.g. Wagner (1974), Watson et al. (2009), Du Plessis and Malan (2016)) have highlighted that pillar fracturing and failure starts at pillar corners and pillar boundaries and moves then gradually towards the pillar core. A schematic outline of pillar fracturing and failure is provided in Figure 108. Fracturing and detachment of fractured portions result in hourglass shaping of the pillar and finally in complete pillar destruction.

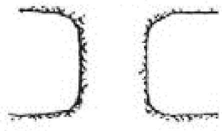
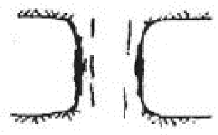
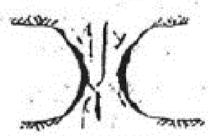
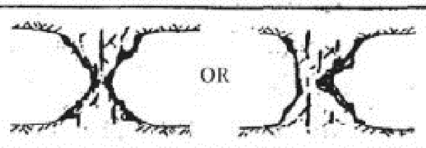
Pillar rating	Pillar condition	Appearance
1	No indication of stress induced fracturing. Intact pillar.	
2	Spalling on pillar corners, minor spalling of pillar walls. Fractures oriented sub-parallel to walls and are short relative to pillar height.	
3	Increased corner spalling. Fractures on pillar walls more numerous and continuous. Fractures oriented sub-parallel to pillar walls and lengths are less than pillar height.	
4	Continuous, sub-parallel, open fractures along pillar walls. Early development of diagonal fractures (start of hourglassing). Fracture lengths are greater than half of pillar height.	
5	Continuous, sub-parallel, open fractures along pillar walls. Well developed diagonal fractures (classic hourglassing). Fracture lengths are greater than half the pillar height.	
6	Failed pillar, may have minimal residual load carrying capacity and be providing local support to the stope back. Extreme hourglassed shape or major blocks fallen out.	

Figure 108: Stages of pillar fracturing and failure (Roberts et al., 1998)

Measurements of stress distributions and the associated location of fracture and failure zones inside pillars during increased stages of pillar loading are reported by Iannacchione (1990), Gale (1992) and Mark and Iannacchione (1992) in coal pillars in longwall mining or by Watson et al. (2007), Watson et al. (2008a) and Watson et al. (2009) in hard rock crush pillars. These measurements show generally that stresses drop first at pillar boundaries indicating pillar fracturing at pillar boundaries and that stress dropping moves gradually towards the pillar core. Pillar fracturing may also stop at a certain distance into the pillar and fractured portions may still be able to transfer a certain amount of stress.

Probably, Wagner (1974) conducted one of the most detailed investigations on the pillar stress strain behavior and fracture and failure characteristics. He tested coal pillars of varying width-to-height ratios in-situ with a displacement-controlled setup. Therefore, a coal pillar of desired size was cut and afterwards a horizontal slot at half height of the pillar was created. In this slot hydraulic jacks were installed and subsequently elongated in direction of pillar height with the same rate such that the induced pillar deformation throughout the pillar was constant. The pressure was read from the jacks at certain intervals. This setup enabled on the one hand to determine coal pillar strength and behavior in realistic, in-situ, full-scale conditions and on the other hand to derive axial stress profiles at half height of the pillar at different stages of pillar loading. Figure 24 shows pillar stress – pillar compression curves and corresponding stress profiles at selected stages. It can be seen that corners of pillars and portions of pillar boundaries fracture and crush first that failure moves gradually towards the pillar core and that fractured portions provide still some residual strength. Interesting observations are further that the pillar portions towards the pillar core can withstand considerably larger loads than the pillar corners and pillar boundaries and that the pillar core is most highly stressed at an advanced stage of the pillar test in the post-peak region of the pillar. It can be concluded that fractured pillar portions seem to have a noticeable impact on the overall pillar behavior, because they provide confinement to inner portions of the pillar and thereby increase the strength of respective portions. Fracturing of rock mass is principally associated with dilation leading to a volume increase. This volume increase creates a confinement pressure in nearby rock mass portions. Besides that, previously fractured (and dilated) rock mass portions counteract the dilation of currently fracturing neighboring rock mass portions, whereby the confinement in currently fracturing portions is increased. It is critical that the fractured portions of the pillar stay in place. Otherwise, their advantageous, confining effect is lost. The latter could be realized naturally by frictional constraints at the pillar – rock mass contacts or artificially by support or backfill placed adjacent to the pillar.

Different generic situations based on the location of fracture and failure must be considered in pillar strength calculation methods and approaches. Experience shows that either the pillar itself or the pillar foundation is limiting pillar strength. Hence, it is first differentiated on basis, whether fracturing and failure occur predominantly in the pillar or the pillar foundation. Second, the frictional constraint at the pillar – rock mass contact is critical for pillar strength and behavior. Therefore, it is reasonable to distinguish further based on the pillar – rock mass contact properties. Accordingly, following relevant situations can be derived. Figure 109 provides corresponding sketches.

- <u>Pillar strength and behavior are predominantly governed by the pillar and there is a contact plane between the pillar and the surrounding rock mass:</u> (Situation (a) Figure 109) This situation is typically present, if the pillar is comprised of a different rock mass than the rock mass surrounding the pillar. Moreover, the rock mass of the pillar is weaker than the surrounding rock mass or of approximately the same strength. These conditions cause that fracturing and failure occur predominantly inside the pillar itself. The properties of the pillar – rock mass contact affect the pillar behavior considerably.
- <u>Pillar strength and behavior are governed by the pillar and potentially in combination with pillar foundations and there is not a contact plane between the pillar and the surrounding rock mass:</u> (Situation (b) Figure 109) This situation is typically present, if the pillar and its surroundings are comprised of the same rock mass. There is also not a distinct contact plane between the pillar and the surrounding rock mass. Again, the pillar behavior is usually governed by the pillar itself, because fracturing and failure inside the pillar are more likely due to the higher confinement and thus the higher strength of the pillar foundations. Indeed, localized fracture of pillar foundations becomes important, because it can affect the retention of fractured portions inside the pillar and thus their positive impact on pillar strength. This

localized fracturing of pillar foundations can cause a gradual transition between pure failure inside the pillar and pure pillar foundation failure.

- Pillar strength and behavior are governed predominantly by pillar foundation independent whether or not there is a contact plane between the pillar and the surrounding rock mass: (Situation (c) Figure 109) This situation occurs, if the strength of the pillar foundation is lower than the strength of the pillar itself. First, this instance could be the case, if the rock mass forming the pillar foundations is significantly weaker and softer than the rock mass forming the pillar. In this case the pillar punches into the foundation and the weak and soft rock mass in the pillar foundation expands sideways. As a consequence, the pillar is pulled apart and extension fractures, which can reach deep into the pillar emerge. Second, a pillar foundation failure can limit the pillar strength, if the pillar width-to-height ratio and restraining conditions are such that the pillar foundation gives way before the pillar itself would have been loaded beyond peak strength. This situation is shown in Figure 109c. This aspect marks the transition from the first two situations, where the pillar itself dominates behavior, to the third situation, where the pillar foundation dominates behavior. Accordingly, the pillar foundation strength poses an upper limit of the pillar strength.

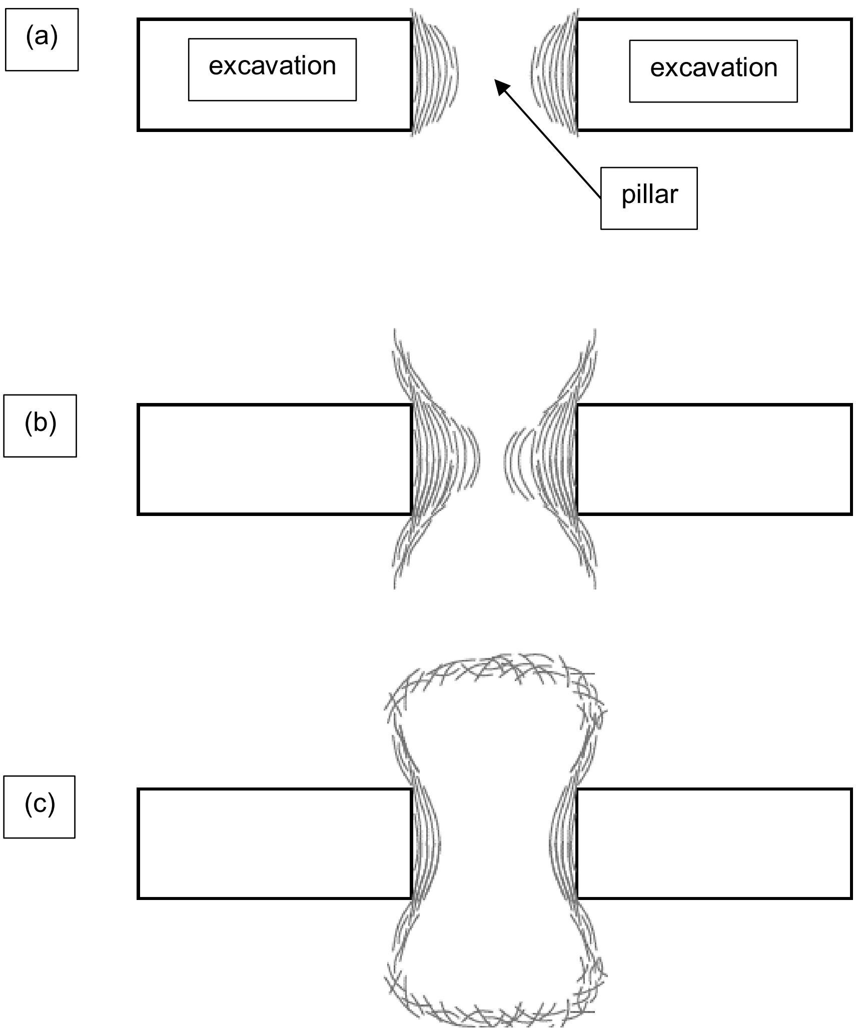


Figure 109: Different generic situations of pillar fracture and failure and corresponding schematic sketches fracture and failure

6.1.2.2.1.3 Analytical pillar strength models

Analytical models have been developed and applied to study pillar strength. (Wilson (1972), Barron (1984), Salamon (1992), Du Plessis et al. (2011)) These models are generally constraint to the situation, where pillar fracture and failure occur inside the pillar only. The approach after Salamon (1992), which is considered to be the most advanced, but also most complex, is utilized here to highlight the effect of pillar width-to-height ratio on pillar strength qualitatively. With his model Salamon studied the strength of two-dimensional, infinitely long coal pillars.

The principles of Salamon's model are shown in Figure 110 for a horizontal pillar. Fracturing starts at the pillar boundaries and moves gradually inwards, as the load acting on the pillar is increased. The pillar core between the fractured zones remains unfractured and elastic. The fractured zone is referred to as "yield zone" and the unfractured zone to as "elastic core". The yield zone is restraint through friction at the contacts with the surrounding rock mass. Hence, the horizontal stresses in the yield zone increase with distance from the pillar boundary. The rising horizontal stresses have two effects. First, they increase the strength of the fractured rock mass in the yield zone. Accordingly, the vertical stresses in the yield zone rise with distance from the pillar boundary. Second, at a certain distance from the pillar boundary the horizontal stresses at the transition between the yield zone and the elastic core are of sufficient magnitude to prevent further fracturing of the elastic core. Overall, the frictional restraint at the pillar – rock mass contact is critical for the pillar strength. The higher this restraint is, the faster the increase of horizontal stresses in the yield zone and hence the smaller the yield zone and the stronger the pillar.

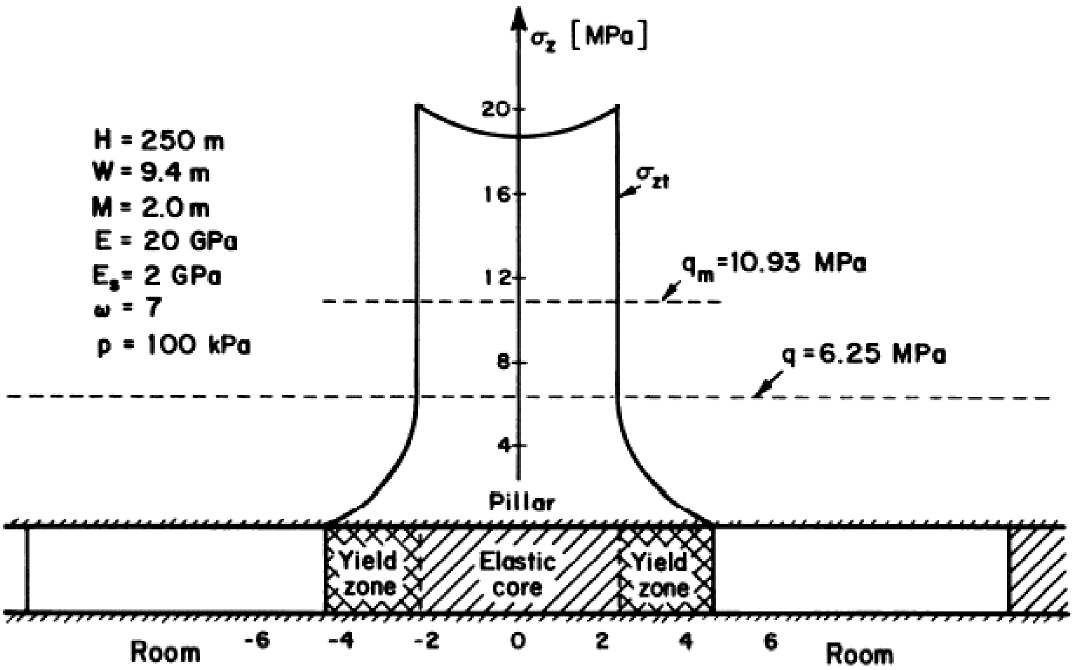


Figure 110: Pillar strength model and corresponding vertical stress distribution in a partially fractured pillar (Salamon, 1992)

The pillar strength model after Salamon (1992) shows that the pillar strength increases exponentially with increasing width-to-height ratio and that the properties of the contact plane between the pillar and the surrounding rock mass have a significant impact. The higher the friction angle in the contact plane is, the larger is the frictional restraint and the faster is the strength increase with the width-to-height ratio. A similar relation and a considerable influence of the properties (friction angle) of the pillar – rock mass contact were found by Gale (1999), who conducted numerical simulations of coal pillars with varying properties of the pillar – rock mass contact; compare Figure 111.

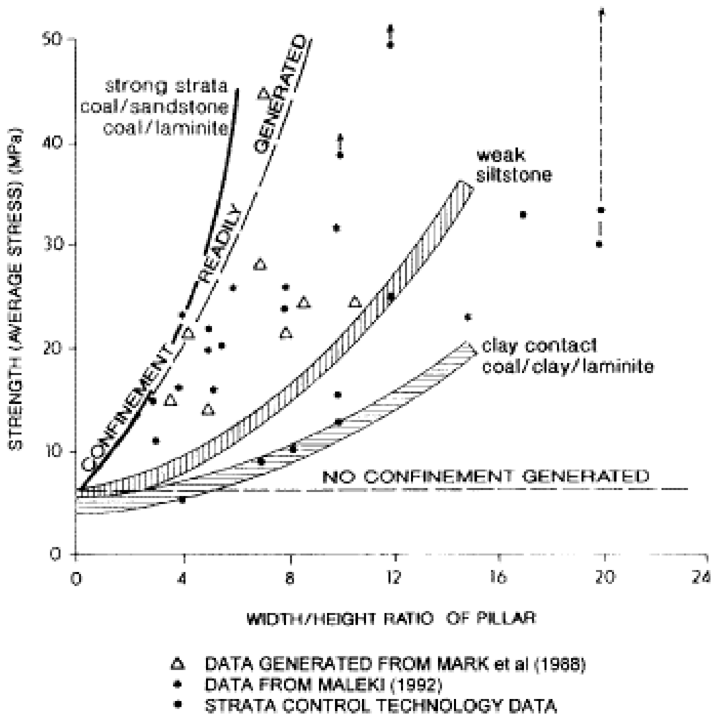


Figure 111: Coal pillar strength from numerical models with outlined data derived from site measurements (Gale, 1999)

6.1.2.2.1.4 Numerical investigations related to pillar strength

Analytical pillar strength models are mostly constraint to certain, idealized situations and idealized material behavior. In contrast, numerical models enable the investigation of pillar strength and stress strain behavior in a wider variety of conditions and they are able to replicate all of the outlined pillar fracture and failure situations in Figure 109. However, the major constraint of numerical models is their representation and replication of rock mass behavior. Numerical modelling has been widely applied for pillar strength investigations, whereby different continuum, discontinuum or hybrid continuum-discontinuum approaches have been deployed. The pillar strength and behavior, which are derived with numerical models, depend on the assumed rock mass strength and behavior and the modelling framework, but also significantly on the chosen simulation and modelling approach. Hence, the critical issue in numerical simulations is the realistic replication of the rock mass behavior in the model. However, the rock mass strength and behavior are associated with considerable uncertainty; compare section 3.3.3. Accordingly, the correct replication of rock mass strength and behavior in numerical modelling is rather difficult or even impossible.

It is far beyond the scope of the present work to discuss these approaches, conducted studies and their outcomes in detail. Instead, the results of the studies of Iannacchione

(1999), Martin and Maybee (2000), Esterhuizen (2007), Watson et al. (2008b), Mortazavi et al. (2009), Elmo and Stead (2010), Kaiser et al. (2010), Rafiei Renani and Martin (2018), Sinha and Walton (2018) and Li et al. (2019) are discussed briefly on a qualitative basis. The comparison of the numerical studies addressing pillar strength with the pillar strength deduced from mining experience (Figure 106), from Salamon's analytical model and from Gale's investigations (Figure 111) shows that the pillar strength derived from numerical studies corresponds in general to the pillar strength deduced from mining experience, which instance is also strongly related to the fact that numerical models are often calibrated to in-situ mining experience. Furthermore, the numerical studies concentrated on pillars with width-to-height ratios of around 0.5 to 3. For these reasons, the available numerical studies do principally not enhance the knowledge related to pillar strength beyond the available knowledge from mining experience.

Overall, it can be concluded that hard rock pillar strength is associated with considerable uncertainties particularly at width-to-height ratios, where limited or no in-situ data is available. Principally, except of hard rock pillars with a width-to-height ratio below about 2, the data and knowledge are very limited and the strength is rather uncertain. Hence, further research is required. In-situ observation and data generation are therefore central.

6.1.2.2.2 Knowledge related to hard rock pillar post-peak behavior

So far, pillar strength has been discussed. Knowledge of pillar strength is essential to determine, whether pillars can withstand the loads, which they are exposed to. However, besides the strength the post-peak behavior of pillars is important, because it determines in combination with the loading system stiffness, whether a pillar failure is stable or unstable; compare section 3.3.4.

After the pillar peak stress (pillar strength) (σ_p) was exceeded, pillars may show three different types of post-peak behavior, a strain softening, a strain hardening and a yielding behavior; compare Figure 112. Pillars with a strain softening behavior are commonly referred to as "crush pillars" and pillars with yielding behavior to as "yield pillars". The so-called "post-peak modulus" can be used to describe the post-peak behavior quantitatively. The post-peak modulus describes the average rate of the increasing or decreasing, respectively, resistance against deformation with increasing deformation. In order to describe the average rate, the first point for its determination is taken from the position of the stress – strain curve, where the stress strain curve starts to change noticeably after peak strength, and the second point is taken from the stress strain curve, where the stress strain curve changes noticeably again; compare Figure 112. A strain softening behavior shows a negative post-peak modulus, which corresponds to a decreasing resistance against further deformation. The more negative the post-peak modulus is, the larger is the post-peak strain softening rate and the more brittle is the post-peak behavior of the pillar. A yielding behavior shows a post-peak modulus of zero and thus a constant resistance against deformation. A strain hardening behavior has a positive post-peak modulus. The more positive the post-peak modulus is, the larger is the post-peak strain hardening rate.

It is important to consider that the post-peak modulus represents an average rate of strain softening and strain hardening, respectively. Accordingly, the post-peak modulus does not allow to point out, whether a pillar failure is stable or unstable for a pillar with a strain softening behavior for a given constant loading system stiffness. For the latter the steepest part of the curve in the post-peak region or in other words the highest strain softening rate has to be considered. Despite this shortcoming the post-peak modulus is well suited to represent the general post-peak pillar behavior.

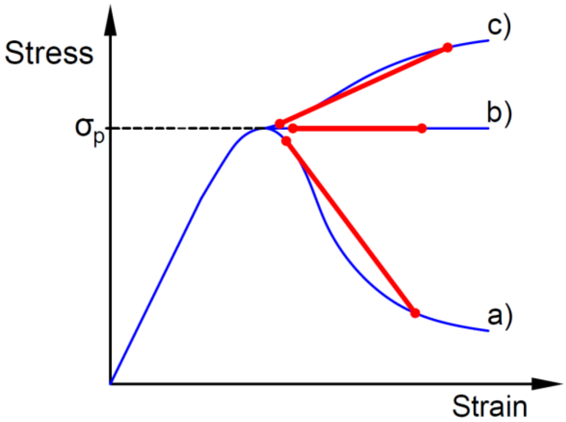


Figure 112: Different types of post-peak pillar behavior and corresponding line, which is used for the determination of the post-peak modulus, is shown in red color; (a) strain softening, (b) yielding, (c) strain hardening

The knowledge regarding post-peak pillar behavior is outlined in the following briefly. The emphasis is again on hard rock pillars. It is reasonable starting the discussion from in-situ observations and experience. In contrast to pillar strength the conducted in-situ investigations addressing post-peak pillar behavior are significantly less. In-situ coal pillar tests (e.g. Wagner (1974), van Heerden (1975)) provide probably most comprehensive data regarding the post-peak modulus. Vardar et al. (2017) summarize the post-peak moduli of various coal pillar tests. Their data as a function of the pillar width-to-height ratio is outlined in Figure 113. The post-peak moduli are normalized with the Young's modulus (E). For coal a Young's modulus of 4 GPa, which represents a typical Young's modulus of coal (compare van Heerden (1975)), is used therefore. Besides the individual data points of in-situ coal pillar tests the derived relationships between the post-peak modulus and the pillar width-to-height ratio after Zipf (1999) and Vardar et al. (2017) are shown. Ozbay (1989) derived a similar relationship from in-situ coal pillar tests and laboratory tests, which is provided in Figure 113 as well. In-situ pillar tests on hard rock pillars comparable to the in-situ coal pillar tests have not been conducted. The in-situ measurements of pillar stress and pillar strain from crush pillars conducted by Watson (2010) come probably closest to in-situ pillar tests. The post-peak moduli from these measurements are plotted in Figure 113. Regarding the data on crush pillars it is remarked that the pillar stress was measured some distance above the pillar and that the pillar crushing takes typically place at the stope face in the prevailing mining conditions. These aspects could potentially affect the post-peak modulus. Additionally, post-peak moduli derived from numerical simulations of hard rock pillars from Mortazavi et al. (2009), Zhang et al. (2015), Sinha and Walton (2018), Rafiei Renani and Martin (2018) and Li et al. (2019) are outlined in Figure 113. As these studies had different modelling approaches and objectives and as these studies were conducted in different mining environments, their reported post-peak moduli are considered to be qualitative.

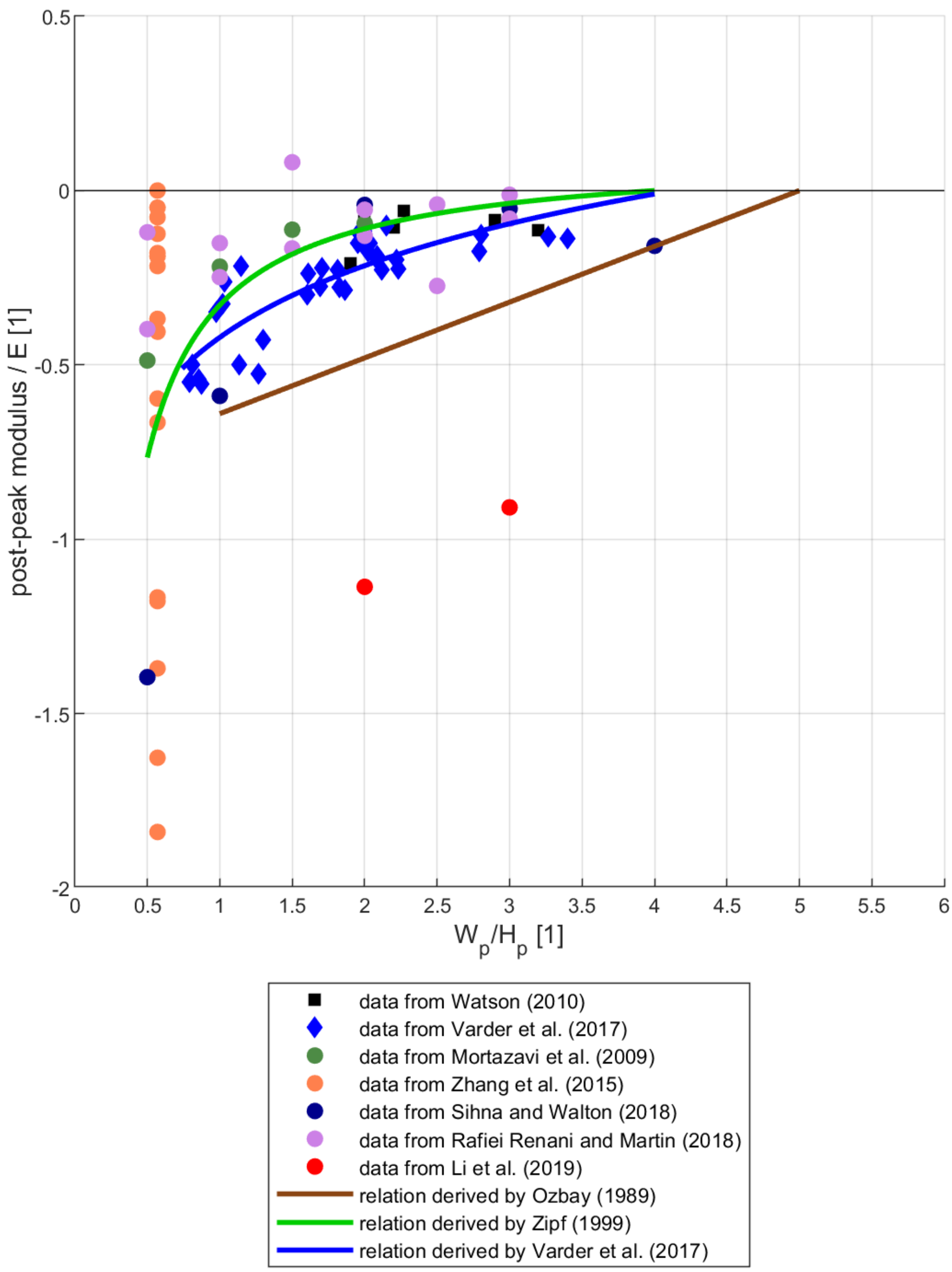


Figure 113: Summary of pillar post-peak modulus knowledge

Figure 113 summarizes post-peak moduli from in-situ and laboratory tests and measurements, derived relations therefrom and from numerical studies. Generally, it shows that the post-peak modulus increases with increasing pillar width-to-height ratio and that it becomes positive at width-to-height ratios of about four to five. However, the conducted analysis and the summary highlight as well that despite the general trend the knowledge regarding the post-peak modulus is very limited in particular for hard rock pillars. In-situ studies and measurements of hard rock pillars are rather sparse. Numerical models suffer from the drawback that the model setup and numerical replication of the rock mass behavior, which is insufficiently known, have a considerable impact on the post-peak behavior.

For these reasons, it is finally concluded that the post-peak pillar behavior particularly of hard rock pillars is not well understood and requires further research, wherefore comprehensive in-situ investigations would be of paramount importance.

6.1.2.2.3 Knowledge related to hard rock pillar residual strength

Crush pillars have a strain softening behavior and lose their resistance against deformation with increasing deformation. However, at a certain deformation the resistance against deformation stays often constant. This resistance against deformation is referred to as the residual strength of the pillar; compare Figure 114. The magnitude of the residual strength is of interest for crush pillars.

Research and investigations on the residual strength of crush pillars have been predominantly conducted in South Africa, where crush pillars are an integral part of stope support in platinum mines (Du Plessis and Malan, 2015b) and where crush pillars are utilized for de-stressing at South Deeps mine (Andrews et al., 2019). The crush pillar residual strength has been investigated by in-situ observations, measurements and back analyses (e.g. Roberts et al. (2005), Watson et al. (2009), Watson et al. (2008a), Du Plessis and Malan (2016)), analytical models (e.g. Du Plessis et al. (2011)) and numerical studies (Du Plessis and Malan (2011), Du Plessis and Malan (2015b)). Overall, investigations concentrated in general on pillars with rather small width-to-height ratios in a limited number of mining environments. Thus, it can be concluded that, similar to hard rock pillar strength and post-peak modulus, the current knowledge regarding crush pillar residual strength is limited.

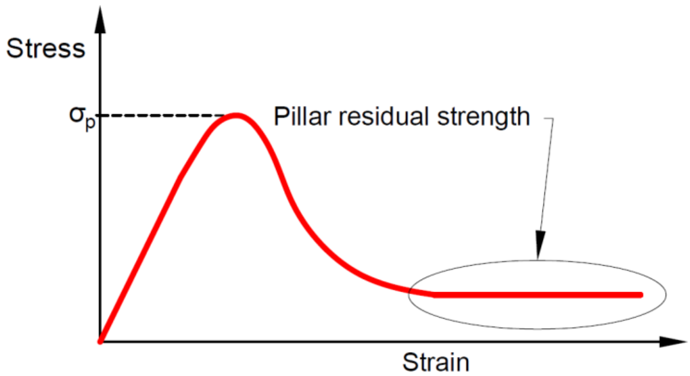


Figure 114: Stress strain curve of a crush pillar showing its strain softening behavior and its residual strength

6.1.2.2.4 Influence of pillar size on hard rock pillar strength, post-peak behavior and residual strength

The discussion above concentrated on the pillar width-to-height ratio and the prevailing rock mass conditions. Besides the width-to-height ratio the actual size of the pillar influences the pillar behavior considerably. Figure 115 shows two pillars, which have the same width-to-height ratio and which are situated in the same rock mass conditions. The jointing of the rock mass of the larger pillar does not differ from the jointing of the rock mass of the smaller pillar. However, pillar dimensions vary significantly. Therefore, the question arises, whether both pillars show the same behavior. It is reasonable to assume that the strength of the larger pillar is lower, because rock mass strength decreases with increasing volume and because the restraining and confining effect of fractured pillar portions may be reduced. Furthermore, the actual pillar size may have an influence on the pillar post-peak modulus and the pillar residual strength.

The effect of pillar size is covered to some extent in pillar research and pillar knowledge. Certain pillar strength equations consider the impact of the pillar size; compare for example Salamon and Munro (1967), Hedley and Grant (1972) or Esterhuizen et al. (2011). However, most of the research and investigations have been concentrating on pillars with relatively small dimensions. Accordingly, the impact of rock mass conditions on the behavior of larger pillars is not known in detail. This circumstance is especially critical, if pillars of large size are required.

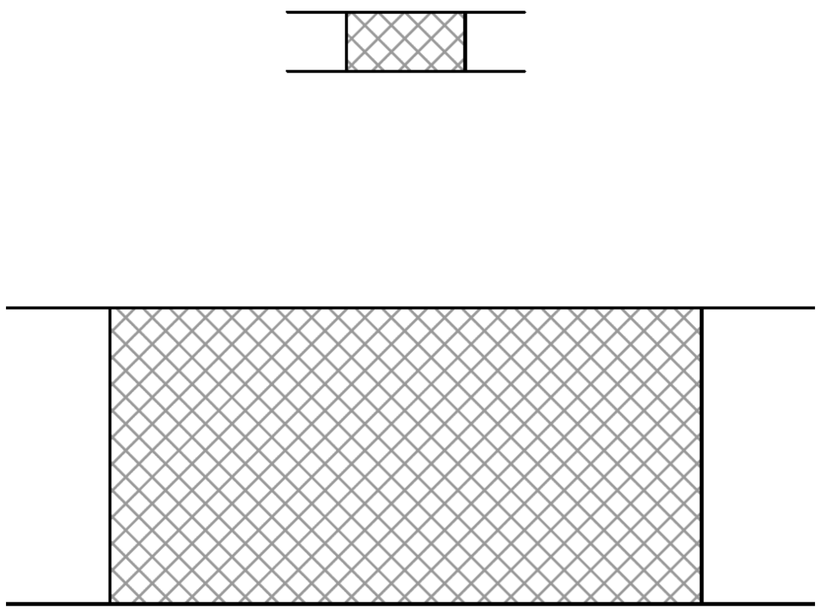


Figure 115: Pillars with the same width-to-height ratio, but different dimensions in the same rock mass conditions

6.1.2.2.5 Concluding remarks related to pillar strength and pillar stress strain behavior

Pillars are a main element of the proposed stress management concept. Their physical effects, which are central for the desired functions of pillars, are strongly influenced by the pillar strength and pillar stress strain behavior. For certain functions pillars must not fail, whereas for other functions stable pillar failure and pillar crushing are required. Independent of the function a reasonably good knowledge of pillar strength and behavior is decisive. However, the conducted review highlights that there are considerable uncertainties related to the pillar strength and the pillar stress strain behavior of hard rock pillars. At this point is also noted that the investigation regarding pillar strength and stress strain behavior concentrated on the pillar itself and pillar foundation failure, which is predominant for pillars with large width-to-height ratios, was not discussed further. However, the general situation regarding the knowledge related to pillar foundation strength and behavior is comparable to the situation regarding the knowledge of pillar strength and behavior. Hence, also pillar foundation strength and behavior is relatively uncertain for hard rock pillars. The prevailing uncertainties are critical for the stress management concept, where pillars have to be specifically designed to fulfill a certain function. Moreover, some pillar functions in the stress management concept rely on the use of pillars with quite large dimensions but relatively low width-to-height ratios or on the use of pillars, which width-to-height ratio is decreased considerably during mining. For these reasons, the knowledge of the complete stress strain behavior of pillars is essential.

An instance, which may have contributed to the limited knowledge related to the strength and to the stress strain behavior of hard rock pillars, is that in contrast to quite sophisticated pillar design requirements for certain pillar functions in the proposed stress management concept the design of pillars in many of the currently utilized mine layouts and sequences is not as demanding. Current mine designs rely in most instances either on pillars, which must not fail, or on pillars, which are allowed to yield or crush in a rather stiff loading environment such that unstable pillar failure is prohibited. In the case of pillars, which must not fail, knowledge of the pillar strength and the expected (maximum) pillar stress is required. Pillar dimensions are then chosen such that pillars can always withstand the pillar stress. The limited knowledge of pillar strength is normally overcome by conservative design approaches, which could comprise downgrading the pillar strength, overestimating pillar stress or using a sufficiently high factor of safety in the design. An illustrative example are room and pillar or stope and pillar mining methods, which rely on the use of permanent panel pillars for regional support of the overlying rock mass formations.

Indeed, it may not be possible to design sufficiently strong pillars at acceptable extraction ratios in all situations and furthermore there is always a certain risk that pillars are overloaded and fail subsequently (in an unstable manner). A prominent example therefore are pillar systems in mining methods, such as room and pillar, which rely on the use of pillars to support the mine structure on a regional scale. The following approaches are in such situations commonly applied:

- Use of pillars with width-to-height ratios, which prevent unstable pillar failure due to transition to a strain hardening behavior, is typically made. Thereby, it is ensured that overloaded pillars deform in a stable manner. Such pillars can be used on a regional scale, for example in pillar extraction methods. Furthermore, individual mining panels are separated by large pillars (inter-panel or barrier pillars) with high width-to-height ratios. These pillars have a high strength and a strain hardening behavior. Therefore, these inter-panel and barrier pillars ensure that a potential unstable pillar failure is constrained locally to individual mining panels in the mine.
- Pillars inside mining panels are not created at all or crush pillars, which crush reliably and reach their residual strength in a stiff loading environment, which prevents unstable pillar failure, are utilized. Furthermore, neighboring mining panels or mining areas are in this situation usually separated by inter-panel or barrier pillars with large width-to-height ratios. Extensive use of crush pillars is for example made in South

African platinum mines. Research and mining experience show that crush pillars must crush to their residual strength at the stope face, where a stiff loading environment and high stresses are provided. (Du Plessis and Malan, 2018) Otherwise, there is a risk of pillar bursting, as mining progress and as pillars move backwards into the stope. Accordingly, the prevailing stresses at the stope face and the sufficiently small dimensions of crush pillars such that pillars cannot withstand stresses at the stope face are critical. Another example of the use of crush pillars are sublevel stoping operations at great depths, where pillars are (temporarily) used to separate neighboring stopes. Mining experience shows that these pillars crush and de-stress in the course of stoping, which can be recognized by an absence of mining-induced seismicity in or near these pillars and the corresponding concentration of mining-induced seismicity in the abutment areas of mining panels. (Jalbout and Simser, 2014) Indeed, such pillars in sublevel stoping are referred to as crush pillar seldom and specific research addressing the crushing behavior of these pillars and associated requirements for stable crushing is very limited. Decisive in the latter situation is probably that pillars crush and de-stress soon after their creation and that a stiff loading environment is provided, which can be realized for example by limiting panel spans.

Foregoing considerations highlight that an exact knowledge of pillar stress strain behavior is in general not required for (most of) the outlined, currently used pillar designs. Pillars are designed such that they are associated with a stable behavior throughout their lifetime, wherefore

- pillars must be sufficiently strong to prevent pillar failure at all, or
- pillars must be of a sufficiently large width-to-height ratio, which prevents unstable pillar failure at all, or
- the loading environment must be sufficiently stiff to ensure stable pillar yielding and crushing.

However, there are certain situations, where rock pressure problems arise because of an insufficient knowledge of the strength and stress strain behavior of currently utilized pillars. Highly stressed regional pillars or remnants, which are extracted at an advanced stage of mining, are one of these situations. In the course of extracting these pillars the pillar dimensions and correspondingly the pillar width-to-height ratio are reduced gradually. Accordingly, the pillar strength and pillar post-peak modulus decrease. Moreover, the loading environment could be rather soft due to the advanced stage of mining and due to the already high extraction ratio. In summary, conditions, which make an unstable pillar failure more likely, are prevailing. Mining experience shows that the extraction of such highly stressed regional pillars or remnants is frequently associated with rock pressure problems (see for example Le Roux (2008), Murphy (2012), Varden and Esterhuizen (2012), Townend and Sampson-Forsythe (2014)).

Finally, for the successful implementation of the proposed stress management concept the central issue, how the identified knowledge deficiency related to pillar strength and behavior can be addressed in practice, must be considered already at an early stage of mine design. Following approaches can be utilized therefore:

- Improving understanding of rock mass strength and stress strain behavior: Pillars are comprised of rock mass and their behavior is strongly linked to rock mass behavior. It has been highlighted that rock mass strength and behavior are insufficiently understood. Targeted research is an approach of overcoming this deficiency. Basically, such a targeted research requires extensive in-situ observations, where rock mass behavior can be investigated and analyzed in full-scale. Laboratory or numerical studies can enhance but principally not replace extensive in-situ observations. The underlying reasons are that both laboratory and numerical studies can barely capture the complexity of rock mass. Hence, they are a simplification and they therefore require calibration, which should be based on observed in-situ rock mass behavior to produce meaningful results. Potentially, pillars themselves can contribute to in-situ research on rock mass, because pillars are geometrically defined structures of limited size and they can therefore reduce the complexity by reducing the volume of observed rock mass and the number of variables. Furthermore, the development of unsophisticated, low-cost monitoring devices would be a major step forward, because their development would allow observing rock mass behavior in large areas of the mine continuously and in a quantified way. However, the research approach on rock mass is rather long-term and can therefore not contribute in the near future to overcome the critical knowledge deficiency regarding pillar strength and pillar stress strain behavior.
- Utilizing flexible mine layouts and mining sequences: Another possible approach overcoming the knowledge deficiencies of pillar behavior is the application of flexible mine layouts and flexible mining sequences in combination with observation and monitoring. Thereby, it is possible to detect potentially problematic developments or circumstances at an early stage and moreover to react on observations and mining experience on short notice. Overall, flexible mine layouts and mining sequences are considered to be currently the best approach to deal with the limited knowledge regarding pillar strength and pillar stress strain behavior.
- Minimizing consequences of pillar failure: Lastly, another approach, even though only a damage minimization one, is to design mine layouts and mining sequences such that stable or unstable pillar failures do not affect the operation severely. An example therefore are inter-panel and barrier pillars, which separate neighboring mining panels or mining areas and which are designed such that a collapse of pillars is constrained locally to individual mining panels or mining areas. Obviously, this approach has a clear passive character and hence does not seem to be preferable on the long-run or on a large-scale.

6.1.2.3 Summary of stress changes in the vicinity of pillars, of pillar strength and of pillar stress strain behavior

The effect of pillars on the resultant stress situation as well as the importance of pillar strength and pillar stress strain behavior were outlined in the foregoing sections. The emphasis was on relevant aspects for the element functions of the proposed stress management concept. In summary, important points are:

- Pillars transfer stresses and act as stress raisers.
- The stress raising effect of pillars diminishes with increasing distance from the pillar.
- The orientation of the pillar is critical for its stress raising effect.
- The pillar strength and stress strain behavior have a considerable impact on the stress raising effect, the stability of the pillar and the stability of a potential pillar failure.
- The knowledge of (hard rock) pillar strength and stress strain behavior is limited and deficient, which instance aggravates the successful implementation of the proposed stress management concept.
- Possible approaches to address the limited knowledge of pillar strength and stress strain behavior were outlined and a flexible mine layout and mining sequence are found to be most effective.

The derived results will be utilized in subsequent chapters, when discussing individual element functions as well as the implementation of the stress management concept in practice.

The influence of pillars on deformations in the surrounding rock mass has not been discussed yet. The deformations are particularly relevant for the loading system element and will thus be discussed in the corresponding section 6.1.3.

6.1.3 Loading system

In contrast to excavations and pillars, which have a defined geometry that can be used for their definition, the loading system does not have a specific geometry. The loading system is in general comprised of the rock mass in the vicinity of excavations, pillars, extraction areas and the mine. Correspondingly, a loading system element is formed as a consequence of creating excavations and pillars and hence it is a dependent main element.

The physical effects of the loading system are relevant for element functions of the stress management concept and they are:

1. Distributing stresses
2. Influencing the resultant stress situation
3. Governing the stability of failure (in combination with the failing rock mass, pillar etc.)

The first and the second function are closely linked. Based on the properties of the loading system the stresses are distributed in the rock mass. Accordingly, the resultant stress situation is influenced. An illustrative example therefore was given in Figure 41, which highlights pillar loading for two cases, namely where the hangingwall strata bridges and where it does not bridge a mining panel. The deforming hangingwall strata is the loading system for the pillars. If the hangingwall does not bridge the panel, load transfer to abutments does not take place and the pillars must transfer the far-field stresses. In contrast, if the hangingwall bridges the panel, stress transfer to abutments takes place. A portion of the far-field stresses is transferred to abutments and pillars are not as highly stressed as for the case, where the hangingwall strata does not bridge the panel. The third function, which is the impact of the loading system on the stability of fracture and failure processes, is closely linked with the post-peak behavior of the failing rock mass, pillar, fault etc. The impact of the loading system on the stability of fracture and failure processes has been discussed in section 3.3.4.

The physical effects of the loading system are a function of the loading system properties, which depend on the prevailing mining environment, the nearby excavations and the nearby pillars. Important properties of the loading system comprise its stiffness and the direction and magnitude of the occurring deformation.

6.1.3.1 Magnitude and direction of deformations of loading systems

The magnitude and direction of deformations are important, where a loading system element distributes stresses to other adjacent elements, such as pillars, or within the nearby rock mass. Relevant aspects are briefly outlined below on basis of idealized situations and short examples in a qualitative manner.

The influence of the magnitude and direction of deformations can be illustrated on basis of a rectangular shaped, elongated excavation. The excavation boundaries deform and move inwards as a consequence of creating the excavation; compare Figure 116a. Now consider a pillar, which is left in the middle of the excavation; compare Figure 116b. The inwards moving rock mass in the hangingwall and footwall of the excavation represent the loading system for the pillar. The pillar is compressed and builds up a resistance against this deformation, which results in increasing stresses in the pillar. The stiffness of the pillar has a significant impact on the stress increase inside the pillar. These increased stresses inside the pillar counteract the deformation and the final deformation of the hangingwall and footwall rock mass are smaller than in the case of the excavation without the pillar. The final pillar stress as well as the final deformations depend on the prevailing rock mass conditions and primary stress situation, the pillar properties and the excavation dimensions. Furthermore, the pillar alters the deformations in the vicinity of the excavation and has therefore an influence on the loading system itself.

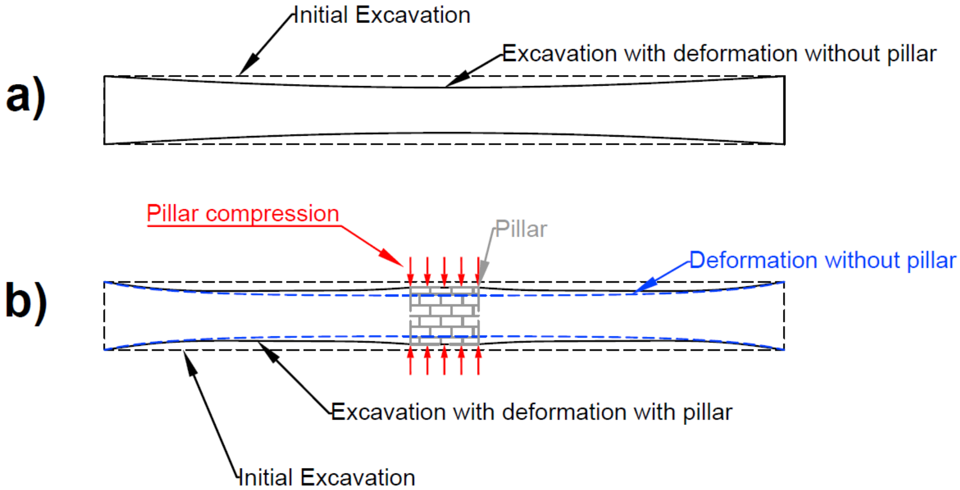


Figure 116: (a) elongated excavation with sketched deformed excavation boundaries (b) excavation with a pillar in the middle, which is loaded by the deforming excavation boundaries, and sketched changes of the deformations

The average pillar stress increases with increasing deformations of the excavation boundaries. This aspect is illustrated by means of a flat-lying mining panel with pillars and a varying width; compare Figure 117. The loading system for the pillars is comprised of the hangingwall and footwall rock mass of the panel and the corresponding deformations of the panel boundaries. As the panel width increases, the deformations increase as well. Accordingly, the average pillar stress rises with increasing panel width and levels out at the average pillar stress according to the tributary area theory, which constitutes the maximum possible average pillar stress in the given example. Furthermore, it can be seen that the average pillar stress increases towards the center of the panel, which is a result of the larger deformations of the panel boundaries in the center of the panel. This circumstance implies that the mine layout and mining sequence can be utilized to control the deformations of the loading system spatially and temporarily.

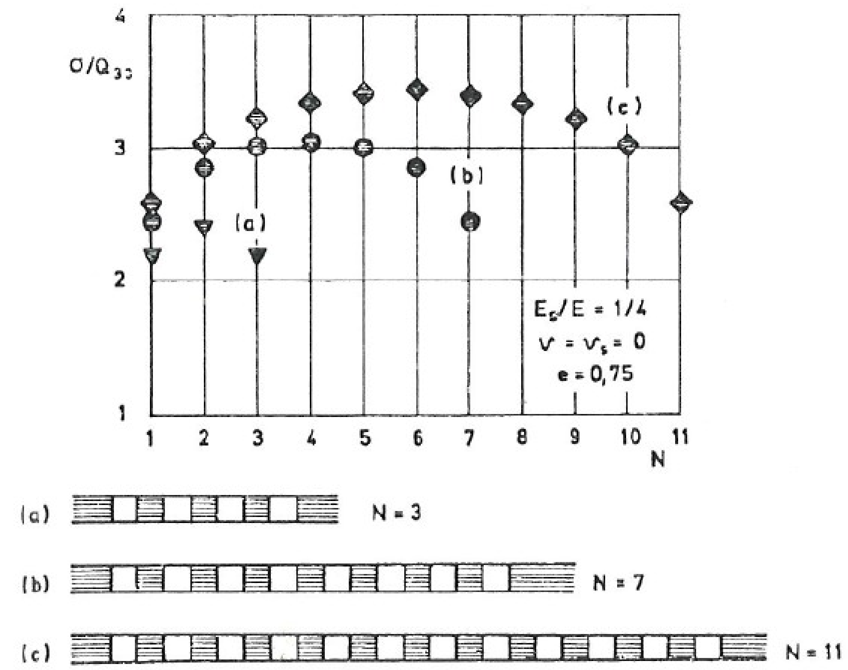


Figure 117: Average pillar stress as a function of panel width, which is varied by the number of pillars in the panel. The x-axis shows the individual pillars and the y-axis the normalized average pillar stress. For the outlined extraction ratio of 75 % the maximum possible average pillar stress after tributary area theory corresponds to four times the primary vertical stress. (Salamon, 1983b)

Another relevant aspect is that the deformations of the loading system are determined by the prevailing mining environment. Particularly critical are the bridging capabilities of the rock mass. If the rock mass can bridge mining panels (or other structures) in the mine, the deformations are significantly lower than for the case, where the rock mass cannot bridge. This circumstance has a direct impact on the stresses, which are transferred into pillar (or structures). For the situation, where the rock mass can bridge, the stresses can be significantly lower, because stress transfer to abutments takes place. Figure 41 provides an illustrative example therefore. Furthermore, the bridging capabilities of rock mass and its impact on the stability of pillars (or structures) are discussed in section 6.1.3.2.2.

The direction of movement of points, which are opposite on excavation walls or panel boundaries, is important as well. Figure 118a shows a situation, where opposite points move directly towards each other. In contrast, Figure 118b shows a situation, where opposite points do not move towards each other. This situation is commonly referred to as “ride” (Ryder and Jager, 2002) and occurs for example in case of inclined mining panels. As a consequence, shear stresses are generated in pillars inside this panel as well as in the contact area of the pillar with the surrounding rock mass. These shear stresses can reduce the pillar strength significantly.

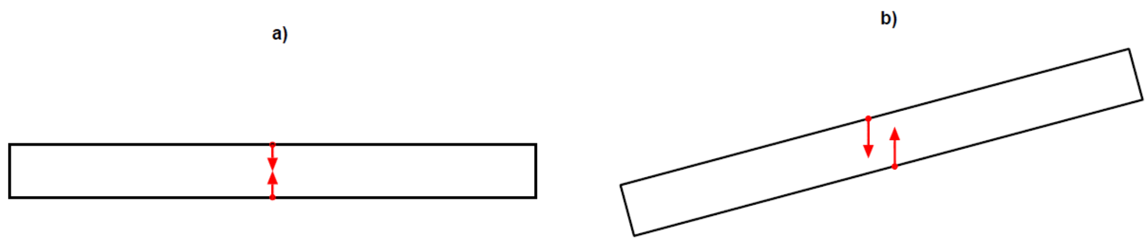


Figure 118: (a) Opposite points move directly towards each other; (b) Opposite points do not move towards each other

In summary, the magnitude and direction of the deformations of the loading system depend on the prevailing conditions, the mine layout and the mining sequence. The main reason for this is that the loading system is principally formed through the creation of the adjacent excavations and pillars. Thus, for the determination of the loading system deformations, it is necessary to consider the actual mine layout as well as the mining sequence. Important general aspects in practice are that

- the prevailing rock mass properties and primary stress situation have a significant impact on the magnitude and direction of deformations
- the deformations increase with decreasing stiffness of the rock mass
- the magnitudes of deformation increase with increasing excavation or extraction area dimensions
- the occurrence of ride can generate significant shear stresses.

6.1.3.2 Stiffness of loading systems

The stiffness of the loading system determines in combination with the stress strain behavior of the failing structure, whether the failure is stable or unstable; compare section 3.3.4. The stiffness of the loading system (k_{LS}) in a certain direction is defined by the occurring deformation (ΔD_{LS}) due to a force change (ΔF_{LS}) in the considered direction; compare Equation 14. The smaller the occurring deformation is for a given load change, the higher is the stiffness of the loading system.

$$k_{LS} = \frac{\Delta F_{LS}}{\Delta D_{LS}}$$

Equation 14

Figure 119 illustrates the calculation of the stiffness of the loading system on basis of a pillar between two excavations. The pillar transfers a certain average pillar stress ($\sigma_{p,avg}$) in the vertical direction. The loading system of the pillar in the hangingwall and footwall rock mass is indicated. (Figure 119a) In order to determine the loading system stiffness, the pillar is removed and the pillar stress is replaced by an equivalent force ($F_{p,equ}$), which is calculated by multiplying the average pillar stress with the pillar cross-section area (Figure 119b). Accordingly, the system is still in equilibrium and deformations have not occurred so far. Then, in Figure 119c the equivalent force is increased slightly by ΔF_{LS}. Consequently, the hangingwall and footwall rock mass deform each by ΔD_{LS}. Equation 14 can now be utilized to calculate the loading system stiffness.

The outlined approach can also be used to calculate the loading system stiffness in other situations, such as for example the failure of rock mass in the sidewalls of an excavation; compare section 3.3.4.2.

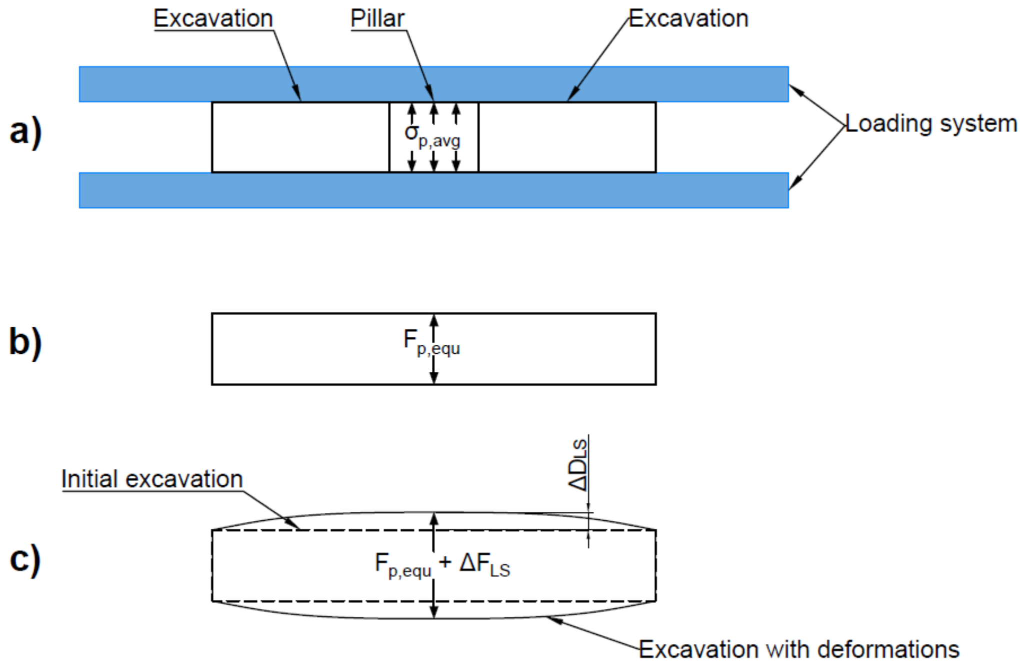


Figure 119: Model illustrating the stiffness of the loading system by means of a pillar between two excavations; (a) pillar between excavations and sketched loading system, (b) replacement of pillar with equivalent force, (c) increase of force and corresponding occurrence of deformation for the calculation of the loading system stiffness

The loading system stiffness is particularly important for the pillar element of the proposed stress management concept. Therefore, the loading system stiffness and its governing parameters are investigated for a number of relevant situations in practice, which are:

- Distribution of loading system stiffness inside a mining panel
- Influence of the rock mass properties
- Influence of the panel span
- Influence of large barrier pillars separating adjacent panels

The loading system stiffness is calculated with FLAC3D. Slice models with a thickness of 1 m are utilized and the pillars and excavations are thus infinitely long representing a two-dimensional case. The primary vertical stress is constant at 54 MPa and the ratio of primary horizontal to primary vertical stress is 0.5. Both primary horizontal stresses are equal. The rock mass has a linear elastic material behavior. Except of the situation, where the rock mass elastic properties are varied, the rock mass has a Young's modulus of 40 GPa and a Poisson ratio of 0.25.

6.1.3.2.1 Distribution of loading system stiffness inside a mining panel

The distribution of the loading system stiffness inside a mining panel is discussed on basis of an isolated panel. The panel is comprised of ten pillars with a width of 5 m and a height of 5 m. The excavations between pillars have a width of 5 m as well. The complete panel width is 105 m accordingly. Figure 120 outlines the considered mining panel and the corresponding pillars. The pillars are numbered from left to right in ascending order. Pillar 1 and pillar 10 are closest to the panel abutments and thus they are referred to as “edge pillar”. The pillars 5 and 6 are farthest away from the panel abutments and located in the center of the panel. Hence, pillar 5 and 6 are referred to as “center pillar”.

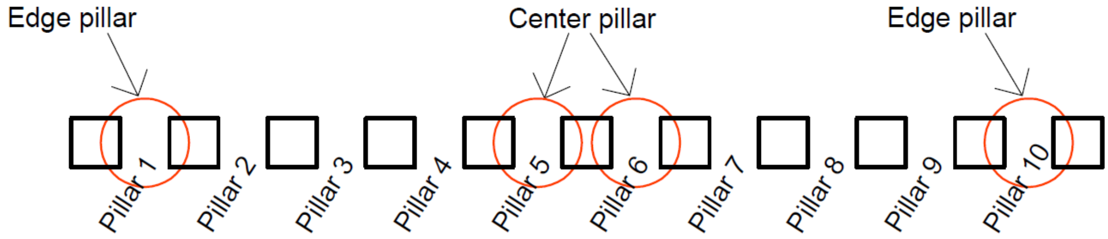


Figure 120: Considered mining panel and corresponding pillars in a vertical cross-section for the calculation of the loading system stiffness at the position of the pillars

Figure 121 displays the loading system stiffness at the position of individual pillars. It can be seen that the loading system stiffness is highest for the edge pillars (pillar 1 and pillar 10), that it decreases towards the center of the panel and that it is lowest at the panel center (pillar 5 and pillar 6). This distribution of the loading system stiffness has following implications on stable and crush pillar layouts:

- Stable pillar layout: These are layouts where the pillars inside the panel provide regional support to the surrounding rock mass, and hence the pillars transfer significant amount of stress. In such layouts the stresses in the center pillars are highest; compare Figure 117. Accordingly, under the assumption that all pillars have the same strength and stress strain behavior, failure of the center pillar is most likely. As the loading system stiffness is softest for the center pillar, the potential for an unstable pillar failure is highest as well. A failure of the center pillar has further adverse consequences. Namely the stresses in neighboring pillars are increased, which instance facilitates the collapse of the complete panel.
- Crush pillar layout: In these layouts pillars are loaded beyond their peak strength. Accordingly, pillars crush to their residual strength and the pillars provide a local support to the immediate hangingwall rock strata. For a safe implementation of crush pillar layouts pillar crushing must be stable. As the loading system stiffness is highest at the panel boundaries (for edge pillars), pillar crushing should occur close to or directly at the panel boundaries, because the likelihood of unstable pillar crushing is lowest at these positions.

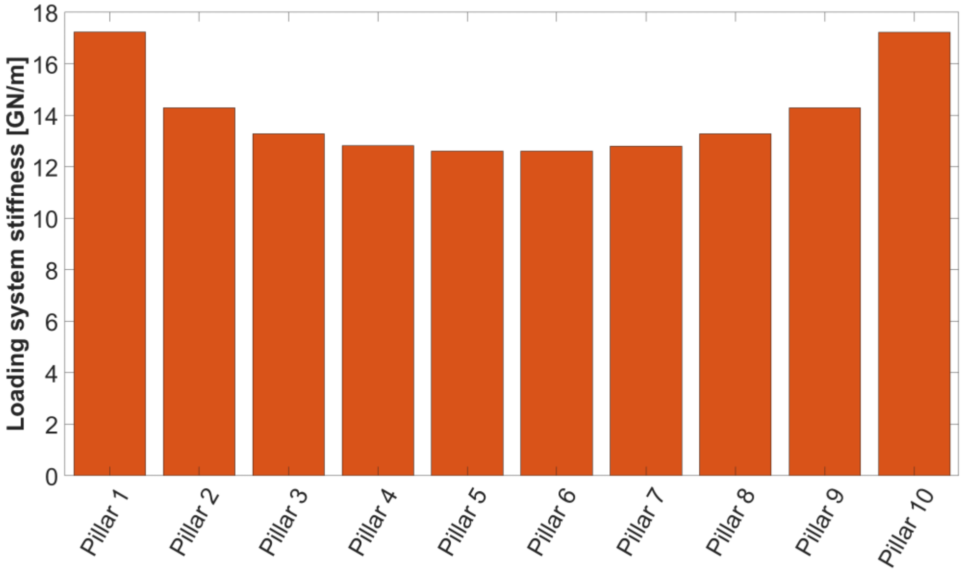


Figure 121: Loading system stiffness at the position of individual pillars inside the considered mining panel.

6.1.3.2.2 Influence of rock mass properties

The influence of the elastic properties of the rock mass on the loading system stiffness is outlined by varying the Young's modulus. Considered Young's moduli are 5 GPa, 10 GPa, 20 GPa, 40 GPa and 60 GPa. The mining panel has the same width of 105 m, comprises ten pillars with a width of 5 m and a height of 5 m and the excavations between pillars have a width of 5 m. The loading system stiffness is shown in Figure 122 for an edge pillar and a center pillar; compare Figure 120. These two pillars are chosen, because the loading system is the stiffest and softest, respectively, for these pillars.

Figure 122 outlines that the elastic properties of the rock mass have a significant influence on the loading system stiffness. The loading system stiffness for both the edge pillar and the center pillar is lowest for the softest rock mass conditions and the loading system stiffness increases with increasing Young's modulus of the rock mass. Due to the linear elastic rock mass behavior this increase of the loading system stiffness is linear. The increase is faster for the edge pillar than for the center pillar.

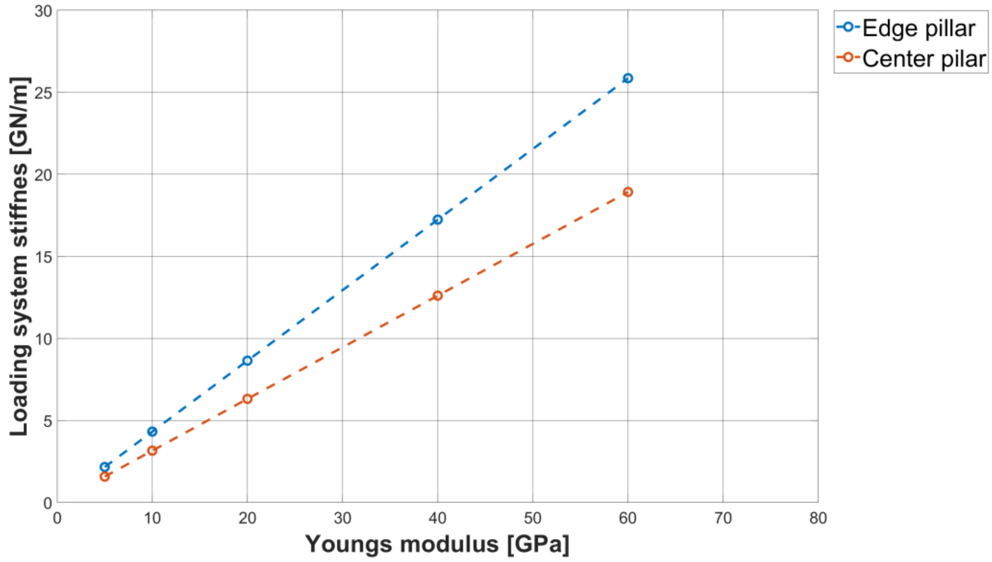


Figure 122: Loading system stiffness for edge and center pillars inside the considered mining panel for varying elastic rock mass properties

Besides the influence of the elastic properties of the rock mass the presence of large, distinct discontinuities influences the loading system stiffness. In most instances their presence reduces the loading system stiffness significantly. Three examples are therefore given in Figure 123. In situation (a) there are no large discontinuities prevailing and the rock mass bridges the panel. This is the situation, which has been investigated numerically. In situation (b) two large discontinuities affect the bridging capabilities of the rock mass. The loading system stiffness is principally reduced. The properties of the large discontinuities have a significant impact on this reduction. The weaker the discontinuities are, the larger is this reduction. Under the assumption that these discontinuities do not have any strength the loading system stiffness is infinitely soft. This represents a dead-weight loading situation. In situation (c) a single large discontinuity intersects the rock mass and changes the bridging characteristics. The intersecting discontinuity decreases the loading system stiffness. The changed bridging characteristics can be demonstrated well by comparing the maximum deflection of a beam, which is clamped at both ends, and of a beam, which is clamped at one end only. Both beams are loaded by a constant line load p. The span of the beam, which is clamped at both ends is S_{beam} and the span of the beam, which is clamped at one end, is $S_{beam}/2$. The Youngs' modulus (E) and the moment of inertia (I_{beam}) of both beams are the same. This situation reflects a beam, which is cut into two beams at half span. Equation 15 shows the maximum deflection (D_{beam}) of the beam, which is clamped at both ends. The maximum deflection is at half span of the beam. Equation 16 shows the maximum deflection of the beam, which is clamped at one end only. The maximum deflection occurs at the free end of the beam. The comparison shows that the maximum deflection of the beam, which is clamped at one end only, is three times larger than the maximum deflection of the beam, which is clamped at both ends. As the deflection for the same load is larger, the stiffness of the loading system comprised of the beam, which is clamped at one end only, is lower. The difference in the maximum deflection increases further, if the beam is not cut into two beams at its half span. This situation is illustrated in Figure 123c.

$$D_{beam} = \frac{1}{384} * \frac{p * S_{beam}^4}{E * I_{beam}}$$

Equation 15: Maximum deflection of a beam, which is clamped at both ends.

$$D_{beam} = \frac{1}{128} * \frac{p * S_{beam}^4}{E * I_{beam}}$$

Equation 16: Maximum deflection of a beam, which is clamped at one end only.

Besides large distinct discontinuities fracturing and failure of rock mass, which forms the loading system, have an impact on the loading system stiffness. Fracturing and failure of rock mass reduce in general the bridging capability and thus the loading system stiffness is decreased. The extent of mine workings and the span of panels are critical. The larger the extent or the larger the span is, the more likely rock mass fracture and failure become.

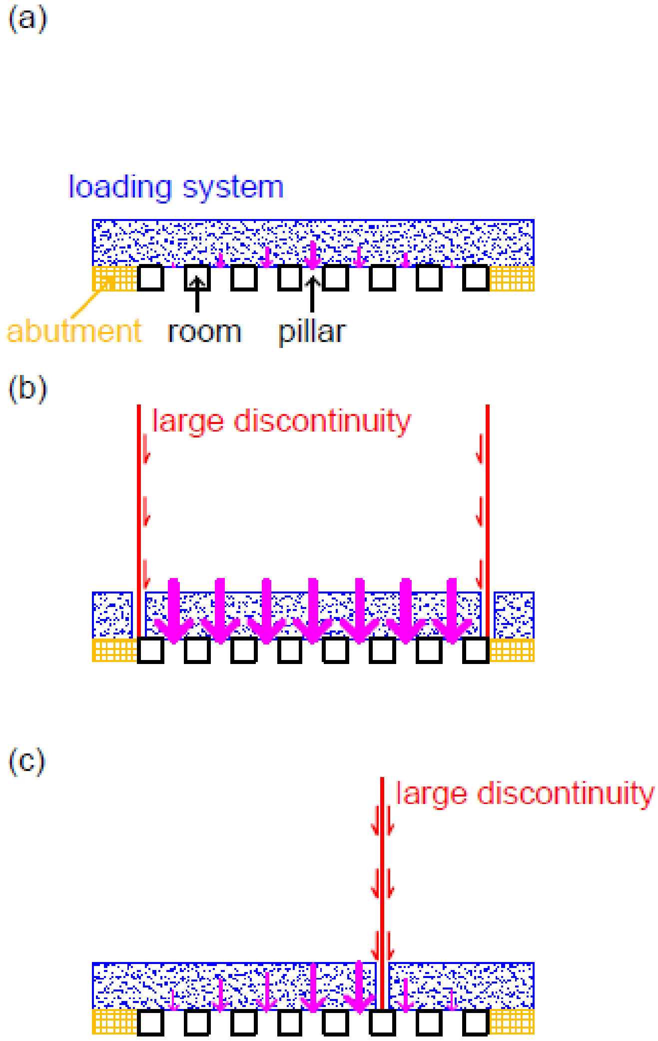


Figure 123: Influence of large discontinuities on loading system stiffness for a room and pillar mining panel; (a) absence of large discontinuities and rock mass (loading system) bridging panel, (b) two large discontinuities preventing bridging of the panel, (c) one large discontinuity changing the mode of bridging; the thickness and size of the pink arrows indicate the deformation of the loading system above pillars.

Overall, the reduction of bridging capabilities of the rock mass because of large distinct discontinuities or because of rock mass fracture and failure is important, because it can change the prevailing loading system and because it can affect the stability of structures (pillars) considerably. The loss of the bridging capabilities increases first the deformations of the loading system and hence the stresses acting inside structures (pillars), which are loaded by the system; compare section 6.1.3.1. Second, the loading system stiffness is reduced. These are circumstances, which promote failure of structures (pillars) and which increase the likelihood of unstable failure. The reduction or loss of the bridging capabilities of rock mass is particularly critical, if it occurs unexpectedly and suddenly. This could be the case, when strong, competent rock mass formations in the hangingwall break because of ongoing mining activities, or when mining advances through large, distinct discontinuities.

6.1.3.2.3 Influence of the panel span

The influence of the panel span on the loading system stiffness is shown by varying the number of pillars inside a panel. The pillar and excavation dimensions are constant and each 5 m in height and 5 m in width. The considered number of pillars in a panel are 4, 7, 10, 20 and 30. The corresponding panel spans are 45 m, 75 m, 105 m, 205 m and 305 m. The loading system stiffness is determined for the edge pillar and center pillar of each panel, because the loading system is stiffest and softest, respectively, for these pillars. Figure 124 shows that the calculated loading system stiffness for the edge pillar and center pillar as well as trends in the loading system stiffness as dashed lines. The loading system stiffness decreases with increasing number of pillars in the panel and hence with increasing panel span. The reduction of the loading system stiffness is much more significant for the center pillars and the loading system stiffness seems to level out to a constant magnitude at larger panel spans. The loading system stiffness for the edge pillar is only reduced slightly with increasing panel span and it remains at a comparatively high magnitude even at larger panel spans.

The decreasing loading system stiffness for center pillars with increasing panel spans can be critical for stable pillar layouts, if the pillar strength is exceeded, because the likelihood of unstable pillar failure increases. In contrast, for crush pillar layouts, where pillars crush close to or at the panel boundaries, the increasing panel span is not as critical as for stable pillar layouts, because the loading system stiffness at the panel boundaries remains relatively constant.

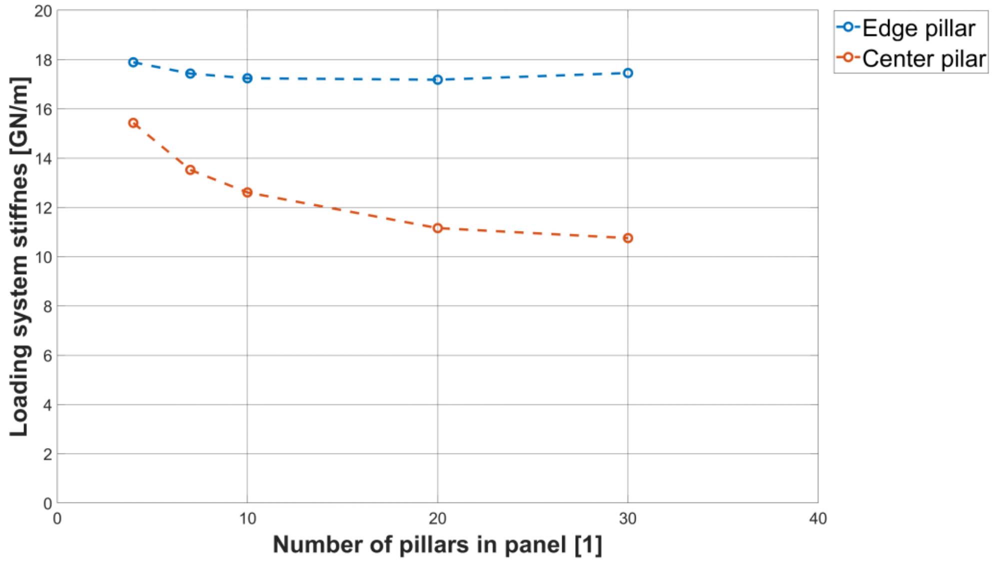


Figure 124: Influence of panel width on the loading system stiffness for an edge pillar and a center pillar; the calculated loading system stiffness is represented as circle and the trends in loading system stiffness are represented as dashed lines.

6.1.3.2.4 Influence of large barrier pillars separating neighboring excavations

Large barrier pillars are commonly left between neighboring mining panels. The purpose of these large barrier pillars is to separate neighboring mining panels so that potential failures in a mining panel are constrained to a single panel and so that these failures cannot spread out over larger areas. Furthermore, large barrier pillars can improve the stability of the mine, because they can reduce the stresses acting on pillars inside individual panels and because they can have a positive impact on the bridging capabilities of the rock mass by limiting panel spans.

The influence of large barrier pillars on the loading system stiffness is shown on basis of three neighboring mining panels with each seven pillars and pillar and excavation dimensions of 5 m in height and 5 m in width. The neighboring panels are separated by barrier pillars of 30 m width; compare Figure 125. The pillars, for which the loading system stiffness is calculated, and their corresponding names are outlined in Figure 125. The loading system stiffness is calculated for the edge pillars in panel 1 and panel 2 and for the center pillars in panel 1 and panel 2. Moreover, the loading system stiffness for the barrier pillar between panel 1 and panel 2 is derived.

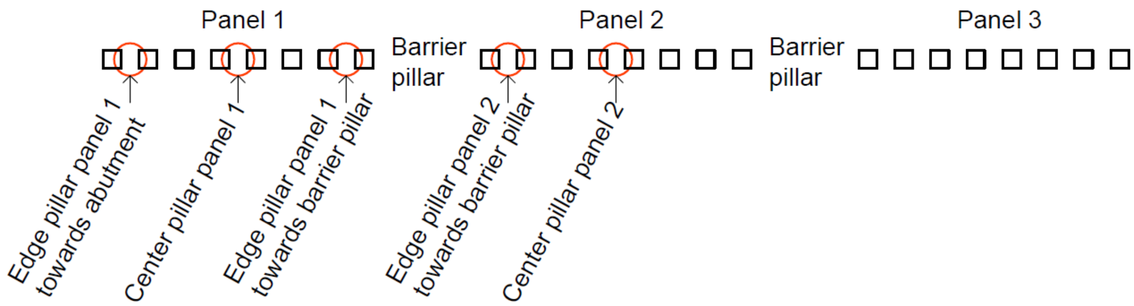


Figure 125: Three adjacent mining panels separated by barrier pillars in a vertical cross-section; the positions of pillars, for which the loading system stiffness is calculated, and their corresponding names are outlined.

The calculated loading system stiffness is provided in Figure 126 and compared with the loading system stiffness of the edge and center pillar of an isolated panel with 7 and 30 pillars, respectively. The isolated panel with 7 pillars corresponds to the span of each of the panels separated by the barrier pillars. The isolated panel with 30 pillars has approximatively the same span as the system of three panels separated by the two barrier pillars. The results show:

- Edge pillars: The loading system stiffness for the edge pillar of panel 1, which is located closest to the abutments of the three mining panels, is comparable to the loading system stiffness for the edge pillars of isolated panels with 7 and 30 pillars. However, the loading system stiffness for the remaining edge pillars, which are situated near the barrier pillar, is significantly lower.
- Center pillars: The loading system stiffness for the center pillar in panel 1 is higher than for the center pillar in panel 2. Moreover, the loading system stiffness for the center pillar in panel 1 is even higher than for the edge pillar in panel 1, which is situated near the barrier pillar. The comparison with the center pillars in an isolated panel with 7 and 30 pillars shows that the loading system stiffness for the center pillar in an isolated panel with 30 pillars is approximatively equal to the loading system stiffness for the center pillar in panel 2. The loading system stiffness for the center pillar in an isolated panel with 7 pillars is higher than that for the center pillar in panel 1 and panel 2. From this observation can be concluded that the barrier pillars do not have a significant influence on the loading system stiffness for panel pillars. The loading system stiffness for panel pillars is highest closest to the abutments of the three mining panels, it decreases with distance from the abutments and it reaches comparable magnitudes as for a panel without barrier pillars of similar span distant from the abutments.
- Barrier pillar: The loading system stiffness for the barrier pillars is highest. In comparison with the panel pillars near the barrier pillars the loading system stiffness for barrier pillars is considerably higher.

In summary, the barrier pillars do not change the loading system stiffness for individual panel pillars and the overall span of all three panels (extent of mining activities) is critical for the loading system stiffness for pillars. Hence, the loading system stiffness depends mainly on the overall extent of mining, whereas panel and barrier pillars have only a minor influence on the loading system stiffness. However, the loads and deformations in the mine are influenced by the barrier pillars considerably. Moreover, an important role of barrier pillars is to separate neighboring panels so that a potential failure inside a mining panel is constrained to the affected panel. Furthermore, barrier pillars can have a positive effect on the loading system. Barrier pillars limit provide regional support to loading systems. Hence, they improve the stability of loading systems and reduce the potential of fracture and failure in the rock mass forming the loading system. Thereby, barrier pillars can prevent a deterioration of loading system characteristics. Moreover, large distinct discontinuities, which can have an adverse impact on the loading system, can be incorporated in barrier pillars. These indirect effects of barrier pillars on the loading system are not considered in the conducted calculations, which are based on a linear elastic rock mass behavior.

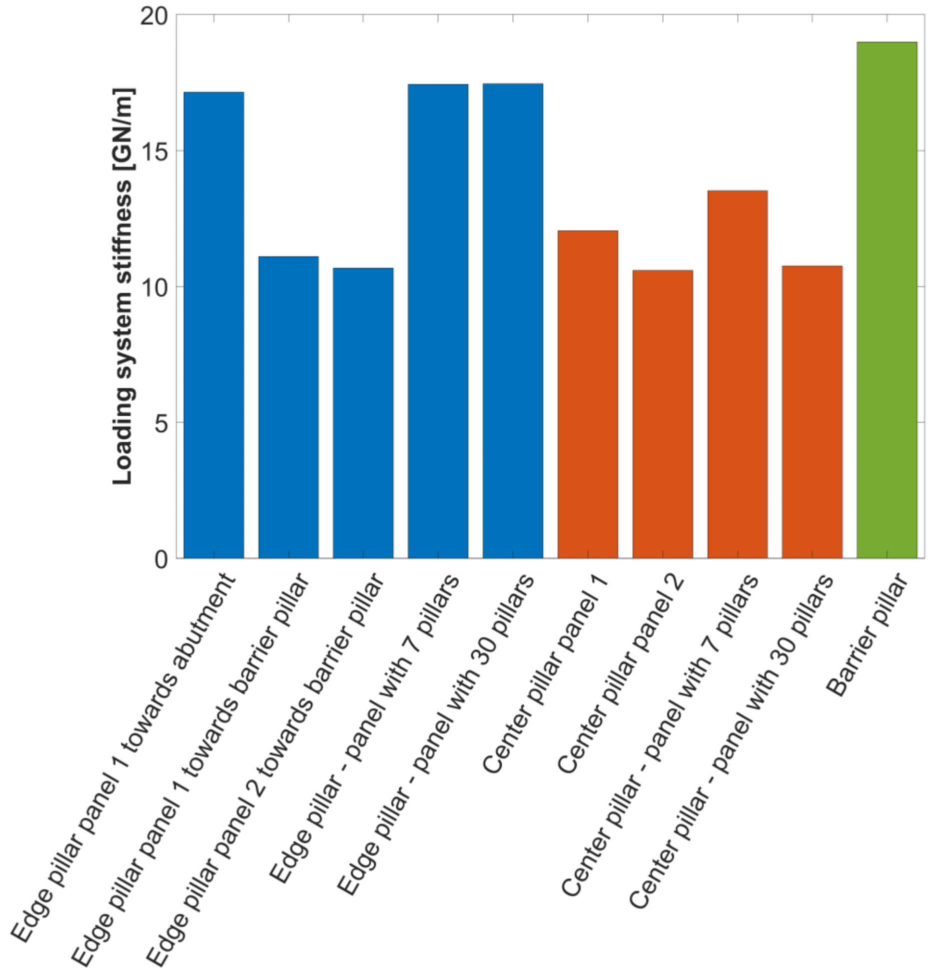


Figure 126: Comparison of the loading system stiffness for panel and barrier pillars, which are located in three adjacent panels separated by barrier pillars, with the loading system stiffness for panel pillars in individual, isolated panels

6.1.3.2.5 Summary loading system stiffness

The analyses of a number of relevant situations in practice outline that the loading system stiffness depends strongly on the prevailing rock mass conditions and the mine layout.

Furthermore, the loading system stiffness of a mine layout varies spatially. Important aspects for the proposed stress management concept are that

- the loading system stiffness is highest near abutments and decreases with increasing distance from the abutments.
- the loading system stiffness decreases with increasing extent of extraction areas in extraction areas but it remains relatively constant near abutments.
- the rock mass properties, particularly large, weak discontinuities, and fracture and failure in the rock mass forming the loading system can have adverse effects on the loading system stiffness and they can reduce the loading system stiffness considerably, if the bridging capabilities are lost.
- the utilization of large barrier pillars does not have a significant direct effect on the loading system stiffness, however barrier pillars can have a positive effect on the overall stress situation and the overall stability of the mine.

Besides the mine layout the mining sequence is critical, because it governs the loading system stiffness from a temporal perspective. Furthermore, it has to be considered that the loading system stiffness decreases in most instances with ongoing mining activities, because the extent of extraction areas is increased.

6.1.3.3 Summary of loading system properties

In the foregoing sections, the magnitude and direction of deformations of loading systems have been briefly described and the stiffness of loading systems has been discussed for a number of relevant situations in practice. Therefore, illustrative examples and linear elastic numerical simulations were used. Important findings are that the mine layout has a considerable influence on the characteristics of the loading system and thus that the mine layout can be utilized to alter the characteristics of the loading system. Another important parameter is the extent of mining, namely the loading system stiffness decreases in general, as the extent of mining increases. This circumstance implies that at an advanced stage of mining a comparatively soft loading system must be expected. This is also a stage, where the rock pressure situation becomes more difficult to manage, because large portions of the deposit were already extracted. The regional mine layout and mining sequence become particular important in this advanced stage of extraction; compare also section 6.1.4.2. Furthermore, the rock mass properties have a prominent influence. Particularly critical are large, weak discontinuities, as well as fracturing and failure of rock mass, which forms the loading system. These conditions can either result in rather soft loading systems or they can change the loading system characteristics significantly and suddenly.

6.1.4 Time

The first three main elements, excavation, pillar and loading system, have a defined spatial extent as well as defined physical effects on the prevailing mining environment. Thus, the three main elements, excavation, pillar and loading system, can be referred to as the mine layout. The main element time differs from these other three elements, because the time element does neither have a defined spatial extent nor in the case of hard rock masses a defined physical effect on the prevailing mining environment. The time element defines the order, in which the other main as well as auxiliary elements are created, applied, extended etc. For this reason, the time element is responsible for the temporal occurrence of the physical effects of other elements. The time element is also referred to as the mining sequence.

The time element adds a fourth dimension to the proposed stress management concept. The first three dimensions are defined by the position, size, orientation etc. of the other main elements and the location and spatial extent of their physical effects. Considering the time as being the fourth dimension, highlights first its importance and second outlines the relativity and variability of physical effects of the remaining elements. For the successful implementation of the stress management concept the physical effects, which are responsible for the element functions, must be provided at a certain time and at a certain location. For this the time element is central.

In the following sections, situations, which are of relevance in practice and of relevance for the implementation of the stress management concept, are outlined and discussed. These situations highlight further the importance of the time element. The first situation outlines the relation between excavations of large extent, such as extraction excavations or extraction areas, and excavations of small extent, such as infrastructure excavations. The second situation outlines the effects of increasing the spatial extent of extraction areas. Therefore, a single isolated extraction area, which is increased in width, two adjacent extraction areas separated by a pillar, which are increased in width, and two adjacent extraction areas separated by a pillar, which are increased in height, are considered

6.1.4.1 Creating an infrastructure excavation near an extraction excavation

Infrastructure excavations are required to access extraction excavations and extraction areas. The spatial extent of the stress changes caused by extraction excavations and extraction areas increases with the dimensions of extraction excavations and extraction areas; compare section 6.1.1.1. As infrastructure excavations are considerably smaller than extraction excavations or extraction areas, the spatial extent of stress changes caused by extraction excavations and extraction areas is considerably larger. Accordingly, the extraction excavations and the extraction areas determine the stress state at the positions of the smaller infrastructure excavations. Contrary, infrastructure excavations do not influence the stress situation at the position of extraction excavations and extraction areas. Relevant aspects in practice are the relative position of an infrastructure excavation to extraction excavations and extraction areas as well as the sequence, in which the excavations are created.

The impact of extraction excavations and extraction areas on infrastructure excavations is outlined on basis of an elongated, rectangular, infinitely long, flat-lying, completely mined extraction excavation, which is referred to as stope in the following, and an infrastructure excavation, which is referred to as tunnel, situated below the stope. The tunnel orientation is out-of-plane. Figure 127 shows the final geometry of the completely mined stope and the positions of the tunnel. Two tunnel positions are shown. Position 1 is below the middle of the stope and position 2 is below the abutment of the stope. As shown in section 6.1.1.1, the abutment areas of the stope are highly stressed, whereas a stress shadow forms in the middle below the stope. Consequently, the tunnel in position 1 is protected from high stress magnitudes and the tunnel in position 2 is subjected to high abutment stresses. This example highlights the impact and importance of the relative position of the tunnel to the stope.

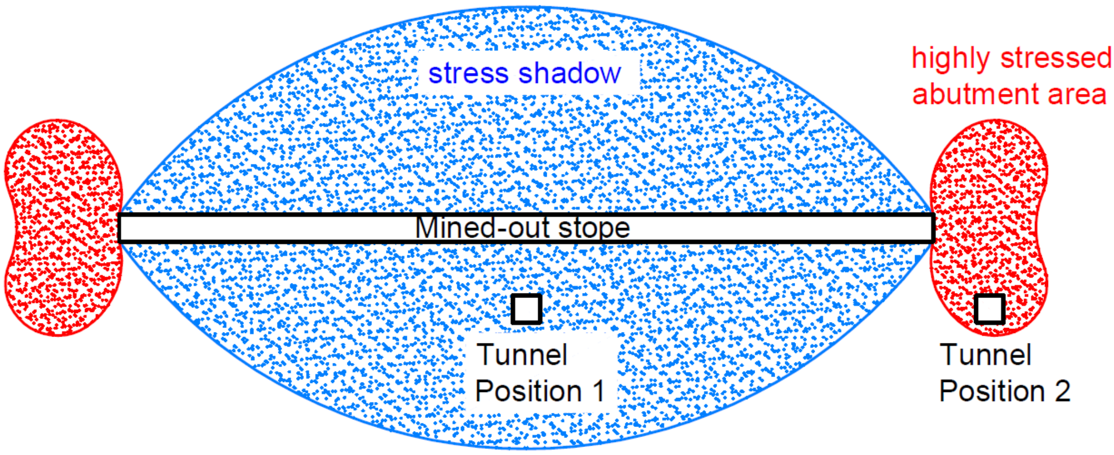


Figure 127: Vertical cross-section of an elongated, rectangular, flat-lying, mined-out stope with tunnels at positions 1 and 2

The relative position of the tunnel to the stope is not static, because mining advances and hence the position and extent of low and high stress magnitudes change over time. This effect of the mining sequence is highlighted for the situation outlined in Figure 127 for the tunnel at position 1. The stope is extracted in several steps and the stope width is increased by 10 m in each step. Two extraction sequences are considered, namely from left to right (Figure 128a) and from the center outwards (Figure 128b). Step 0 refers to the primary state, before stoping commences, and step 15 to the final state, after the stope was completely extracted. The major and minor principal stress perpendicular to the tunnel axis for a tunnel located at position 1 are calculated with FLAC3D. A slice model with a thickness of 1 m, which represents an infinitely long stope, is used therefore. The distance, at which the tunnel is situated below the stope, is varied and it is 10 m, 20 m, 30 m, 40 m and 50 m respectively. The tunnel is not modelled explicitly, because the resultant stresses at the position of the tunnel are governed by the stope and because the tunnel does not have a significant influence on the general resultant stress distribution. Instead, the major and minor principal stresses are picked at the position of the tunnel. The primary stresses are 54 MPa in vertical and 27 MPa in horizontal direction. The rock mass is modelled linear elastic with a Young's modulus of 40 GPa and a Poisson ratio of 0.25.

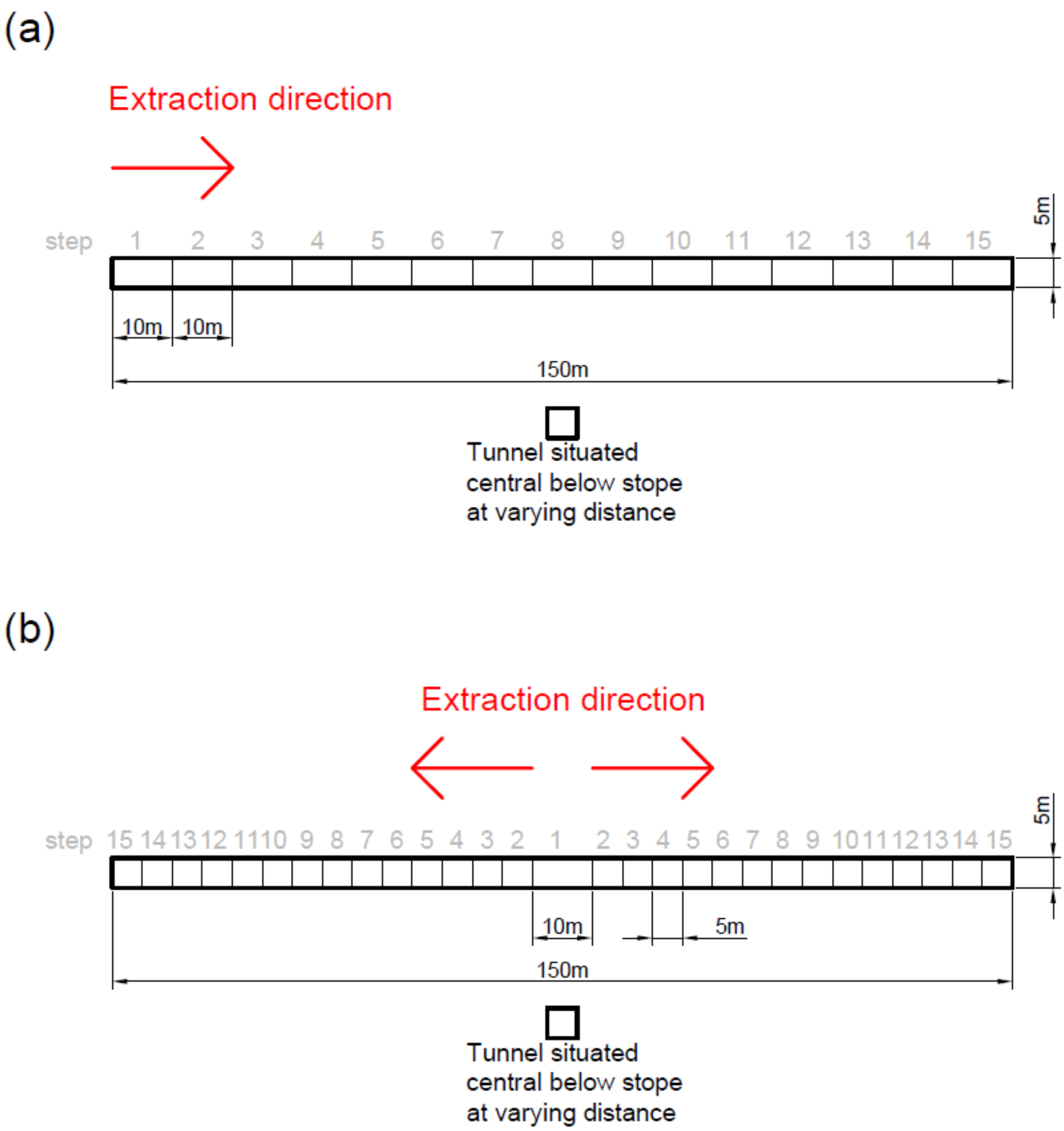


Figure 128: Vertical cross-section showing considered stope extraction sequences for analyzing the impact of the mining sequence on a tunnel located below the stope; (a) first sequence with stope advance from left to right; (b) second sequence with stope advance from center outwards

The major and minor principal stress perpendicular to the tunnel axis as well as RCF values for a uniaxial compressive strength of rock of 150 MPa and a degradation factor F of 0.75 are outlined for each extraction step in Figure 129 and Figure 130. Regarding the RCF values it is remarked that they are not appropriately describing conditions for the tunnel, which is situated 10 m below the stope, in the two sequences after step 8 and 9, respectively, because significant tensile stresses occur at the position of the tunnel. These tensile stresses change the failure mode of the tunnel, which is anticipated in the RCF criterion. Moreover, these tensile stresses are the consequence of the linear elastic rock mass behavior and they do usually not occur in-situ because of rock mass fracture and failure.

The stress situation and the RCF values at the considered tunnel positions show:

- For the stope extraction sequence from left to right (Figure 128a, Figure 129a, Figure 130a) the principal stresses at the position of the tunnel correspond to the primary stresses, as stoping commences. As stoping approaches the tunnel (step 3) the stress magnitudes start to increase and they become very high, when the stope is closest to the tunnel (step 7), because the tunnel is then situated in the abutment of the stope. As a consequence, tunnel conditions deteriorate rapidly, which can be seen by the strongly increasing RCF values. After the stope face passed by the position of the tunnel (step 8), the stress magnitudes as well as the RCF values begin to drop. After the tunnel was completely overstoped (step 9), the tunnel is situated in the stress shadow provided by the stope. However, the tunnel was already exposed to high abutment stresses, which can cause significant damage to the tunnel. Accordingly, the beneficial effect of the stress shadow on tunnel stability, once the tunnel was overstoped, is lower compared to the situation, when the tunnel is developed in the stress shadow, after the stope was extracted. Besides high stresses the tunnel is also exposed to significant energy changes and the associated release of seismic energy, while it is overstoped. The analysis shows furthermore that the vertical distance between the tunnel and stope is critical. The closer the tunnel is situated below the stope, the higher are the stresses near the tunnel and the more pronounced are the stress changes during overstoping.
- For the stope extraction sequence from center outwards (Figure 128b, Figure 129b, Figure 130b) the tunnel is already overstoped in step 1. Consequently, the tunnel is not exposed to high abutment stress magnitudes and from step 1 on already located in the stress shadow, which is provided by the stope. As stoping commences, the stress magnitudes drop further and the RCF values show that the tunnel conditions improve significantly. As the tunnel is not exposed to high abutment stresses, the potential damage to the tunnel resulting from abutment stresses is absent and the tunnel can benefit better from the provided stress shadow compared to the extraction sequence from left to right. The vertical distance between the tunnel and stope has again an impact on the tunnel. The closer the tunnel is situated to the stope, the quicker stress magnitudes and RCF values drop and the lower are the stress magnitudes and RCF values, after the stope was completely extracted.

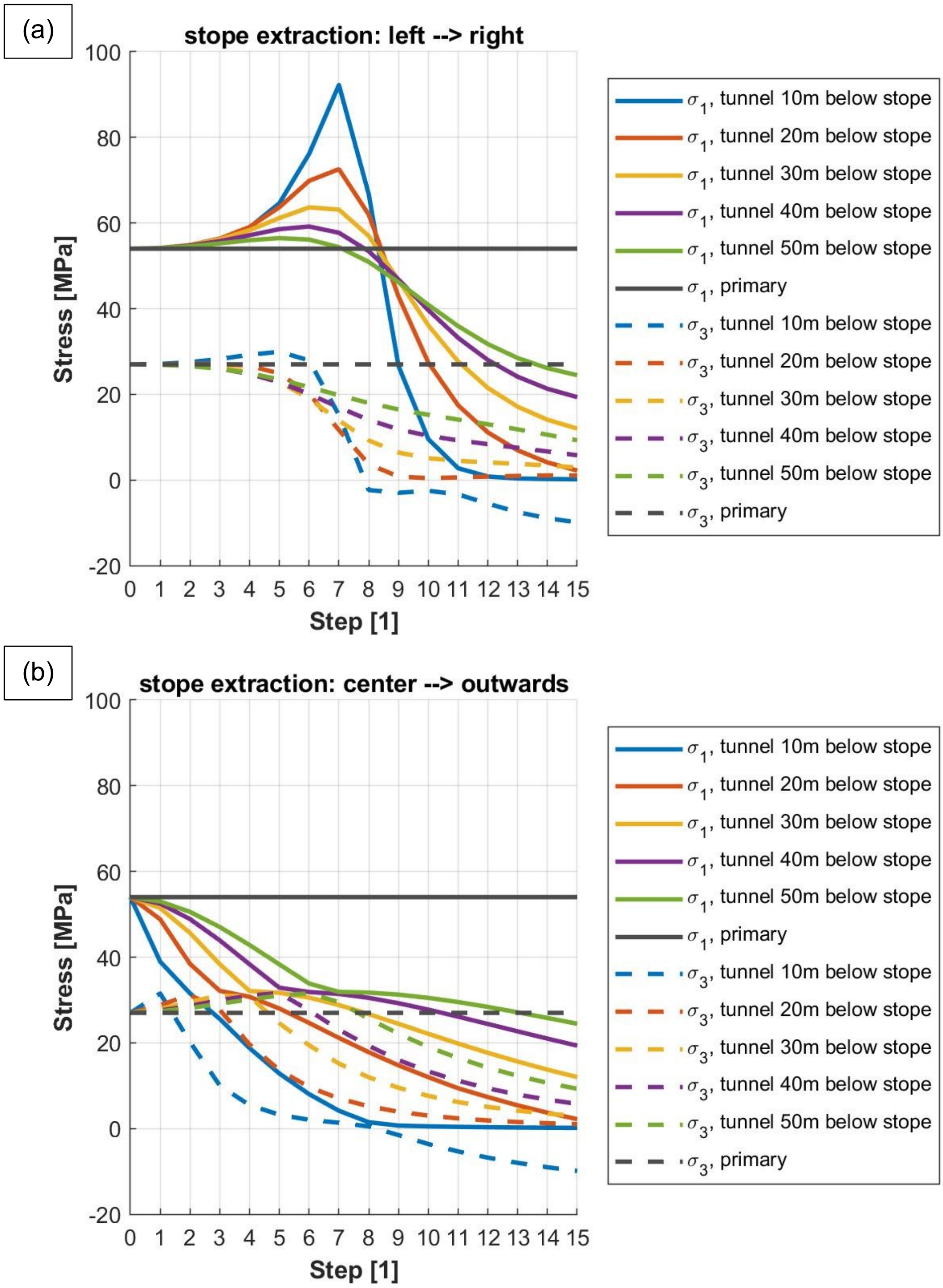


Figure 129: Major and minor principal stresses perpendicular to the tunnel axis as a function of stope extraction steps for a tunnel situated below a stope (a) for stope extraction from left to right and (b) for stope extraction from the center outwards

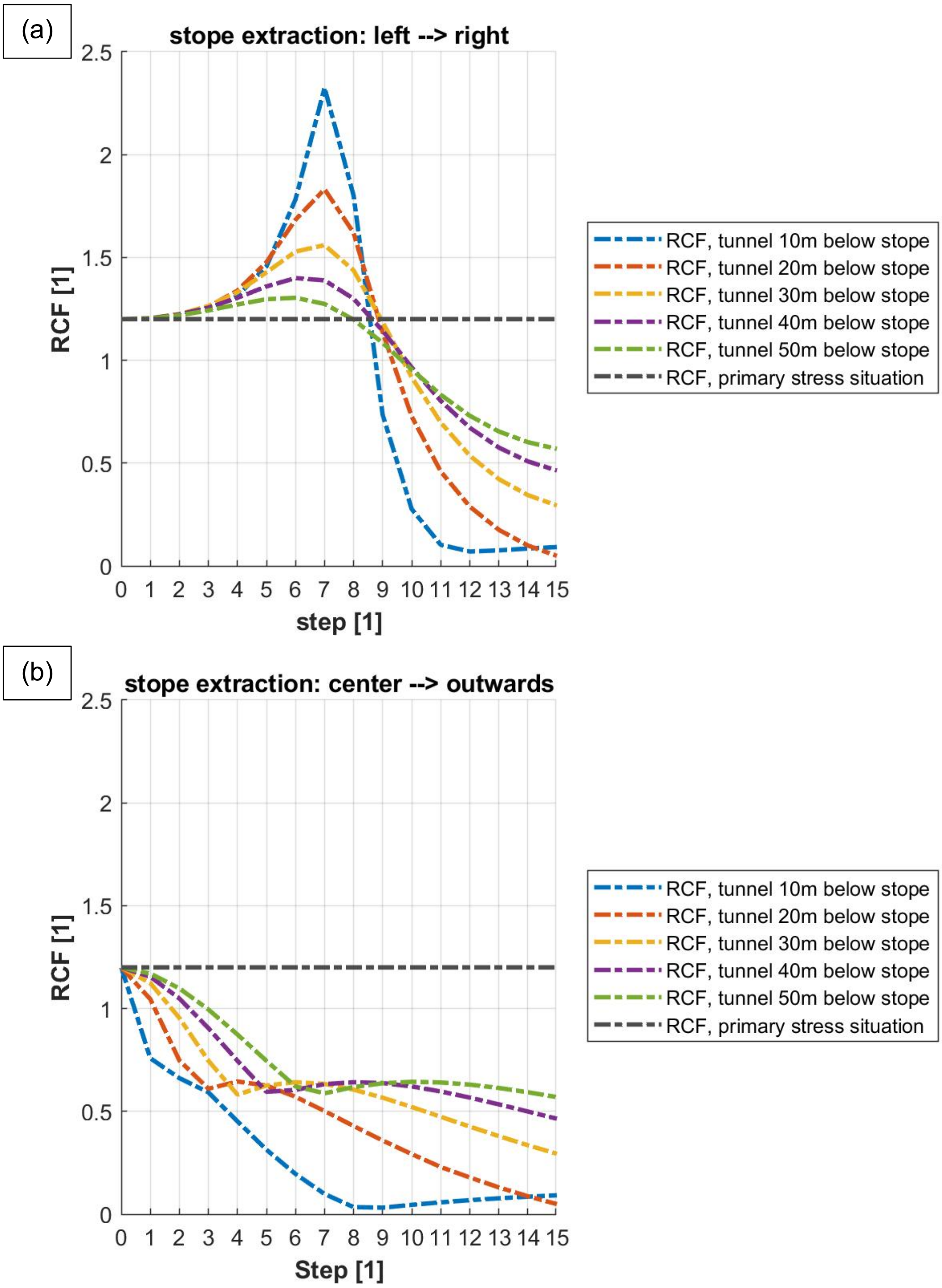


Figure 130: RCF values as a function of stope extraction steps for a tunnel situated below a stope (a) for stope extraction from left to right and (b) for stope extraction from the center outwards

In summary, the outlined examples show that already developed infrastructure can be exposed to extreme stress conditions and mining-induced seismicity, if extraction fronts and the associated abutment areas pass by. The distance between the infrastructure and the extraction area and the time of overstoping are decisive, namely:

- If extraction areas are already advanced and if their corresponding extraction fronts must pass by infrastructure because of for example logistical or operational reasons, the infrastructure should be placed distant from these extraction areas to avoid damage.

- If extraction areas pass by infrastructure, when production commences, the investigations showed that the infrastructure benefits already at an early stage from stress shadows and that it is not exposed to abutment areas. In this case the infrastructure can also be situated close to extraction areas.

Probably, the preferable option from a rock mechanics perspective is to develop infrastructure delayed in the stress shadow, which is provided by the stope. In this case, the tunnel can benefit best from the stress shadow. The stress magnitudes at the time of tunnel development are low and stress magnitudes do not change considerably because of ongoing stoping activities. However, one specific aspect to consider is that the rock mass in the abutment areas of the stope can be significantly damaged due to the prevailing high stress magnitudes and specific fracture orientations and fracture patterns can be generated. The characteristics of the damage and the generated fracture orientations depend on the prevailing mining environment, the stope layout and the stoping sequence. As stoping advances, these damaged zones "move" into the mined-out areas and hence they are located in the de-stressed zones. For tunnels, which are subsequently developed inside the stress shadow, this damage zone around the stope has to be considered in the design of the tunnel position, cross-section and orientation as well as in the design of the tunnel support and reinforcement.

6.1.4.2 Increasing the spatial extent of extraction areas

6.1.4.2.1 Isolated extraction area being increased in width

The consequences of increasing an extraction area in width are discussed on basis of an isolated, elongated extraction area. The extraction area is comprised of several excavations separated by crush pillars, which provide local support to the hangingwall and footwall rock mass. Due to the low residual strength and the corresponding low average pillar stress in crush pillars the crush pillars do not diminish the stress shadow, which is created by the extraction area. The surrounding hangingwall and footwall rock mass constitute the loading system. As shown in Figure 131, the width of the extraction area is increased from initially 3 pillars to finally 10 pillars. The resulting consequences related to the prevailing main elements are qualitatively summarized below. The analysis related to the physical effects of the main elements, which were derived in the foregoing, corresponding sections, form the basis for this qualitative outline. The effects are sketched in Figure 131.

- The abutment stress magnitudes of the extraction area increase considerably.
- The extent of the de-stressed zone below and above the extraction area increases.
- The deformations of the loading system and thus pillar deformation increase.
- The stiffness of the loading system decreases.

The advantage of increasing the width of the extraction area from a stress management perspective is clearly the increasing extent of the stress shadow. The remaining effects, particularly the rising abutment stress magnitudes and the decreasing loading system stiffness, are principally disadvantageous, because they favor fracture and failure.

Moreover, fracture and failure are more likely to be unstable. In conclusion, this instance implies that rock pressure phenomena and rock pressure problems are more likely to occur at an advanced stage of mining in or near an extraction area.

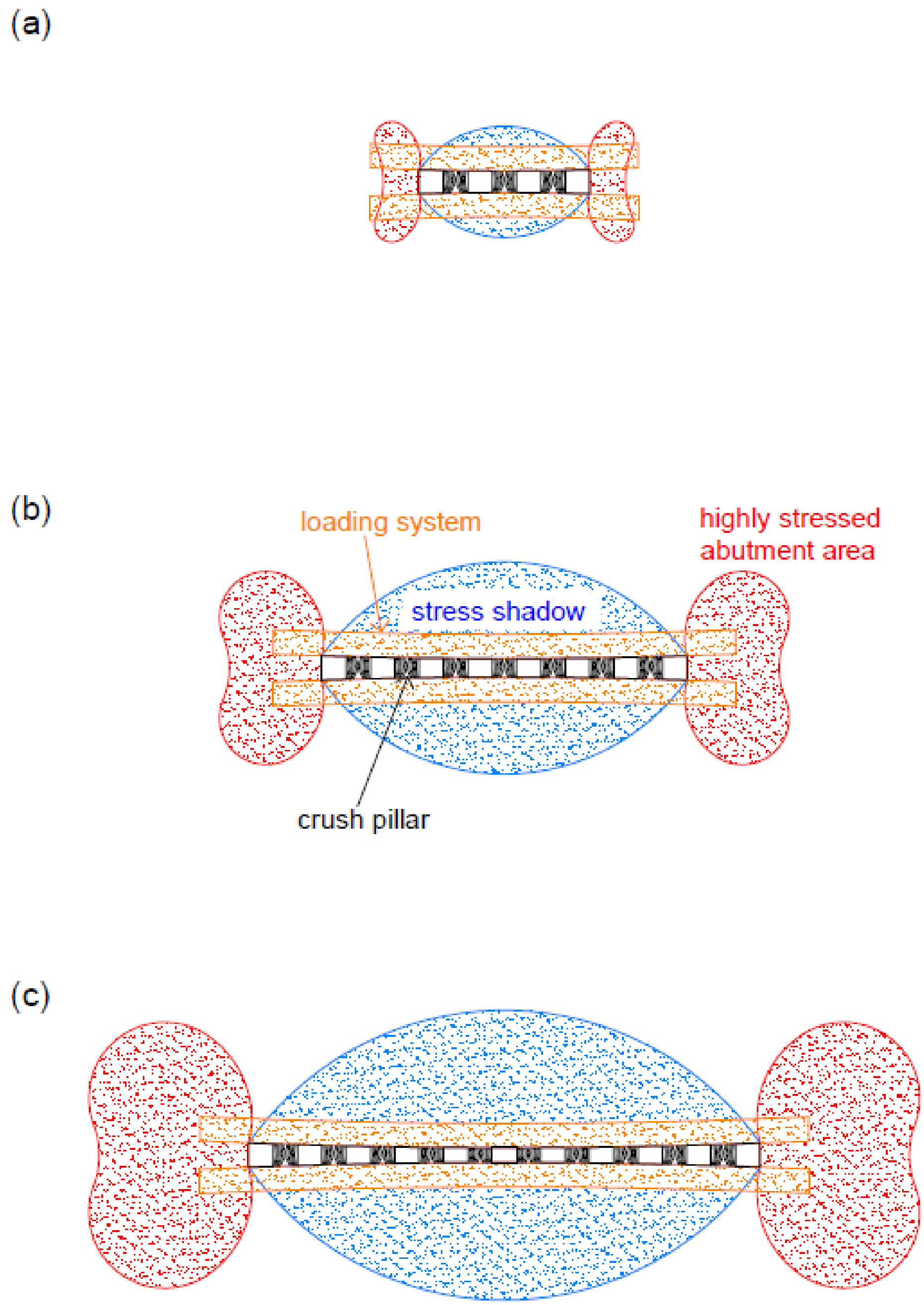


Figure 131: Vertical cross-section of an isolated extraction area comprised of excavations, crush pillars and the associated loading system; the width of the extraction area is increased; (a) width = 3 pillars, (b) width = 7 pillars, (c) width = 10 pillars; The corresponding effects related to the stress shadow, abutment stresses, deformations and loading system are sketched.

The considerations for increasing an isolated extraction area in width are also relevant for increasing the overall spatial extent mineral extraction. With increasing maturity of the mine the stress situation in structures, which transfer regional stresses, such as large, massive pillars, abutments and remnants, becomes principally adverse and prevailing stress magnitudes rise considerably. Moreover, the stiffness of the loading system of these stress transferring structures decreases. Hence, the rock pressure situation becomes in general most difficult to handle at an advanced stage of mining. Foresighted planning of the regional mine layout and regional mining sequence are central to handle the rock pressure situation at an advanced stage and to avoid the occurrence of rock pressure problems.

6.1.4.2.2 Two adjacent extraction areas separated by a pillar being increased in width

Adjacent extraction areas are commonly separated by strong, massive pillars. The consequences of different extraction sequences in adjacent extraction areas are outlined on basis of two extraction areas, which are separated by a massive pillar; compare Figure 132. Therefore, extraction areas are increased in width and three different regional mining sequences are considered, namely:

- Center – outside: In this sequence extraction commences in the center at the position of the massive pillar and advances away from the pillar. Hence, the pillar has already its final dimensions, after mining commenced.; compare Figure 132a. Extraction starts in both extraction areas at the same time.
- Outside – center: In this sequence extraction commences at the outer boundaries of the extraction areas and advances towards the pillar. The pillar reaches its final dimensions, after both extraction areas are completely mined; compare Figure 132b. Extraction starts in both extraction areas at the same time.
- Outside – outside: In this sequence extraction commences at the outer boundary of one extraction area, advances towards the pillar, leaves the pillar behind and then advances to the outer boundary of the second extraction area. The pillar is formed, after mining in the first extraction area finished and after mining in the second extraction area started. The pillar has already its final dimensions, after the pillar was formed; compare Figure 132c.

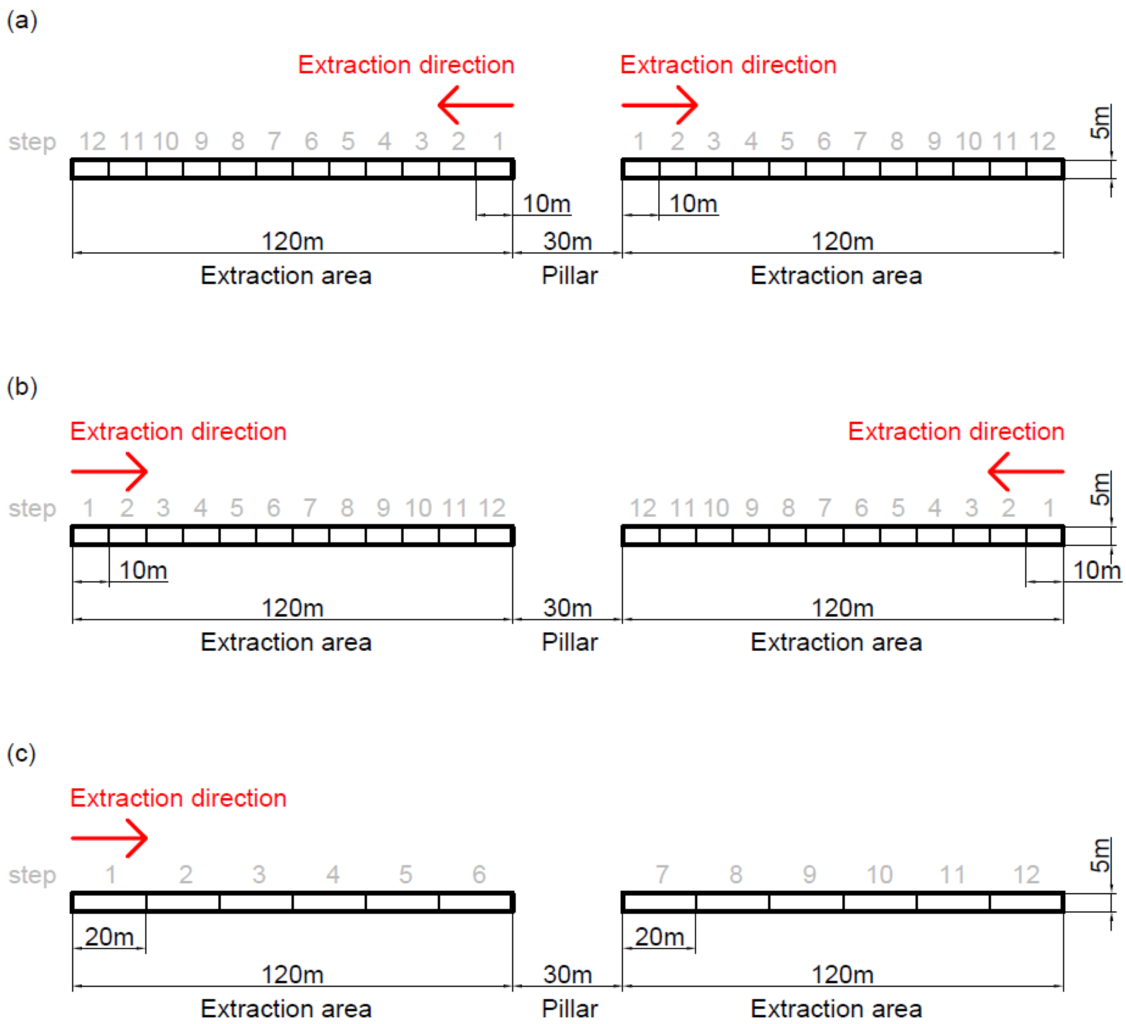


Figure 132: Vertical cross-section showing two adjacent extraction areas separated by a massive large pillar and considered regional mining sequences; (a) center – outside sequence; (b) outside – center sequence; (c) outside – outside sequence

Assuming an elastic rock mass behavior the final physical effects of all elements are the same, after both extraction areas are mined-out completely. The resultant stress distribution in the vicinity of the extraction areas is equal, the loading system stiffness of the massive pillar is equal and the pillar stress magnitudes are equal. However, there are distinct differences between the outlined sequences, how this final state is reached. These differences are discussed on basis of the average vertical stress magnitudes at the active (advancing) extraction face(s), the average vertical stress magnitudes at the passive (still standing) extraction face(s) and the average vertical pillar stress. The vertical stresses are most relevant, because the prevailing extraction areas disturb due to their geometry and orientation the primary vertical stress field strongest.

Numerical simulations with FLAC3D are conducted. The model is a slice model with a thickness of 1 m and thus the extraction areas are infinitely long. The extraction areas are flat-lying and have a height of 5 m and width of 120 m. The massive pillar between the extraction areas has a width of 30 m. Both extraction areas are mined-out with twelve steps, which results in 10 m and 20 m, respectively, to be extracted from an extraction area in each step; compare Figure 132. The primary stress state is 54 MPa vertical and 27 MPa horizontal. The rock mass is modelled linear elastic with a Young's modulus of 40 GPa and a Poisson ratio of 0.25.

The average vertical stress magnitudes at the active and passive extraction face and in the pillar are calculated by utilizing three measurement lines; compare Figure 133, which outlines the position of measurement lines for the considered sequences in step 8. The active extraction face is the extraction face of an extraction area, which is advanced in the next step. Contrary, the passive extraction face is the other face of the extraction area, which is not advanced in the next step. At the extraction faces 10 m long horizontal measurement lines at half height of the extraction areas are utilized for calculating the average vertical stresses. The average vertical pillar stress is calculated along a horizontal measurement line at half height of the actual pillar. For the analysis of the results it has to be noted that the pillar in the outside – outside sequence is only formed after step 6 and that the pillar for the outside – center sequence is initially very wide. Furthermore, there is no active extraction face in the outside-outside sequence in step 6, because the first extraction area is completely mined in step 6 and extraction commences then in step 7 in the second extraction area. This is also the reason that the passive extraction face moves from the first to the second extraction area in the outside – outside sequence in step 7.

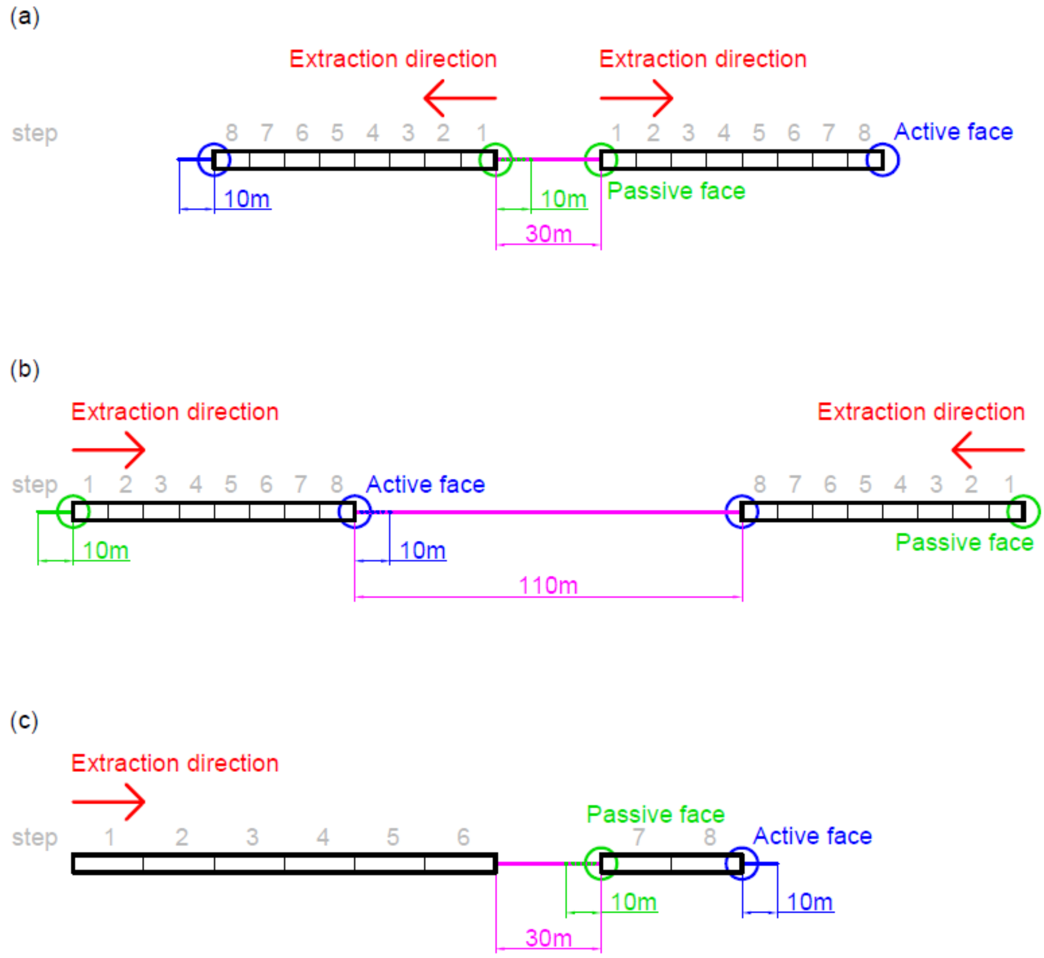


Figure 133: Position of the active and passive extraction faces in step 8 and position of measurement lines used for deriving the average vertical stresses in a vertical cross-section; the blue lines are the measurement lines at the active face; the green lines are the measurement lines at the passive face; the pink lines are the measurement lines inside the pillar.

The average vertical stresses at the active and passive extraction face and the average vertical pillar stress are displayed in Figure 134. The stresses for the different sequences show:

- Center – outside sequence: The stresses at the active and passive face as well as in the pillar increase continuously, as mining progresses. The reason for this is that the extent of the extraction areas is increased, which disturbs the primary stress field more strongly. The stresses at the passive face are throughout higher than at the active face. Besides the lower stresses at the active face an advantage of the center – outside sequence is that the highly stressed pillar is created behind the advancing extraction faces and that the pillar stresses build up gradually and slowly. Thus, active infrastructure is normally not required near the highly stressed pillar. Moreover, the stress inside the pillar builds up comparatively slowly and gradually.
- Outside – center sequence: At an early stage of extraction, the stresses at the active and passive face are approximatively equal and the stresses inside the pillar are relatively low. However, at an advanced stage of mining (step 7), at which the two extraction fronts approach each other, the stresses at the active face as well as in the pillar increase considerably. In comparison with the other sequences the outside – center sequence is disadvantageous. The stresses at the active face are in the initial stage of extraction only slightly lower, but more important the stress situation deteriorates rapidly at an advanced extraction stage. The stress magnitudes at the active face become considerably higher and the pillar stress increases drastically. Moreover, the highly stressed pillar is created ahead of the advancing extraction faces and the pillar width and hence the pillar strength are reduced continuously. Overall, these circumstances promote the (violent) failure of the pillar or (violent) failure in the abutments of the active extraction face. For this reason, the outside – center sequence is least preferable.
- Outside – outside sequence: The stresses at the active and passive face are equal, while mining takes place only in the first extraction area (until step 6). In comparison to the other sequences the stresses at the active and passive face are higher for the same mining step. Indeed, this circumstance is mostly related to the model, because in the outside – outside sequence the width of the extraction area is increased by 20 m in each step, whereas the width of the extraction areas in the other two sequences is increased only by 10 m in each step. Thus, the extraction area width for the outside – outside sequence is wider, while only one extraction area is mined, and the stresses at the face should be compared with the other sequences, when their extraction areas have the same width. The stresses at the active and passive face drop significantly, after the pillar was formed (step 7). Afterwards, the stresses at the active and passive face as well as in the pillar increase, as mining advances. The stresses at the active face are throughout lower than at the passive face. The outside – outside sequence shows that the pillar, which is formed behind the advancing extraction face, reduces the stress magnitudes in the active extraction area and at the active extraction face noticeably. Moreover, the highly stressed pillar is created behind the advancing extraction face and pillar stresses build up gradually and slowly.

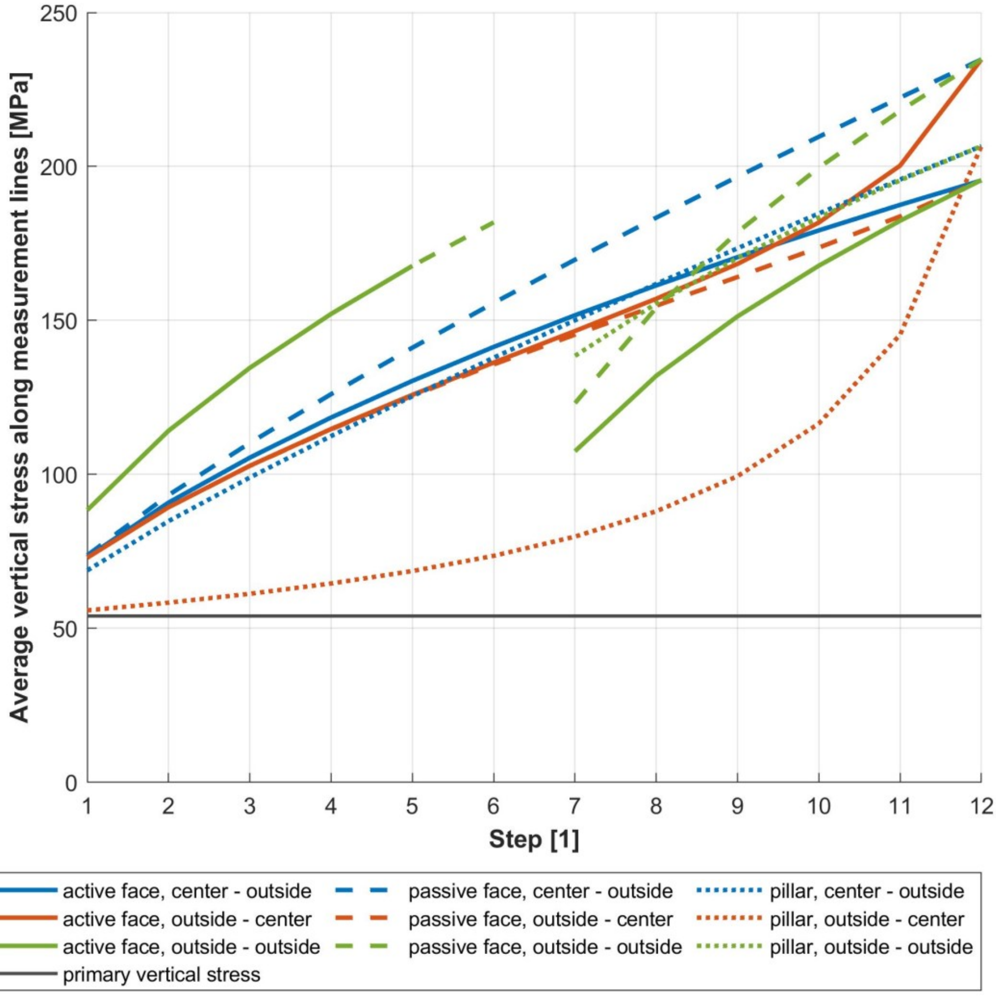


Figure 134: Comparison of the average vertical stresses at the active and passive extraction face calculated along considered measurement lines and the average vertical pillar stress for the three different extraction sequences

Besides the stresses in the pillar and at the extraction faces the loading system stiffness at the position of the massive pillar as well as the likelihood of an unstable pillar failure are of interest and discussed below qualitatively.

- In the center – outside sequence the pillar is formed, when extraction commences and it has already its final dimensions. The loading system stiffness at the position of the pillar is largest at the time, when the pillar is formed, and then gradually reduced, as extraction moves away from the pillar. Furthermore, the pillar stresses are lowest at the time of pillar formation and they increase with ongoing extraction. Consequently, the likelihood of a sudden, unstable pillar failure is lowest at the time of pillar formation, at which also active extraction faces are close-by. The likelihood of unstable pillar failure increases with advancing extraction. However, at these stages the active mining faces are no longer close-by the pillar.
- In the outside – center sequence the pillar reaches its final dimensions at the end of extraction. At this stage the loading system stiffness of the pillar is also softest. Moreover, the pillar stresses are highest. These two instances, first, facilitate pillar

failure and, second, promote unstable pillar failure. The circumstance that the active extraction faces are at the pillar walls at this stage is adverse. Moreover, the loading system stiffness at the active extraction faces is also softer, which instance promotes unstable rock mass failure at the active extraction faces.

- In the outside – outside sequence the pillar is formed at its final dimension, after extraction in the second extraction area commenced. The outside – outside sequence in respect to the loading system stiffness, pillar stresses and likelihood of an unstable pillar failure at the time of pillar creation is between the two other sequences.

In summary, the center – outside sequence and outside – outside sequence are more favorable than the outside – center sequence, because unstable failure is less likely and because active infrastructure can be situated distant from the highly stressed pillar. The highly stressed pillar is formed behind active extraction faces, the loading system stiffness at the time of pillar formation is higher and the pillar stresses build up more gradually and slowly. Moreover, the stresses at the active extraction face are significantly lower at an advanced extraction stage and the loading system stiffness is higher.

The center – outside and outside – outside sequence are examples for sequences, where highly stressed pillars are formed behind advancing extraction faces, and the outside – center sequence is an example for a sequence, where the highly stressed pillar is formed ahead of advancing extraction faces. In general, advancing extraction fronts away from a highly stressed pillar is preferable and should be conducted, whereas advancing towards a highly stressed pillar should be avoided.

6.1.4.2.3 Two adjacent extraction areas separated by a pillar being increased in height

So far the lateral extension of extraction areas separated by massive pillars has been discussed. The extension of extraction areas in height affects the pillars between them considerably. This effect on pillars is discussed on basis of two adjacent extraction areas. Figure 135a and Figure 135b show the two extraction areas and the pillar between them, before and after the height of the extraction areas was increased. The resultant stresses as well as the loading system characteristics are influenced. However, the most important effect is on the pillar. The pillar width-to-height ratio is decreased. Accordingly, the pillar strength and the pillar post-peak modulus decrease; compare section 6.1.2.2. Thus, pillar failure becomes more likely. Moreover, the likelihood of an unstable pillar failure increases. In summary, increasing the height of adjacent extraction areas can have adverse consequences on pillar stability and the stability of pillar failure. Therefore, increasing the height of adjacent extraction areas requires a careful and detailed rock engineering design as well as an accompanying monitoring program, which allows to detect potentially critical situations at an early stage so that appropriate, counteracting measures can be implemented timely. The post-pillar mining method is an extreme example of increasing the pillar height.

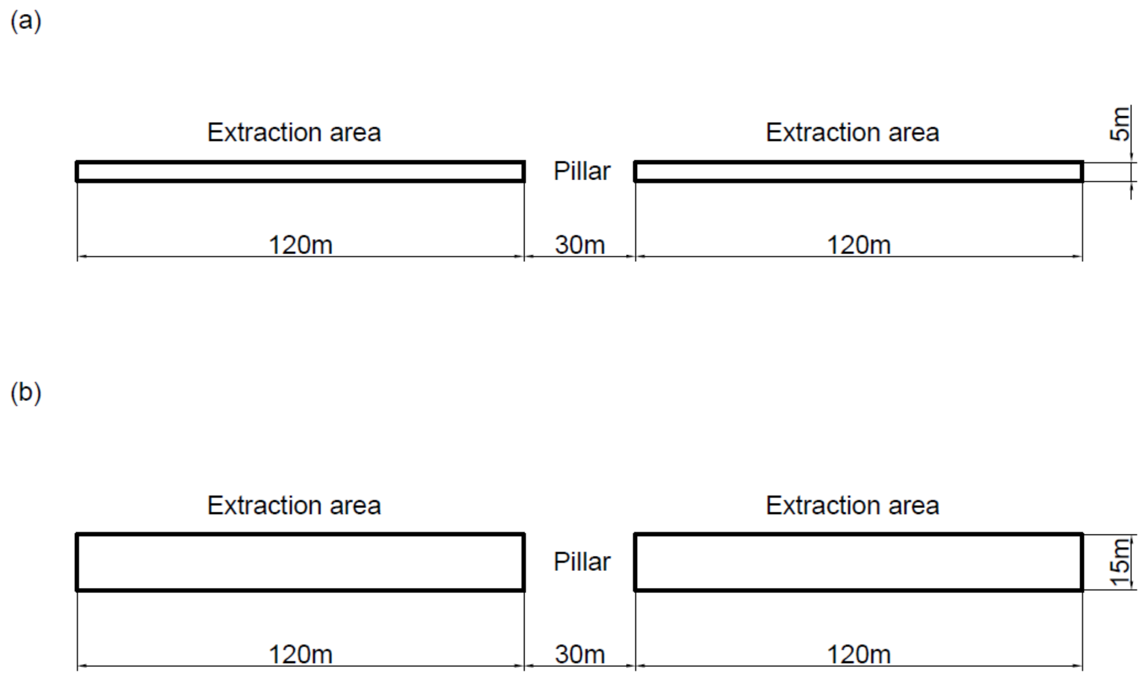


Figure 135: Vertical cross-section of two flat-lying extraction areas separated by a pillar (a) before and (b) after the height of the extraction areas was increased

6.1.4.3 Summary of the impact of time

In the foregoing sections the impact of the time element (the mining sequence) on the resultant stress situation, pillars and the loading system were outlined on basis of important situations in practice. The mining sequence governs the temporal occurrence and temporal spatial extent of high and low stress zones. Moreover, in a given (final) mine layout, the mining sequence determines, whether active infrastructure or active extraction faces are exposed to adverse stress situations or areas of significant seismic energy release. Further important points are that the rock pressure situation becomes normally more difficult at an advanced stage of mining or if extraction advances towards mined-out areas or towards highly stressed pillars.

In summary, the mining sequence is critical for the implementation of the proposed stress management concept. An appropriate (regional) mining sequence can improve the rock pressure situation significantly. For this foresighted planning is decisive.

6.2 Auxiliary elements

6.2.1 Support and reinforcement

Support and reinforcement are auxiliary elements. Typical support and reinforcement elements comprise rock bolts, cable bolts, mesh, lacing and shotcrete. Their objective (physical effect) is to stabilize localized fracture and failure zones. The function of support and reinforcement enables to tackle localized rock pressure phenomena, to prevent fracture and failure of main elements and to maintain the integrity and functionality of other elements. It is beyond the scope of the present work to discuss support and reinforcement elements, their functional principles and their physical effects on rock mass, particularly because support and reinforcement have an assisting role and because the majority of the stress management is done with the main elements. A short overview of support elements and their main functional requirements was provided in section 4.1.1.

In summary, support and reinforcement as auxiliary elements are an integral part of the stress management concept, but the majority of stress management is conducted with main elements and their physical effects.

6.2.2 Monitoring and observation

Monitoring and observation are auxiliary elements of the proposed stress management concept. Their purpose (physical effect) is to collect data and experience. Targeted back analyses utilizing this data and experience should be conducted to improve the knowledge and understanding of the prevailing mining environment, the rock mass conditions, the stress situation, the strength and stress strain behavior of pillars etc. Typical monitoring and observation elements comprise various types of measuring devices, such as cameras, extensometers, accelerometers and stress measurement cells. Furthermore, the mining personnel, which reports on the behavior of rock mass, pillars, tunnels etc. in a structured and systematic way, is a central part of monitoring and observation.

7 Element functions of the stress management concept

In this chapter the individual element functions are discussed. All element functions are based on the physical effects of main and auxiliary elements. The aim and purpose of the functions are quite different and comprise the creation of access, the extraction of the ore body, the transfer of stresses through the mine as well as the collection of data and experience. All functions are outlined in this chapter and relevant aspects related to rock mechanics and production are highlighted. Following functions are distinguished:

- Access function
- Extraction function
- Stress blocking function
- Regional stress transfer function
- Stress distribution function
- Protection function
- Strength enhancing function
- Data and experience collection function

7.1 Access function

The access function makes use of the physical effect of creating a void of the excavation element. The access function is required for all mining activities. The objective of the access function is to provide access to certain areas in the mine. Furthermore, the access function is utilized to transport different types of material, air, machinery, water, energy and personnel as well as to enter stopes and extraction areas. The access function of excavations is principally required for the implementation of further main and auxiliary elements. The excavations providing access are commonly referred to as infrastructure (excavations). Infrastructure is further grouped according to their importance and lifetime into main, primary, secondary and stope infrastructure as well as according to their use in entry and non-entry infrastructure; compare section 3.2.1.

7.1.1 Rock mechanics aspects of the access function

The infrastructure must be stable and must fulfil its access function as long as it is required for the mineral extraction. Occurring rock pressure phenomena in infrastructure must be such that they can be managed with the auxiliary support and reinforcement element. Indeed, preventing or limiting the occurrence of rock pressure phenomena by the utilization of an active stress control approach is superior over support and reinforcement. Depending on the importance and the use (entry or non-entry) a certain degree of rock mass fracturing or even failure and corresponding deformations in or near infrastructure may be tolerable. Fracturing and associated deformations in or near stope infrastructure are tolerable, as long as they do not constitute a safety hazard, prevent efficient operation of equipment or call for undue amount of repair work. Contrary, in and near critical main infrastructure, such as for example main shafts, main ramps or main haulage tunnels, deformations or fracturing, which cannot be stabilized and stopped with support and reinforcement are mostly not tolerable, because they finally result in production losses at some point due to required repair work.

Infrastructure excavations are typically comparatively small excavations. Dimensions of cross-sections of tunnels, drifts, shafts and raises are mostly in the range of some meters. Dimensions of larger infrastructure excavations, such as crusher chambers, workshop caverns or caverns hosting installations, are in the range of some meters to a couple of tens of meters. Dimensions of stoping excavations and stoping areas can and mostly do exceed the dimensions of infrastructure excavations by far. The stress changes caused by excavations of varying dimensions were discussed in section 6.1.1.1.1, from which it can be concluded that infrastructure does not have a regional influence on the resultant stress situation. Its influence is of rather localized nature and restricted to its vicinity. Accordingly, infrastructure excavations and their access function do generally not influence other elements and element functions from a rock mechanics perspective, on the contrary, infrastructure excavations are affected by the other elements and element functions.

This aspect implies for the rock engineering design of infrastructure excavations that the stress situation at their position is governed by the other main elements in particular by extraction excavations and regional stress transfer structures. Hence, the relative position of infrastructure to extraction areas and elements with a regional stress transfer function is critical. If infrastructure is placed inside highly stressed abutments or near regional stress transfer pillars, the infrastructure can be severely damaged by the prevailing high stress magnitudes. In contrast, if the infrastructure is situated in de-stressed zones, which are provided by large extraction excavations or extraction areas, it can first be protected from high stresses and second it can benefit from reduced stress magnitudes. The outlined resultant stress distributions around excavations (section 6.1.1.1) and pillars (section 6.1.2.1) show the position and spatial extent of high stress and low stress zones and hence unpreferable and preferable positions for infrastructure. As mining progresses, the location and extent of high and low stress zones change; compare section 6.1.4. Thus, the time of infrastructure development relative to advancing mining fronts is critical as well. If infrastructure is developed ahead of mining fronts, so-called pre-developed infrastructure, it is exposed to high stress magnitudes, as mining fronts approach and pass by; compare section 6.1.4.1. Furthermore, a significant amount of seismic energy can be released close to infrastructure, as mining fronts approach and pass by. The reason for this are the prevailing high stress magnitudes and the considerable stress changes, which take place near advancing mining fronts. Contrary, if infrastructure is developed delayed, namely behind advancing mining fronts, it can benefit from stress shadows best. The rock mass was already de-stressed before infrastructure development and the de-stressed ground is not as seismically active as highly stressed zones and as zones, where considerable stress changes take place.

In summary, the time of infrastructure development and the relative position of infrastructure to extraction areas and regional stress transfer structures are critical, because they govern the stress state and the mining-induced seismicity at and near infrastructure positions. Accordingly, the time of infrastructure development and position of infrastructure can be utilized to protect infrastructure and to follow the principles of an active stress control approach. In contrast, the installation of support and reinforcement in infrastructure is a clear passive stress control approach. Furthermore, the capacity of support and reinforcement elements can constitute a technical and economic constraint. Concluding, the active stress control approach shall be deployed for protection of infrastructure excavations and for ensuring their access function.

7.1.2 Production aspects of the access function

The main production requirement is that infrastructure (the access function) enables safe, efficient and productive mineral extraction throughout the lifetime of the operation, wherefore rock mechanics considerations are decisive. Rock mass fracture and failure can affect safety adversely and call for ongoing, unproductive maintenance and repair work. Furthermore, rock mass fracture and failure can lead to a deterioration of operational conditions for equipment inside infrastructure and hence can decrease equipment efficiency. Additionally, the prevailing rock mechanics conditions can prohibit the creation of infrastructure with large cross-sections and hence can restrict the utilization of larger (and more productive) equipment or more efficient technology, or the rock mechanics conditions can slow down the speed of infrastructure development due to limiting the development round length or calling for heavier support and reinforcement.

Production itself affects safety within infrastructure for example due to the use of large, heavy machinery. However, these safety aspects, which are not related to rock mechanics directly, are not discussed further in the present work, because they need to be addressed always independent of the presence of a deep mining situation. The efficiency and productivity are further significantly influenced by production and operation aspects. In general, infrastructure should provide a preferably simple, short distance, reliable and readily available access to extraction areas.

- <u>The reliability</u> is related to the usability of infrastructure. Ideally, maintenance and repair of infrastructure are minimal over its lifetime. Besides the operated machinery and the utilization of infrastructure the rock mechanics situation affects the reliability strongly. The required reliability or (more appropriately) the associated consequences of unreliability define amongst other the grouping of infrastructure into main, primary, secondary and stoping infrastructure.
- <u>The simplicity and length of the access</u> provided by the infrastructure influence the efficiency of transportation systems, which are operated in respective infrastructure. Ideally, distances are as short as possible, for what infrastructure must be placed as close as possible to extraction areas. Moreover, complexities in transportation logistics, such as for example large numbers of sharp turns or crossings and intersections or many disposals between transportation systems, should be avoided as good as possible.
- <u>The availability</u> of infrastructure to extraction areas is critical. Ideally, infrastructure is pre-developed so that it is readily available, when production commences in a certain area. Consequently, infrastructure development, which is in most instances slower than the extraction of the deposit, does not slow down the actual mineral extraction. The time required for infrastructure development as well as the advance

rates in extraction areas influence the amount of required infrastructure pre-development. The slower the infrastructure development in comparison with advance rates in extraction areas is, the higher is the amount of required infrastructure pre-development. This instance is especially present in case of highly mechanized and high production extraction methods. Another advantage of infrastructure pre-development is that it ensures that an efficient transportation route for a certain extraction area is available.

Pre-developing infrastructure affects the available flexibility for adaptations in the mine layout, which was identified to be critical for the implementation of the stress management concept (section 5.1.5), considerably. The reason for this is that the infrastructure, once it was developed, defines the mine layout to a large extent. Adaptations and changes of pre-developed infrastructure are associated with following difficulties:

- Additional costs arise for the development of the new, adapted infrastructure.
- The already developed infrastructure can prevent the development of new and adapted infrastructure, because it limits the possible positions for this infrastructure. Reasons for this are that the adapted infrastructure may be situated too closely to existing infrastructure, which would cause adverse rock mechanics interrelations, or that the existing infrastructure may aggravate or prevent the extraction of the ore body from the new developed, adapted infrastructure, for example because drilling production blast holes through existing infrastructure is not possible.
- The development of new infrastructure or the adaption of existing infrastructure requires additional time and hence it can slow down or shut down production. This instance is most critical for main and primary infrastructure, because it usually implies that the production in the mine or at least large areas of the mine must be shut down. Adaptions or changes to secondary and stope infrastructure are generally less critical, because they affect the production in localized, small areas of the mine. Indeed, if secondary and stope infrastructure must be changed and new developed constantly, the consequences on the operation are considerable.

Summing up, in terms of flexibility the infrastructure is ideally developed as late as possible so that the mine layout can be adapted on short notice. However, as outlined above, such a late development of infrastructure can reduce the achievable production rates noticeably. Furthermore, main and primary infrastructure, which are needed to access certain areas of the mine, must mostly be developed long periods ahead. For this reason and because of the production losses, which are associated with changes and adaptations of the main and primary infrastructure, the flexibility for main and primary infrastructure is rather limited. This aspect must already be considered at an early stage in mine planning. It is most important to protect main and primary infrastructure from rock pressure problems at all stages of mine life.

Concluding, the position, layout and time of infrastructure development are particularly critical from a production perspective for their efficient and productive utilization. The position and time of infrastructure development were also identified to be critical from a rock mechanics perspective (compare section 7.1.1) and the time of infrastructure development has a strong impact on the available flexibility, which is also critical from a rock mechanics point of view. For this reason, the rock mechanics and production requirements are largely contradicting. Pre-developing infrastructure is preferable from a production perspective, but from a rock mechanics perspective it is mostly disadvantageous in a deep mining environment, because pre-developing infrastructure implies that infrastructure is subjected to highly stressed and seismically active areas and that the flexibility for changes and adaptions is reduced considerably. Hence, these contradicting requirements from a production and rock mechanics perspective must be addressed by the proposed stress management concept to ensure a safe and efficient extraction at great depths. A central point therefore is that infrastructure design shall not solely be based on production considerations, rather rock mechanics aspects must be incorporated and the objective is to protect infrastructure from high stresses and mining-induced seismicity. Besides protection of the infrastructure the stress management concept must also provide flexibility for the position and time of infrastructure development. Thereby, changes and adaptations can be implemented on short notice and at reasonable cost. Providing this flexibility is probably one of the most difficult aspects for production scheduling, because it requires dynamic adaptions of production plans. The speed of infrastructure development becomes therefore increasingly important.

7.2 Extraction function

The extraction function makes use of the physical effect of creating a void of the excavation element. The extraction function is required in all mines for the extraction of the valuable minerals and it should enable a productive and efficient mineral extraction. The excavations providing the extraction functions are commonly referred to as stopes or extraction excavations. Several stopes situated close to each other form a so-called mining panel or extraction area. Typically, individual mining panels or regional extraction areas comprising a number of smaller extraction areas are separated by pillars, which depending on the mining method can be small and regular or large and massive.

The extraction function is combined with the access function, if infrastructure is developed inside the deposit. However, in this instance the access function and the associated design requirements, rock mechanics aspects and production aspects are dominant. The reason for this is that infrastructure is not utilized for the (large-scale) extraction of minerals and that a malfunction of the access function has generally a more adverse impact on the operation, particularly safety, than a malfunction of the extraction function.

The incorporation of the access and extraction functions into the proposed stress management concept highlights that stress management is an integral part of the mining activities.

7.2.1 Rock mechanics aspects of the extraction function

Stopes must enable a productive and efficient mineral extraction, which can be achieved either by open stopes or caving stopes. Rock mass fracture and failure in the vicinity of open stopes must be kept within acceptable limits, which are prescribed by the operational mode of the stope (entry or non-entry stopes), by the tolerable amount of dilution and the consequences on other nearby elements, such as pillars. In contrast, rock mass failure in the surroundings of caving stopes is required either to fill-up the stope, after the mineral was extracted, or to fragment the rock mass for ongoing mineral extraction. The rock mechanics stope design must ensure either the stability of stopes or the reliable caving of stopes.

The prevailing rock mass properties and the resultant stress situation are central for stope design, because they govern rock mass fracturing and rock mass failure near stopes. The rock mass properties are natural parameters and cannot be influenced at reasonable effort in most instances. However, the resultant stress situation is dependent on the prevailing primary stress situation and on the stope size and shape; compare section 6.1.1.1.1. Furthermore, the regional mine layout and mining sequence influence the stress situation considerably; relevant aspects were discussed in chapter 6. Consequently, the stope design, the mine layout and the mining sequence can be utilized to influence the resultant stress situation at the position of stopes positively and therefore to prevent, control or facilitate rock mass fracture and failure near stopes. Where possible, installing support and reinforcement elements can further enhance stope stability.

Stopes are generally larger than infrastructure excavations and they therefore have a larger spatial influence on the resultant stress situation. Furthermore, stopes are often situated close to each other and within their zone of influence so that they form a mining panel or extraction area. Mining panels and extraction areas have a larger spatial influence on the resultant stress situation than a single stope. Accordingly, the mining panel or extraction area dimensions must be considered in the design of open stopes and caving stopes within the mining panel or extraction areas as well as in the design of the corresponding infrastructure. The sequence of stope extraction, which is incorporated in the time element, has furthermore a strong temporal influence on the resultant stress situation as well as on the stress situation and seismic energy release at advancing extraction fronts; compare section 6.1.4.2.

For stope design the uncertainties related to rock mass strength and behavior and related to the distribution of rock mass properties are particularly relevant. The underlying reason is the comparatively large dimension of stopes. Furthermore, the design of stopes is normally made at an early stage, where the uncertainties are larger than at an advanced stage. Due to these uncertainties the evaluation of the stability or instability of stopes, which is critical for a successful mining operation, becomes more difficult and less accurate. As a result, stope design may be inappropriate and affect the objectives of mining, the safe, as complete as possible and economic extraction, adversely. Examples in this respect are open stopes, which have an intolerably high overbreak or which cave, caving stopes, which do not cave or in which caving does not propagate as planned, or open stopes, which could have been larger in size to increase the efficiency of extraction. From a rock mechanics perspective the inappropriate stope design affects first the stope itself. Second, the inappropriate stope design could have far-reaching, regional consequences on the resultant stress distribution, which is governed by the stopes and corresponding mining panels and extraction areas. As a consequence, significant rock pressure problems may be caused. Support and reinforcement can be installed to address an inappropriate stope design in case of instability of open stopes, which are supposed to be stable. However, the capabilities of support and reinforcement are often limited particularly for larger stopes. The reason for this is that infrastructure, which provides access, is required for the installation of support and reinforcement. This infrastructure for support and reinforcement installation is typically limited for large stopes. Another reason is that the volume of rock mass, which is in the zone of influence of a stope and thus in which fracture and failure may occur, is comparatively large to the volume of rock mass, which can be supported and reinforced technically at acceptable cost. Providing the flexibility for changes in the stope design, mine layout and mining sequence is probably the best approach to deal with an inappropriate stope design and uncertainties, because it enables to address problems actively and to remove their source.

7.2.2 Production aspects of the extraction function

From an operational perspective stope development and stope extraction must enable a safe, efficient and productive mineral extraction. In principle, large stopes are preferable, because they require a reduced amount of infrastructure and because they are less work intensive. Accordingly, a higher productivity can be achieved. However, stope dimensions are limited by different circumstances, which comprise stope stability and instability, which were discussed in the foregoing section, deposit size and shape, available extraction technology, such as possible drill hole length or the availability of remote-controlled machinery, which is able to operate in non-entry stopes, as well as quality control and grade distribution. The productivity and efficiency could be further enhanced, if active stopes are situated close to each other such that the extraction activities are concentrated in specific areas. In this case machinery can be better utilized and stationary equipment may be used. Furthermore, the infrastructure, which needs to be pre-developed and maintained, can be reduced.

The concentrated extraction of preferably large stopes, which facilitates an efficient and productive extraction, is often counteracting the rock mechanics requirements of an appropriate stress management. Aspects and corresponding rock mechanics issues are:

- Infrastructure pre-development long time in advance: At first sight large stopes seem to have a rock mechanics advantage, namely a reduced amount of required infrastructure, which has to be protected from high stresses and mining-induced seismicity. However, the infrastructure of large stopes must in general be pre-developed longer times in advance so that it is available for stope extraction on time. Therefore, infrastructure could be exposed to high stresses and seismicity for longer periods. These instances are even more relevant in the light of the larger spatial rock mechanics effects resulting from larger stopes. Moreover, the flexibility is reduced in most instances significantly. This is particularly a critical issue in complex geology and in case of presence of major geological discontinuities. As the infrastructure must be developed early, the stopes can principally not be redesigned or adapted on short notice. This instance implies further that, if changes in the design are necessary, the required time for infrastructure adaptations is longer resulting in potentially longer production shut downs in the concerned area. In contrast, smaller stopes could be preferable from a rock mechanics point of view due to their improved flexibility and due to their reduced demand of infrastructure pre-development. Moreover, the smaller stopes are in general easier to extract with delayed or at least partially delayed infrastructure development. For larger stopes such a delayed development is in many instances impossible.

- Concentration of production: Operational advantages can be achieved by concentrating production in certain areas. However, this concentration implies a reduced flexibility to react on encountered rock pressure problems or to implement changes due to rising issues caused by rock pressure phenomena at an early stage without losing production. Maintaining production rates in certain areas despite rising rock pressure phenomena or others signs or circumstances indicating the evolvement of rock pressure problems without implementing necessary modifications have led to major mine accidents. (Wagner, 1999) A particularly critical issue is that latter problems tend typically to occur at an advanced stage of extraction (in a certain area of the mine), where the possibilities for quick and easy changes, which would not affect production rates significantly, are generally low. Accordingly, more spread out and independent production areas are preferable for stress management. The overall production is then relatively independent on the performance of certain production areas, because production losses in one area due to encountered rock pressure issues can be compensated by other production areas. For this reason, spread out, independent production areas provide time to implement changes and thereby to reduce the likelihood that critical signs or conditions are neglected due to production pressure.

Another often encountered, contradicting issue between production and rock mechanics aspects related to stope extraction is a high production. First, large, productive stopes must be used principally. Second, a high production requires an efficient, high capacity transportation system, which calls for specifically designed, long-term primary and main infrastructure. Moreover, the pre-development of this infrastructure is generally necessary and this infrastructure must be positioned close to extraction areas, where major stress and energy changes take place. An exposure of the infrastructure to high stresses and mining-induced seismicity is in many instances the consequence. Moreover, the installation of the high capacity transportation system and the associated infrastructure reduce the flexibility and therefore the possibility for changes and adaptations considerably.

7.3 Stress blocking function

The objective of the stress blocking function is to reduce the stress magnitude(s) in a defined volume of rock mass, which is also referred to as de-stressed zone or stress shadow. Therefore, the stress blocking function makes use of the physical effects of main elements, which alter the resultant stress state in the rock mass. The effect of excavation elements on the resultant stresses is therefore most important. Pillar elements and the corresponding loading system elements are relevant in some instances as well.

Possible configurations of excavations, pillars and loading systems, which provide a stress blocking function, are outlined in the following. The excavations, which are specifically created for the stress blocking function, are commonly referred to as de-stressing excavations. Furthermore, extraction excavations (stopes) fulfill often a stress blocking function as well.

Overall, the stress blocking function is central in the proposed stress management concept. As already highlighted in section 2.3.3.1, the provision of de-stressed zones is an effective measure for the control of rock pressure.

7.3.1 Rock mechanics aspects of the stress blocking function

The stress blocking function is utilized to decrease the prevailing stress magnitudes. Figure 136 outlines the effects of the stress blocking function schematically on basis of a rock mass failure envelope in major and minor principal stress space. In case (a) the stress blocking function is used to decrease the magnitude of the major principal stress from state 1 to state 2. (Note that the magnitude of the minor principal stress may be altered as well. However, for illustration purposes it is assumed that the minor principal stress remains constant.) Consequently, the major principal stress magnitude is smaller than it would be without the stress blocking function and the stress state is moved from a position above the failure envelope to a position below the envelope. In other words, the stress blocking function prevents the failure of rock mass. In case (b) the stress blocking function is utilized to reduce the stress magnitude of the minor principal stress from state 1 to state 2. (For simplification it is assumed that the magnitude of the major principal stress remains constant.) Accordingly, the stress state is moved from a position below to a position above the failure envelope. Thereby, the failure of rock mass is provoked by the stress blocking function. This effect of the stress blocking function may be required in situations, where stress driven fracture and failure of rock mass is initiated on purpose, for example caving. However, in the proposed stress management concept the dominant purpose of the stress blocking function is the provision of stress shadows to improve stability (Figure 136a).

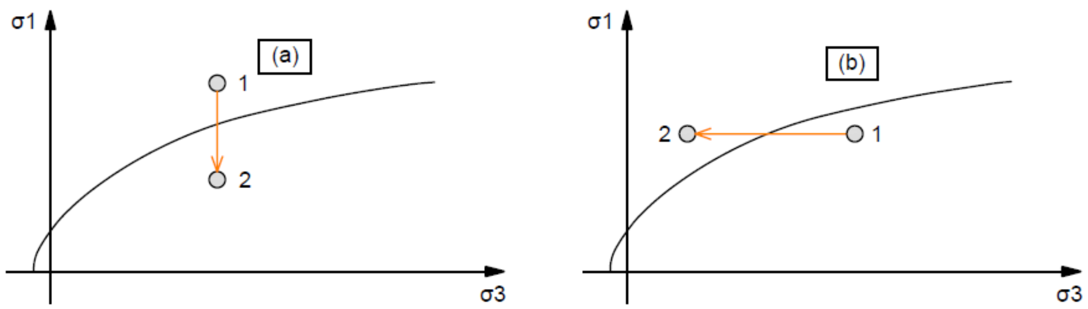


Figure 136: Effect of the stress blocking function on the failure of rock mass

The physical effect of excavation elements on the resultant stress situation is utilized for the stress blocking function. The effects of excavations on the resultant stress situation were studied in section 6.1.1.1. The investigations show that excavations with an elongated, rectangular cross-section are most effective for providing stress shadows and that the stress shadow is located in the vicinity of the longer extension of the excavation. Figure 137 shows the resultant major principal stress distribution, which is derived by numerical simulation, near an elongated, rectangular excavation of infinite length. The excavation height is 5 m, the width is 100 m and primary stress magnitudes are 27 MPa in vertical and 13.5 MPa in horizontal direction. The blue colored areas represent the stress shadow, where the resultant major principal stress magnitudes are lower than the primary major principal stress magnitudes. The presence of high abutment stresses is represented as red colored area. Furthermore, the investigations in section 6.1.1.1 show that the spatial extent of the stress shadow depends on the dimensions of the excavation. Larger excavations can be used to de-stress a larger volume of rock mass. The ratio of primary stress magnitudes and the orientation of the excavation relative to primary stress directions influence the amount of stress reduction in and the extent of the de-stressed zone. De-stressing excavations, which are orientated such that their long axes are perpendicular to the stress direction, which is planned to be blocked, are most efficient for de-stressing.

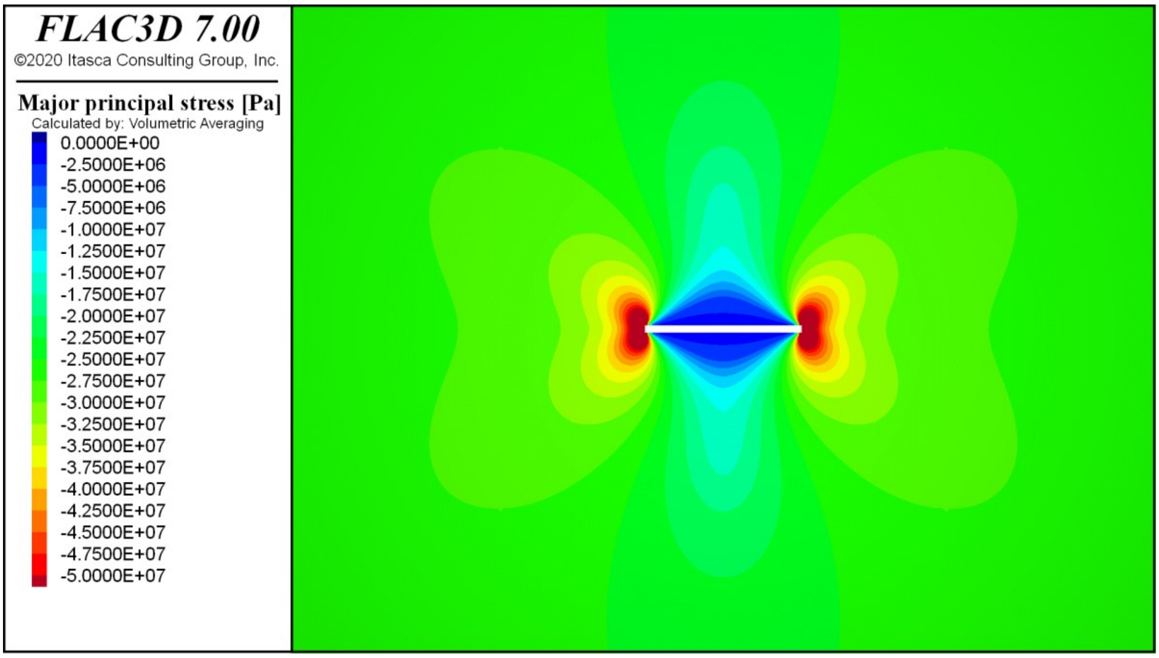


Figure 137: Resultant major principal stress distribution near a flat-lying, elongated, rectangular excavation with a width of 100 m and a height of 5 m. Primary vertical stresses are 27 MPa and primary horizontal stresses 13.5 MPa. Compressive stresses are negative.

As the stress blocking function is strongly linked to the excavation size, shape and orientation, the design of de-stressing excavations can be used to provide stress shadows at required positions. In a broader sense stress shadows are not only generated by de-stressing excavations. Particularly extraction excavations and thus mined-out mining panels and mined-out extraction areas also de-stress rock mass portions. Hence, the mine layout and mining sequence are relevant for the stress blocking function. The mining sequence (time element) is relevant for the position and extent of the stress shadow from a temporal perspective.

Depending on the spatial extent of the stress shadow a grouping in local and regional stress shadows is reasonable. Local stress shadows are of relatively small spatial extent and only present in the vicinity of de-stressing excavations with small dimensions. In contrast, regional stress shadows de-stress relatively large volumes of rock mass and are typically present near mined-out mining panels, mined-out extraction areas and large de-stressing excavations.

The stress blocking function can be realized with different de-stressing excavation types, which can be grouped as follows:

- Unfilled, empty de-stressing excavations
- Completely filled de-stressing excavations
- Partially filled de-stressing excavations

The filling of the excavation can be comprised of crushed rock mass, backfill or pillars. In case of pillars the de-stressing excavation is made out of several (smaller) adjacent excavations separated by the pillars. The different de-stressing excavation types are discussed in the following sections.

7.3.1.1 Unfilled, empty de-stressing excavations

The first and potentially simplest de-stressing excavation type is an unfilled and empty excavation, which is principally a mined-out excavation; compare Figure 138.

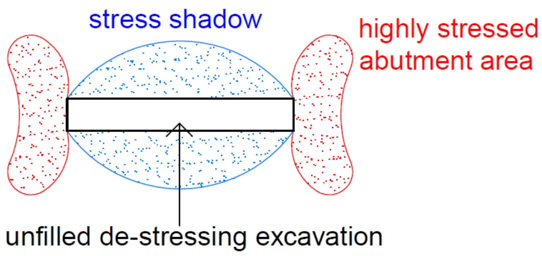


Figure 138: Illustration of a flat-lying, unfilled, empty de-stressing excavation in a vertical cross-section and of the position of the corresponding stress shadows and abutment areas

The resultant stress distribution near and thus the stress blocking function of an unfilled, empty de-stressing excavation is governed by the size, shape and orientation of the excavation itself; compare section 6.1.1.1. Accordingly, the excavation design can be used to control the stress blocking function. The achievable spatial extent of stress shadows of unfilled de-stressing excavations could though be rather limited, if the stability of the de-stressing excavation, which decreases with increasing excavation dimensions, must be ensured, for example for the creation of the excavation. Adapting the de-stressing excavation shape and orientation to improve stability is generally limited, because the excavation shape and orientation are largely prescribed by the needs of the stress blocking function. Support and reinforcement can be used to improve and maintain the de-stressing excavation stability within certain technical and economical limits.

In summary, empty, unfilled de-stressing excavations are in most instances only able to provide stress shadows of comparatively small extent. However, their advantage compared to the other types of de-stressing excavations is a relatively simple and straightforward design and creation of the excavation.

7.3.1.2 Completely filled de-stressing excavations

The completely filled de-stressing excavation is filled with fractured or broken rock mass or backfill, which provides support to the surrounding rock mass; compare Figure 139a. The de-stressing excavation can be filled, after it was developed to its final dimensions, or successively during its development. Consequently, the fill could improve the stability of the de-stressing excavation, which enables to create de-stressing excavations of larger dimensions. Hence, the spatial extent of the provided stress shadows is increased.

Instead of mining out followed by filling a de-stressing excavation, the rock mass can be left in place and fractured in-situ; compare Figure 139b. Hydraulic fracturing or confined blasting techniques may be deployed for this. The fractured in-situ rock mass acts as a soft inclusion. Because of softening the rock mass and because of the fracturing process stress changes are induced and resultant stresses are generated. However, the in-situ fractured rock mass, which acts as a soft inclusion, can be considered as a normally rather stiff fill material without a significant porosity. Hence, the de-stressing effect can be expected to be low.

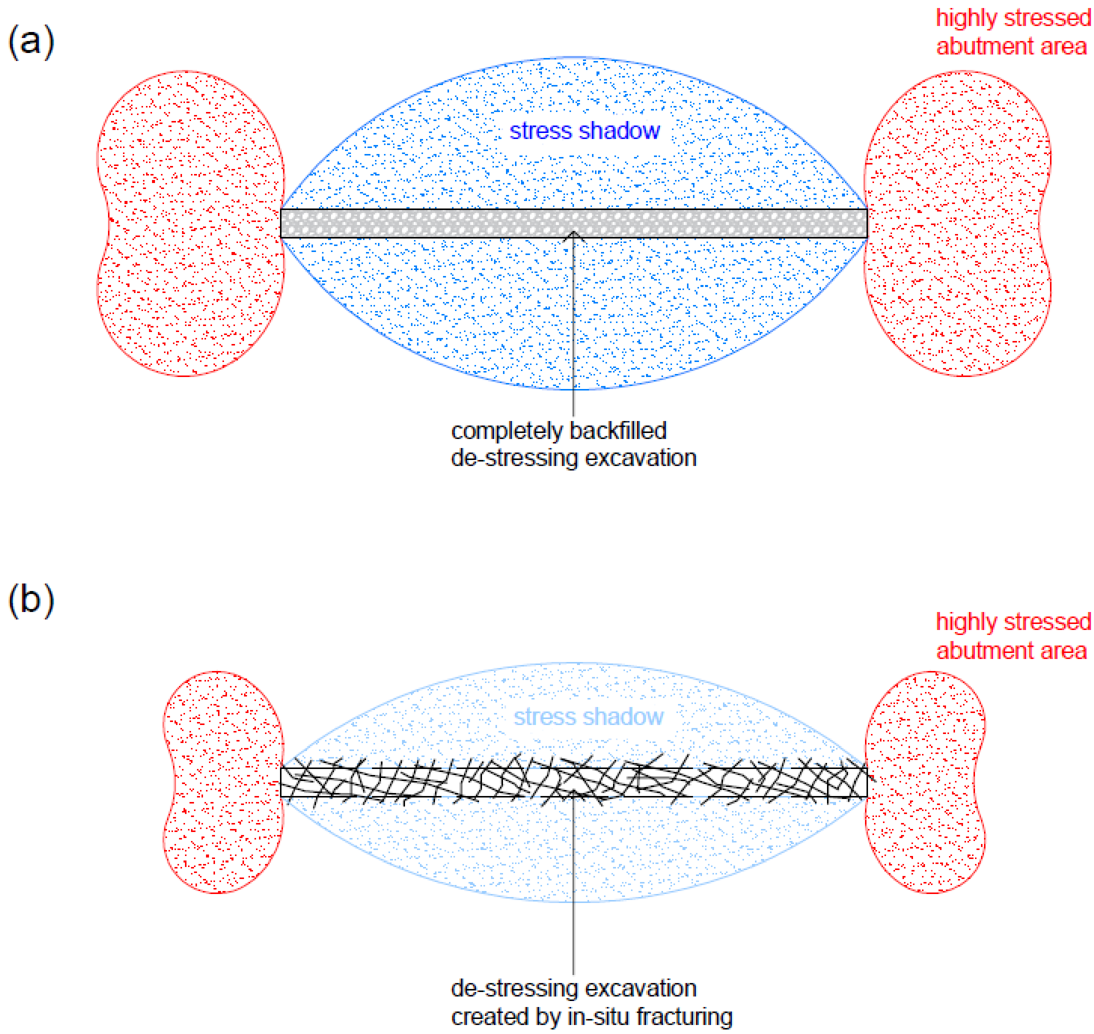


Figure 139: Illustration of (a) a flat-lying completely filled de-stressing excavation with a soft backfill and (b) a flat-lying completely filled de-stressing excavation created by in-situ fracturing of the rock mass in a vertical cross-section. The positions of the corresponding stress shadows and abutment areas and the effectivity of de-stressing are shown.

Besides the excavation size, shape and orientation the properties of the fill material, the properties of the loading system element and the interaction between the fill material and the loading system element are important for the stress blocking function and the design of the completely filled de-stressing excavation. The interaction results from the (inward) deformations of the excavation walls (loading system), which are caused due to increasing the size of the excavation or by fracture and failure processes in the rock mass near the excavation wall, and the corresponding compaction of the fill material. As the fill material is compressed, it generates a reaction stress, which supports the excavation walls and finally stops the occurring deformations. However, this reaction stress increases the resultant stress magnitudes in the excavation walls and thus it reduces the effectivity of the stress blocking function.

The amount of compression and the properties of the fill material are critical for this reduction. Figure 140 shows stress strain curves of different types of backfill under compaction. Initially, the resistance against deformation is rather low, but it increases rapidly after a certain amount of compression. The lower the porosity (n) of the backfill is, the earlier the resistance against deformation increases. As the compression start to reach the porosity of the material, which constitutes a full compaction of the material, the resistance against further deformation increases considerably. This stress strain behavior is typical for the fill material inside completely filled de-stressing excavations. The actual stress strain behavior of the fill material depends strongly on the properties of the fill material. Depending on the porosity, the strength and initial stiffness of the fill material reaction stresses build up relatively fast or slow with increasing compaction. Moreover, the compaction direction of the fill material is critical. The softer and more porous the fill material is, the smaller the deformations of the excavation walls and the larger the excavation in direction of compaction are, the lower is the reaction stress and the lower is the reduction of the effectivity of the stress blocking function.

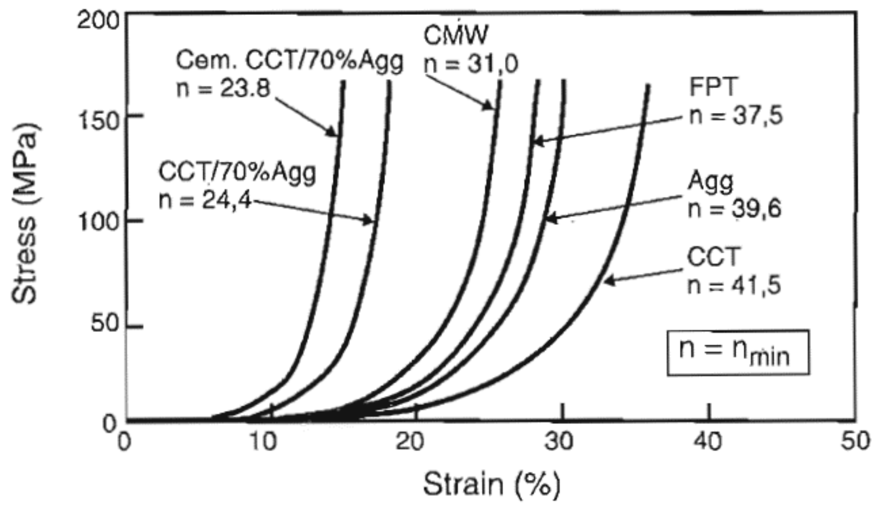


Figure 140: Typical stress strain curve of different types of backfill under compaction (Jager and Ryder, 1999)

A completely filled de-stressing excavation provides an effective stress blocking function, in case the material inside the de-stressing excavation is rather soft, in case the fill material can be compacted without significant reaction stress and in case the loading system of the fill material can bridge the fill material. Important aspects are:

- Different backfill types with a high porosity and low stiffness are ideal, whereas in-situ fractured rock mass may not be ideal, because it can be rather stiff and its porosity can be rather low. Accordingly, the effectivity of de-stressing excavations created by in-situ fracturing can be rather low and hence the provided stress shadows are of smaller extent and the stress drop inside the stress shadows is lower. Furthermore, as a consequence of the reduced disturbance of the primary stress field the abutment stress magnitudes and the spatial extent of abutment areas of de-stressing excavations created by in-situ fracturing are smaller. This lower effectivity of de-stressing excavations created by in-situ fracturing is sketched in Figure 139 schematically. Moreover, the size of the de-stressing excavation in direction of compaction is important for the occurring reaction stress, which depends on the compressive strain and not on the absolute deformations. The larger the extension of the de-stressing excavation in a direction is, the smaller is the compressive strain for the same amount of deformation in the same direction.
- The bridging capability of the loading system element is critical. If bridging is not possible, the stress blocking function diminishes drastically, because the fill material inside the de-stressing excavation would be compacted until the stress magnitudes prior to creation of the de-stressing excavation are transferred. Situations, which can prevent bridging or which cause significant amount of compaction of the fill material inside the de-stressing excavation, are soft rock mass conditions, weak rock mass conditions or the presence of persistent, large and weak discontinuities; compare section 6.1.3.
- Remnants, which are left behind in completely filled de-stressing excavations unintendedly, can diminish the stress blocking function drastically, because such remnant pillars may be able to withstand very high stresses due to the stabilizing effect of the fill material. The risk of unintended formation of remnant pillars is particularly present for completely filled de-stressing excavations created by in-situ rock mass fracturing.

Concluding, completely filled de-stressing excavations offer the possibility to establish stress shadows of large spatial extent due to the support and stabilizing effect of the material inside the de-stressing excavations. For the rock engineering design the excavation size, shape and orientation, the compaction behavior of the fill material and the properties of the loading system are critical. Overall, the complexity of completely filled de-stressing excavations is larger than that of empty, unfilled de-stressing excavations. Particularly in case the rock mass within the element is not extracted but instead fractured in-situ.

7.3.1.3 Partially filled de-stressing excavations

The partially filled de-stressing excavation has fill material only at certain locations inside the excavation. The fill material can be similar to the material inside completely filled de-stressing excavations. In this case the design and important aspects of partially filled de-stressing excavations are comparable to completely filled de-stressing excavations.

However, probably the most important partially filled de-stressing excavation has pillars inside the excavation; compare Figure 141. The behavior and strength of these pillars are essential. The parts of the de-stressing excavation between pillars can either be left open and unfilled or they can be filled with backfill. Even though backfilling these zones results in a completely filled de-stressing excavation, the de-stressing excavation is still considered as a partially filled one, because the pillars are critical for the functionality of the de-stressing excavation. Backfill may though affect pillar behavior positively. Similar to completely filled de-stressing excavations the partially filled de-stressing excavations enable to increase the size of de-stressing excavations compared to the size of unfilled, empty de-stressing excavations, because pillars provide support to surrounding rock mass formations.

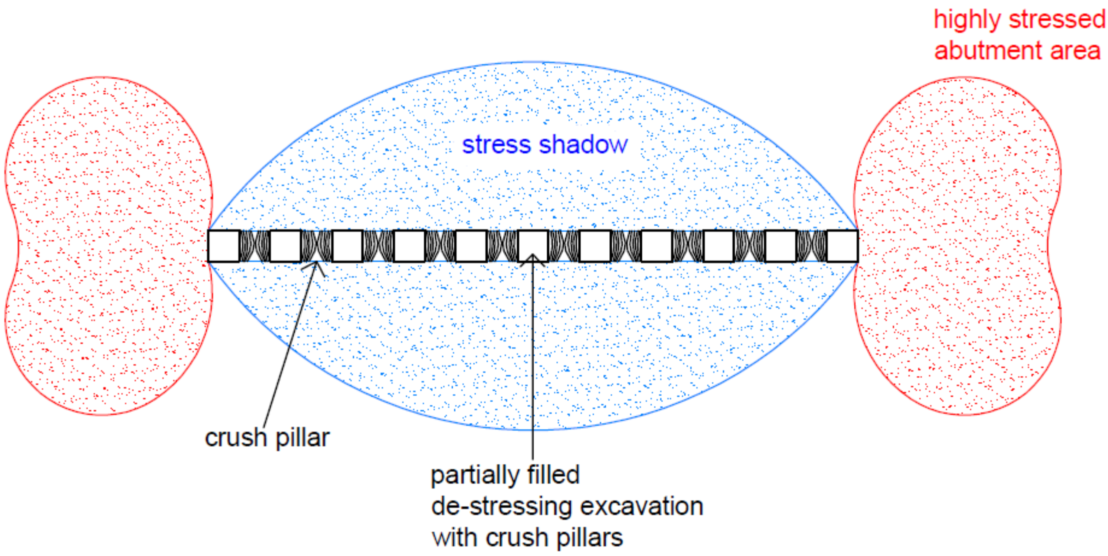


Figure 141: Illustration of a flat-lying partially filled de-stressing excavation with crush pillars inside the de-stressing excavation in a vertical cross-section and of the position of the corresponding stress shadows and abutment areas

Besides the excavation size, shape and orientation the properties of the pillars inside the de-stressing excavation, the characteristics of the loading system element and the interaction between the pillars and the loading system element are important for the effectiveness of the stress blocking function and the design of the partially filled de-stressing excavation. Pillars transfer stresses and the resultant stresses increase in the rock mass in the vicinity of the pillar. This influence of the pillar on the resultant stresses in its vicinity diminishes with distance from the pillar. As outlined in section 6.1.2.1, the stress magnitudes in the vicinity of the pillar depend strongly on the average pillar stress and hence on the stresses, which are transferred through the pillar. The higher these transferred stresses are, the higher are the stresses in the vicinity of the pillar. Moreover, the spatial extent of the increased stress magnitudes in the vicinity of the pillar depends on the width of the pillar and the magnitude of the average pillar stress. A wider pillar and a more highly stressed pillar have a larger spatial effect. The influence of the pillar on the resultant stress situation in the surrounding rock mass is critical for the stress blocking function. A significant stress transfer of pillars causes the loss of the stress blocking function. Strong pillars and wide pillars are particularly critical.

In order to ensure the functionality of the partially filled de-stressing excavation, the pillars inside the de-stressing excavation must only transfer relatively low stress magnitudes and they must be able to support the surrounding rock mass to ensure the stability of the de-stressing excavation. Crushed pillars with a low residual strength fulfill this requirement, whilst all other pillars, namely intact pillars, yield pillars or pillars with a strain hardening post-peak behavior, do not fulfill it. Furthermore, crush pillars are generally of smaller size than the other outlined types of pillars so that they crush reliably. Due to the smaller size of crush pillars the spatial influence of crush pillar is smaller as well. As discussed in section 6.1.2.2, the pillar strength and behavior are dependent on the pillar dimensions. Accordingly, the pillar dimensions can be used to design pillars with a specific behavior inside partially filled de-stressing excavations. A critical aspect for the design of these pillars is though the identified limited knowledge related to the strength and behavior of pillars; compare section 6.1.2.2.

The stability of pillar crushing is critical for the stability of the partially filled de-stressing excavation. The post-peak behavior of crush pillars in combination with the stiffness of the loading system element are relevant; compare section 3.3.4. The post-peak behavior of crush pillars can be influenced by pillar design (section 6.1.2.2). The stiffness of the loading system depends on the size, shape and orientation of the de-stressing excavation. As shown in section 6.1.3.2, the loading stiffness is highest closest to the abutments of the excavation and decreases quite rapidly with increasing distance from the abutment.

Two aspects are acting against each other for the application of pillars inside de-stressing excavations, namely:

- First it is required that pillars affect the resultant stress situation near the de-stressing excavation only locally. As outlined in section 6.1.2.2, pillars with a low width-to-height ratio are therefore preferable, because they have a comparatively low peak strength, which facilitates pillar crushing, as well as a comparatively low residual strength, which reduces the influence of the crushed pillar on the resultant stress situation. The knowledge regarding the actual residual strength of pillars and the effect of the width-to-height ratio on it is though quite limited.
- Second pillar crushing must be a stable process. Otherwise, the stability of the partially filled de-stressing excavation is endangered. For this purpose crush pillars with a low strain softening rate are preferable. Generally, such a behavior is not provided by pillars with a low width-to-height ratio; compare section 6.1.2.2.

Accordingly, either weak pillars with a low residual strength but therefore with a quite rapid strain softening behavior or quite strong pillars with a higher residual strength but therefore with a slow strain softening behavior can be utilized. This circumstance is not ideal for the application of crush pillars in a partially filled de-stressing excavation, but may be solved by providing a comparatively stiff loading system for the pillars, which ensures stable crushing of pillars with a small width-to-height ratio. As the loading system stiffness varies spatially and temporally, the position and time of pillar formation and crushing are decisive. Ideally, pillars should crush directly at the advancing face of the de-stressing excavation, where these pillars are formed, or shortly behind the advancing face. In these areas the loading system stiffness is higher than in the center of the excavation; compare section 6.1.3.2. Mining experience in South African platinum mines, which utilize crush pillars on a large-scale, shows as well that crush pillars must crush at the face reliably to avoid unstable pillar failure behind the face. (Du Plessis and Malan, 2018) Once the pillar crushed completely, the stiffness of the loading system is no longer critical, because the stress strain curve of the crushed pillar flattened out and hence further unstable pillar failure is prevented effectively.

Concluding, partially filled de-stressing excavations offer the possibility to establish stress shadows of large spatial extent due to the support and stabilizing effect of the crush pillars inside de-stressing excavations. For the rock engineering design the excavation size, shape and orientation, the strength and post-peak behavior of crush pillars and the characteristics of the loading system are important. Overall, the complexity of partially filled de-stressing excavations is larger than that of empty, unfilled de-stressing excavations and than that of completely filled de-stressing excavations, particularly because of the limited knowledge related to the strength and behavior of pillars.

7.3.2 Production aspects of the stress blocking function

The main purpose of the stress blocking function is related to rock mechanics, namely the reduction of stress magnitudes in order to gain safety and operational benefits. From a production point of view the critical aspect related to the stress blocking function is, whether corresponding de-stressing excavations can be created without counteracting the objectives of mineral extraction. Therefore, the safety during establishing the de-stressing excavations as well as additional costs and time have to be considered. However, the costs and time must be seen in context to later gained benefits from the de-stressing excavations. Even though costs and time may be (in absolute) figures quite high, the costs can still be marginal compared to the savings gained later, if for example a more efficient and more productive stope design or mining method can be applied due to improved stress conditions. In summary, de-stressing excavations are an investment into improved mining conditions.

As the objective of the stress blocking function is the reduction of stress magnitudes, corresponding de-stressing excavations must usually be developed in a high stress environment. The implications of this high stress mining situation for the establishment of de-stressing excavations are outlined and possible approaches are discussed in chapter 8.

De-stressing excavations require infrastructure for their creation, which must be developed to reach the position of the de-stressing excavations. An exception may be de-stressing excavations, which are created by in-situ fracturing of the rock mass. Decisive is further, how much infrastructure must be developed outside de-stressing excavations and how much infrastructure can be integrated into de-stressing excavations.

- <u>Infrastructure situated outside de-stressing excavations</u> is for example access infrastructure to de-stressing excavations. This infrastructure is exposed to high stresses and probably mining-induced seismicity. Furthermore, this infrastructure may be further subjected to highly stressed and seismically active abutment areas of de-stressing excavations. The protection of this infrastructure is critical. A specifically designed layout and sequence of the de-stressing activities in combination with support and reinforcement elements are in this instance a reasonable option; compare section 8.2. An advantage of infrastructure situated outside de-stressing excavations is that the de-stressing excavation does not necessarily need to be stable, because the infrastructure utilized for the development of the de-stressing excavation is not integrated into the de-stressing excavation.

- Infrastructure situated inside de-stressing excavations can already be protected from high primary and abutment stresses as well as from mining-induced seismicity. However, in this case the de-stressing excavation must generally be stable (at least at the position of the infrastructure). A typical example for infrastructure inside de-stressing excavations is a partially filled, flat-lying de-stressing excavation, where the excavation between crush pillars serve as infrastructure.

In summary, de-stressing excavations are from a production perspective an investment into improved mining conditions. However, creating de-stressing excavations is in most instances high stress mining and the protection of required infrastructure is critical. Further analysis and discussion of this issue are conducted in section 8.2.

7.4 Regional stress transfer function

The objective of the regional stress transfer function is to direct and control the flow of the far-field stresses through the mine. The objective is further to distribute stresses within the mine systematically and strategically to improve the overall mine stability. Thus, the regional stress transfer function is closely linked with the stress distribution function. For its objectives the regional stress transfer function makes in most instances use of the physical effects of pillars, which can be utilized to transfer stresses, and of loading systems, which can be utilized to distribute stresses within the mine and between pillars. Abutments of mined-out areas participate in the regional stress transfer as well.

7.4.1 Rock mechanics aspects of the regional stress transfer function

7.4.1.1 Utilization of pillars for regional stress transfer

The regional stress transfer function is utilized to direct and control the stress flow through the mine. Figure 142 illustrates the function on basis of mined-out extraction areas, in which small pillars provide local support to the surrounding rock mass, and large massive pillars, which separate the individual mined-out areas. The large massive pillars are referred to as regional stress transfer pillars and they transfer the stresses through the mine and fulfill therefore the regional stress transfer function. Furthermore, the loading system of all mined-out areas directs the stresses into the large massive pillars. Consequently, the small pillars inside individual mined-out areas transfer only low loads, because the regional stress transfer function diverts high loads away from them. For this reason, the regional stress transfer function is able to protect certain areas in the mine, mostly extraction areas, from high loads. As outlined in Figure 142, the abutments of all mined-out areas participate in the regional stress transfer as well.

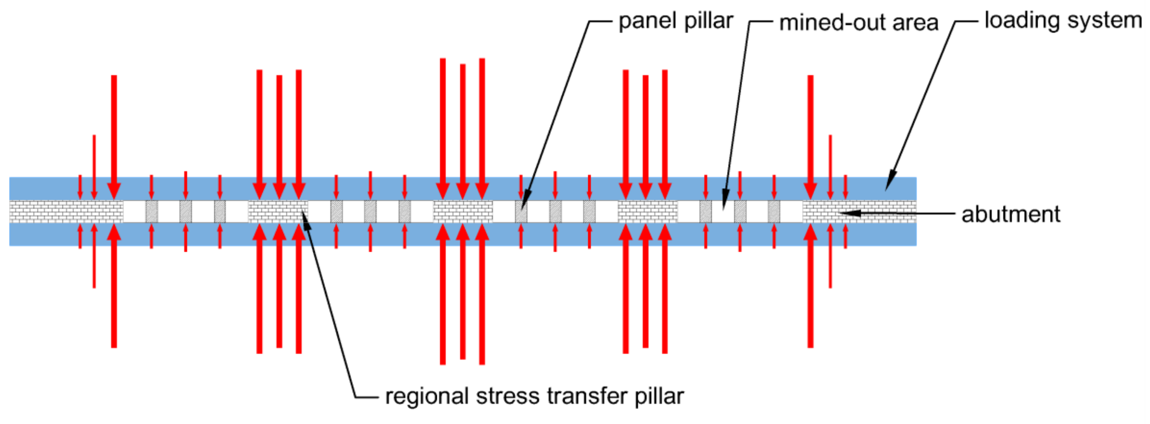


Figure 142: Illustration of the regional stress transfer function in a vertical cross-section with loads on pillars and abutments being indicated with red arrows

Rock mechanics considerations of the involved elements are essential for the regional stress transfer function. Following points are critical:

- Regional stress transfer pillars must be able to transfer high stress magnitudes. In order to fulfill this task, regional stress transfer pillars must have a considerable strength. In general, massive pillars with high width-to-height ratios are suitable; compare section 6.1.2.2. The strength of pillar foundations becomes in this instance often more relevant than the strength of the pillar itself. Furthermore, the post-peak behavior of regional stress transfer pillars and the corresponding pillar foundations is important particularly in situations, where regional stress transfer pillars may fail. A strain hardening or yielding behavior of the regional stress transfer pillar is preferable, because it rules out the possibility of a violent, unstable pillar failure, which is often associated with the release of considerable amounts of seismic energy. As the loading system stiffness of regional stress transfer pillars can be rather soft due to the large extensions of extracted areas (section 6.1.3.2), ensuring a yielding or strain hardening post-peak behavior of regional stress transfer pillars becomes even more important. A (unplanned) failure of a regional stress transfer pillar can have far-reaching, unexpected consequences on the regional stress situation in the mine. Figure 143a illustrates the consequences on basis of the mine layout shown in Figure 142. The failed regional stress transfer pillar lost its regional stress transfer function and hence does not participate in the regional stress transfer anymore. Instead the failed regional stress transfer pillar is still able to transfer small loads. Consequently, the neighboring regional stress transfer pillars, the neighboring small panel pillars and the abutment areas become more highly stressed.
- Abutments of extraction areas must be able to transfer high stress magnitudes. The prevailing high stress magnitudes in the abutments can cause rock mass fracturing or failure in the abutment, which has in most instances a localized effect on the nearby excavations. Reasons for this are that the failure in the abutment is gradual, that the failure moves generally away from mined-out areas and that the stress magnitudes in abutments approach the far-field stress magnitudes with distance from the mined-out areas, which stops fracturing and failure finally. However, in case

of unstable shear failure in abutments, which can extent up to 30 m to 50 m into the footwall and hangingwall of the abutment, significant amounts of seismic energy can be released. In contrast to regional stress transfer pillar failures, abutment fracturing or failure have in most instances a less pronounced effect on the regional stress flow through the mine. Fracturing and failure of the abutment cause that high stress magnitudes are pushed deeper into the abutment. Consequently, the abutment can still transfer considerable stress magnitudes, which results in a significantly lower stress increase in nearby regional stress transfer pillars and small panel pillars; compare Figure 143b.

- <u>The loading system must be able to direct stresses into regional stress transfer pillars and abutments of extraction areas.</u> The loading system must be able to bridge mined-out areas to direct far-field stresses into regional stress transfer pillars and abutments. If the loading system cannot bridge mined-out areas or if the mode of bridging is changed due to for example the presence of weak faults, the control of the far-field stress flow by regional stress transfer pillars and abutments becomes less effective. Figure 143c highlights this situation. As a consequence, the small panel pillars inside mined-out areas could be overloaded causing the collapse of respective area.

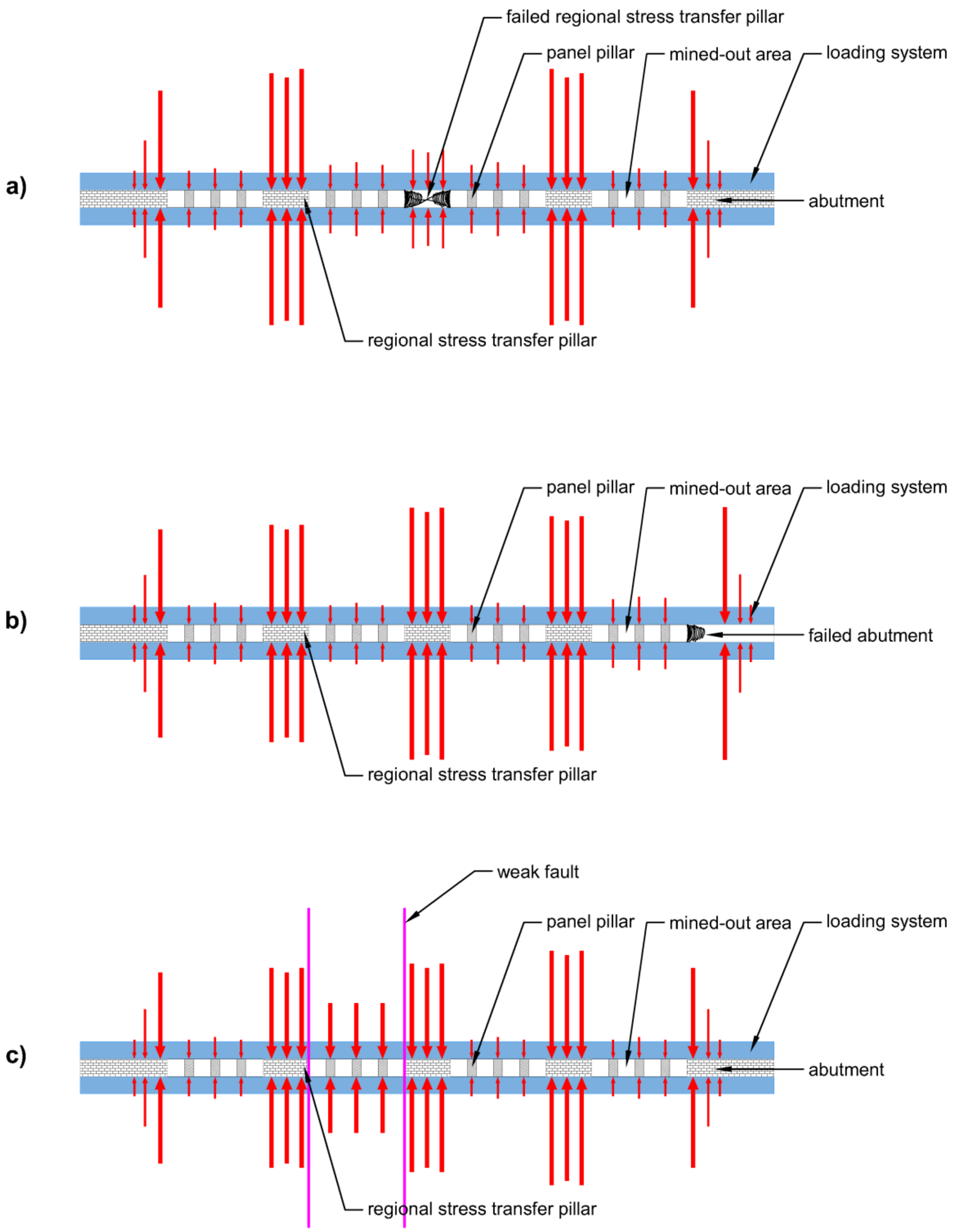


Figure 143: Illustration of the consequences on the regional stress flow through the mine in a vertical cross-section of (a) a failure of a regional stress transfer pillar, (b) a failure of an abutment and (c) a weak fault changing the mode of bridging of mined-out areas. Loads on pillars and in abutments are indicated with red arrows.

7.4.1.2 Utilization of backfill for regional stress transfer

Backfill placed in mined-out excavations can also take over a regional stress transfer function. However, before the backfill can transfer high stress magnitudes and hence provide a regional stress transfer function, the backfill must be completely compressed;

compare Figure 140. Therefore, the size of the excavation in direction of backfill compression, the deformations of the excavation, the properties of backfill and the backfill placement quality are critical. Principally, a stiff, dense and tightly packed backfill and a completely filled excavation are preferable, because the backfill can then transfer higher stresses for the same amount of compression. Furthermore, excavations with a small extent in the direction of backfill compression and large deformations of the excavation boundaries in the same direction are preferable, because the backfill is compressed faster leading to a faster stress transfer through the backfill. Besides the requirements on backfill and backfill compression it has to be considered that the excavation must principally be stable so that placement of (tightly packed) backfill is possible.

In contrast to regional stress transfer pillars the stability of the backfill itself is not critical, because the backfill is typically fully confined. Moreover, the bridging capabilities of the loading system are not as relevant, particularly after the backfill was placed. Despite these advantages the utilization of backfill for regional stress transfer has a distinct, considerable disadvantage, namely that backfill shows only a delayed action, after it was compressed sufficiently. Therefore, regional stress transfer pillars are in most instances by far more effective for regional stress transfer than backfill. An exception are narrow tabular deposits, which ensure that backfill is compressed sufficiently and fast.

7.4.1.3 High stresses in the vicinity of regional stress transfer structures

The transfer of high stresses through regional stress transfer pillars, abutments and backfill causes the formation of high resultant stresses in their vicinity. These effects have been outlined and discussed for pillars in section 6.1.2.1 and for abutments in section 6.1.1.1. The effect of backfill is comparable to that of pillars, which transfer the same stress magnitude as the backfill. But the effect of backfill would in most instances be of larger spatial extent, because backfill utilized for regional stress transfer is placed usually over larger areas compared to the size of regional stress transfer pillars.

Infrastructure and stopes should not be placed inside these high stress zones in and near regional stress transfer structures, because the stress magnitudes are often of such extent that they can cause significant rock pressure problems. However, a critical circumstance is that the extraction activities must often advance into abutment areas or towards mined-out areas, which reduces the size of the (highly stressed) pillar between them. The protection of the therefore required infrastructure and stopes from high stresses becomes decisive. Possible strategies for this aspect are discussed further in section 7.4.2.1.

7.4.1.4 Concluding remarks

The appropriate rock mechanics design of elements and structures undertaking regional stress transfer is crucial for a successful mineral extraction. First, they direct and control the stress flow through the mine and, second, they have a considerable impact on the stress situation at active extraction faces. Out of an inappropriate design severe rock pressure problems can emerge, which can be of such an extent that the continuation of the operation is put at risk. Furthermore, rock pressure problems resulting from an inappropriate design of regional stress transfer structures can be rather difficult to address. The reason therefore is that the regional stress flow through the mine must be rigorously planned and managed from the beginning on, because effective measures for alleviating a poor management of the regional stress flow are principally rare especially on the short run. Eventually, the only option in many situations is to sacrifice (large) portions of the deposit for additional regional stress transfer pillars. This measure counteracts obviously the completeness of deposit extraction.

Another point to consider is that in case of deposits with a large spatial extent regional stress transfer structures, such as pillars or backfill, have to be utilized to separate individual mining panels and extraction areas. These regional stress transfer structures improve the stress conditions in active extraction areas and at active extraction faces. Infrastructure should not be situated in or close to the highly stressed regional stress transfer structures. However, where this is unavoidable, specific measures must be put in place. These measures comprise a carefully and strategically chosen mining sequence, the utilization of sacrificial excavations, special heavy support and reinforcement as well as redundancies in infrastructure design.

7.4.2 Production aspects of the regional stress transfer function

The main purpose of the regional stress transfer function is related to rock mechanics, namely directing and controlling the flow of far-field stresses through the mine. From a production point of view the critical aspect related to the regional stress transfer function is, when and where highly stressed regional stress transfer structures are created relative to extraction activities and active infrastructure.

7.4.2.1 Infrastructure, stopes and other excavations near regional stress transfer structures

Principally, the prevailing high stresses near regional stress transfer structures should be avoided and infrastructure, stopes and other excavations should be placed outside and distant from them. However, mineral extraction often demands that infrastructure, stopes or other excavations must be positioned in or near these high stress areas, because the extraction advances in many situations into abutment areas or into regional stress transfer pillars. Associated stress related issues become principally more relevant at an advanced stage of extraction, at which the disturbance of the primary stress field is larger resulting in higher stress magnitudes in and near regional stress transfer structures. Possible approaches addressing this issue are:

- <u>Formation of highly stressed regional stress transfer structures behind advancing extraction faces:</u> This measure avoids adverse interactions effectively, because the regional stress transfer structures are created in areas, which were mined-out and which do not have to be entered anymore. Furthermore, mining does not advance towards mined-out areas, which would result in the formation of a highly stressed regional stress transfer pillar ahead of the advancing extraction face; compare section 6.1.4.2. Despite this measure is very effective, it cannot solve potential abutment stress issues at active extraction faces or protect infrastructure, which must be positioned near to left-behind regional stress transfer structures to provide access to active extraction areas and extraction faces.

- Limiting the stress magnitudes in regional stress transfer structures, which are close to active infrastructure, stopes or other excavations: This measure can be realized by the remaining regional stress transfer structures, which are distant from the structure, which stress magnitudes should be limited. The distant structures transfer stresses and thus divert them partially away from the structure, where active infrastructure, stopes or other excavations are or are to be established, which is generally at the position of active extraction faces and their corresponding abutments. Figure 142, where regional stress transfer pillars are in place and reduce therefore abutment stress magnitudes, provides an illustrative example for this measure. If these regional stress transfer pillars would not be in place, the abutment stress magnitudes would be considerably larger, because all far-field stresses must flow through the abutment.
- Intercepting regional stress transfer structures locally: This measure is effective for protecting infrastructure, which must be positioned in or in the vicinity of regional stress transfer structures. High stresses are no longer transferred because of the interception, which is a mined-out part of the regional stress transfer structure. This mined-out part provides a stress blocking function. However, such interceptions can only be utilized on a local scale, because the extent of interceptions in regional stress transfer structures must be small. Otherwise their regional stress transfer function is lost.

7.4.2.2 Effectivity of pillars and backfill for the control of abutment stresses

Utilizing regional stress transfer structures, which are left behind in mined-out areas, to limit the abutment stress magnitudes at active extraction faces was outlined as an effective measure to protect infrastructure, stopes and other excavations in respective abutment areas. However, the effectivity of backfill and pillars for this task can be rather limited.

- Backfill: Backfill is only effective, if it is compressed sufficiently; compare section 7.4.1.2. If a sufficient backfill compression cannot be ensured, which is principally the case in most instances, the utilization of backfill is not effective. However, backfill can be very effective, if it is used to improve the strength and stability of regional stress transfer pillars. Therefore, backfill must be placed along regional stress transfer pillars. First, the backfill provides confinement to the pillar and has thereby a positive impact on the pillar strength and pillar behavior. Second, the backfill provides confinement to the surrounding rock mass and can thereby prevent to some extent that a pillar punches into the floor because of a foundation failure.
- Regional stress transfer pillars: Generally, regional stress transfer pillars are more effective than backfill. The pillar strength is decisive. A sufficient pillar strength can be achieved by pillars with a large width-to-height ratio. However, regional stress transfer pillars sterilize portions of the deposit. This instance becomes particularly critical, if the deposit dimensions necessitate pillars of large heights. Hence, pillar width must increase significantly to maintain a certain width-to-height ratio, which results in the sterilization of large deposit portions.

In summary, regional stress transfer pillars and backfill can lose their effectivity rapidly, if the deposit dimensions, particularly the deposit thickness, increase. The consequences are considerably rising stress magnitudes in the abutments of extraction areas, which can have an adverse effect on infrastructure, stopes or other excavation situated in these abutments.

7.4.2.3 Impact of ongoing extraction

The ongoing extraction alters the stress situation in as well as the properties of regional stress transfer structures. In section 6.1.4.2 possible changes were outlined on basis of two neighboring mining panels separated by a regional stress transfer pillar. The effect of ongoing extraction is especially critical for regional stress transfer structures, because they are highly stressed and even small changes can cause their failure. Furthermore, the failure of regional stress transfer structures can have far-reaching, mine-wide consequences. Concluding, these considerations highlight the importance of an in-advance, foresighted planning of the position of regional stress transfer structures and the mining sequence. Moreover, the behavior and performance of regional stress transfer structures during ongoing extraction require special attention for this reason.

7.5 Stress distribution function

The objective of the stress distribution function is to distribute far-field stresses within the mine and in doing so to contribute to the control of the flow of far-field stresses through the mine. The stress distribution function is closely linked with the regional stress transfer function. The stress distribution function relies on the loading system element and its physical effect of distributing stresses. As the loading system has a strong impact on the stability of failure processes, the stress distribution function can also be related to having an impact on the stability of failure processes.

The loading system element, which is responsible for the stress distribution function, is a dependent element, because it is formed as a consequence of creating excavations, pillars and extraction areas; compare section 6.1.3. Thus, its characteristics and properties depend on and are principally a complex function of the excavations, pillars and extraction areas forming the loading system as well as the prevailing rock mass properties and the prevailing stress situation. In section 6.1.3 relevant aspects, dependencies and governing parameters regarding loading system characteristics and properties were outlined.

For the actual determination of the loading system characteristics and properties and the stress distribution function detailed analyses of the whole mine layout, mining sequence and prevailing mining environment are necessary. As the loading system characteristics and properties are influenced by the prevailing mining environment, the overall mine layout and the mining sequence, they cannot be adapted or altered with other measures at a reasonable effort. Moreover, sudden, unexpected changes of a loading system and thus of its stress distribution function can manifest themselves in severe rock pressure conditions. An example for this is mining through a weak fault or failure of the rock mass forming the loading system; compare section 6.1.3.2. For these reasons, careful and foresighted planning from an early stage on is decisive. Foresighted planning becomes even more relevant, because the loading system stiffness decreases generally with the advancing extraction, which in fact increases the probability of unstable failure processes. Furthermore, the stope layout must be adapted, at least at an advanced stage, to the deposit boundaries and the possibilities of influencing the loading system characteristics and properties positively by the stope (mine) layout diminish further.

Finally, it is remarked that the stress distribution function has in combination with the regional stress transfer function a significant effect on the overall stability of the mine. Changes of the stress distribution function can have significant, mine-wide consequences related to stability and the control of stresses and mining-induced seismicity. Besides this regional aspect the stress distribution function is also relevant on a local scale for the stability of individual mining panels or extraction areas as well as for the stability of failure processes.

7.6 Protection function

The objective of the protection function is to protect certain portions of the rock mass or other elements, such as excavations or pillars, from high stresses or mining-induced seismicity. The protected portions of the rock mass, excavations, pillars etc. are referred to as protected object in the following. Furthermore, it is reasonable to distinguish between a direct protection function and an indirect protection function.

- The direct protection function makes use of the physical effect of excavations and pillars on the resultant stress distribution. The resultant stress state is influenced such that fracture or failure of the protected object is prevented. Therefore, the direct protection function typically restricts the stress magnitudes being present at the protected object such that a critical stress magnitude causing fracture or failure is not exceeded. Thereby, the protection of the object can on the one hand prevent the occurrence of rock pressure problems at the position of the protected object or on the other hand eliminate a source, which can cause rock pressure problems distant from the protected object. An example for the protection at the position of the protected object is limiting the stress magnitudes at the position of active, critical infrastructure and an example for the elimination of a source is preventing fault slip, which can cause rock burst damage at positions distant from the activated fault. As sources of potential rock pressure problems are addressed, the direct protection function is an active stress control measure.
- The indirect protection function makes use of excavations and their physical effect of creating a void. The indirect protection function focuses mainly on protecting objects from mining-induced seismicity. Therefore, the indirect protection function either prevents that seismic waves hit the protected object or attenuates seismic waves, before they hit the object. However, the source of the potential rock pressure problem is not addressed by the indirect protection function. Furthermore, the indirect protection function is often a side effect of excavations, which are created because of other purposes, such as mineral extraction or reduction of stress magnitudes. Accordingly, the indirect protection function relates normally to a passive stress control approach.

7.6.1 Rock mechanics aspects of the protection function

7.6.1.1 Direct protection function

The direct protection function is utilized to restrict the prevailing stress magnitudes at the position of the protected object. Figure 144 outlines the effects of the direct protection function schematically on basis of a rock mass failure envelope in major and minor principal stress space. Consider a stress state at point 1, which is prevailing in the rock mass prior to mining. As mining progresses, the stress state moves to point 2 and then to point 3. If mining would progress without the direct protection function, the stress state would advance further to point 4, which is above the failure envelope and which would cause failure. However, the direct protection function can be used to prevent that the stress state moves to point 4 or in general that the stress state moves to a point above the failure envelope.

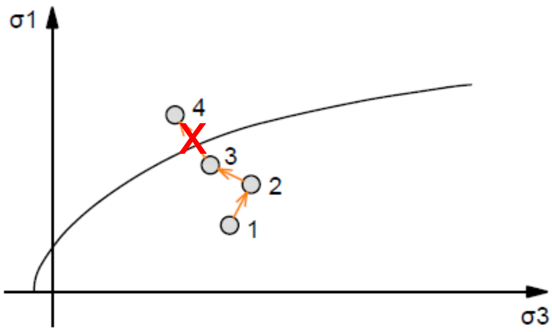


Figure 144: Effect of the direct protection function on the failure of rock mass

The creation of excavations and pillars alters the stress state. Thereby, critical stress states, which cause fracturing and failure of rock mass, can emerge. Such critical stress states are in most instances characterized by a high major principal stress and a low minor principal stress and they are normally prevailing in the vicinity of excavations or pillars; compare sections 6.1.1.1 and 6.1.2.1. The critical stress states diminish with distance from pillars and excavations. Therefore, the direct protection function is realized by maintaining a sufficient distance between excavations and pillars and the object to be protected such that the critical stress state is not prevailing at the position of the protected object. This distance can be considered as a kind of safety pillar. Examples are bracket pillars or shaft pillars. Indeed, portions of the deposit may be sterilized because of these pillars.

In order to determine the distance that must be kept, it is generally necessary to consider the complete mining layout particularly extraction areas and regional stress transfer structures, which cause regional stress redistributions. Furthermore, the effects of ongoing mining activities in extraction areas on protected objects should be monitored continuously. This monitoring enables to determine, whether the direct protection function is provided, and it further allows to optimize the direct protection function to the prevailing mining conditions by adapting the distance between advancing mining fronts and the protected object. The extraction may be stopped earlier than planned, if the rock pressure situation at the position of the protected object deteriorates, or later than planned, if the rock pressure situation at the position of the protected object is still acceptable.

The direct protection function seems to have parallels to the stress blocking function and the strength enhancing function, which also address the resultant stress state and aim for providing improved stress conditions. However, there is a distinct difference, namely that the direction protection function aims for preventing that the stresses exceed a critical magnitude, which causes fracturing and failure, whereas the stress blocking function and the strength enhancing function are utilized to generate a more favorable stress state, which either removes high stress magnitudes or which improves the strength of rock mass.

7.6.1.2 Indirect protection function

The indirect protection function is utilized to protect an object from mining-induced seismicity, which is released distant from the protected object. Figure 145 outlines the effect of the indirect protection function on basis of a mined-out, backfilled area and a tunnel situated in its vicinity. Seismic waves, which are generated due to a seismic event at position 1, hit the mined-out area, a portion of the seismic waves is reflected and a portion of seismic waves passes through the backfilled, mined-out area. Accordingly, a certain amount of seismic energy is diverted and cannot hit the tunnel, which is hence protected by the mined-out area. The effectivity of the indirect protection function may be reduced, if the mined-out area is backfilled with a tightly packed, stiff backfill or if pillars are left inside it. The backfill or pillars cause that seismic waves are not completely reflected. Instead, some seismic waves can pass through the mined-out area. The amount of reflection depends strongly on the properties of the backfill or pillars as well as on the contact between them and the surrounding rock mass. Generally, soft, loose, uncompressed backfill is preferable, because it limits the amount of seismic energy, which can pass through the mined-out area. In contrast, if the seismic event occurs at position 2, the mined-out area does not protect the tunnel at all. Hence, the position of the protected object relative to the position of the seismic event and the excavation (mined-out area) providing the indirect protection function is critical. Furthermore, backfill or pillars inside the excavation (mined-out area) and their properties are relevant for the amount of seismic waves, which are transmitted and which are reflected.

The indirect protection function is mostly a side effect of excavations, which are created for other reasons, such as mineral extraction or de-stressing of rock mass. Thus, these excavations are mainly situated in the ore body. The infrastructure, which is to be protected from seismicity, can then be positioned either in the footwall or hangingwall. Therefore, the major sources of seismic events need to be identified first. If the major sources are in the hangingwall, the infrastructure can be situated in the footwall and the mineral extraction inside the ore body provides the indirect protection function. In contrast, if the major sources of seismic events are in the footwall, the infrastructure may be placed in the hangingwall, if the hangingwall rock mass conditions and the mining method allow it. If conditions do not allow situating the infrastructure in the hangingwall, other measures such as improved support or reinforcement or specifically designed mine layouts and mining sequences, which avoid the activation of major seismic sources (direct protection function), need to be implemented.

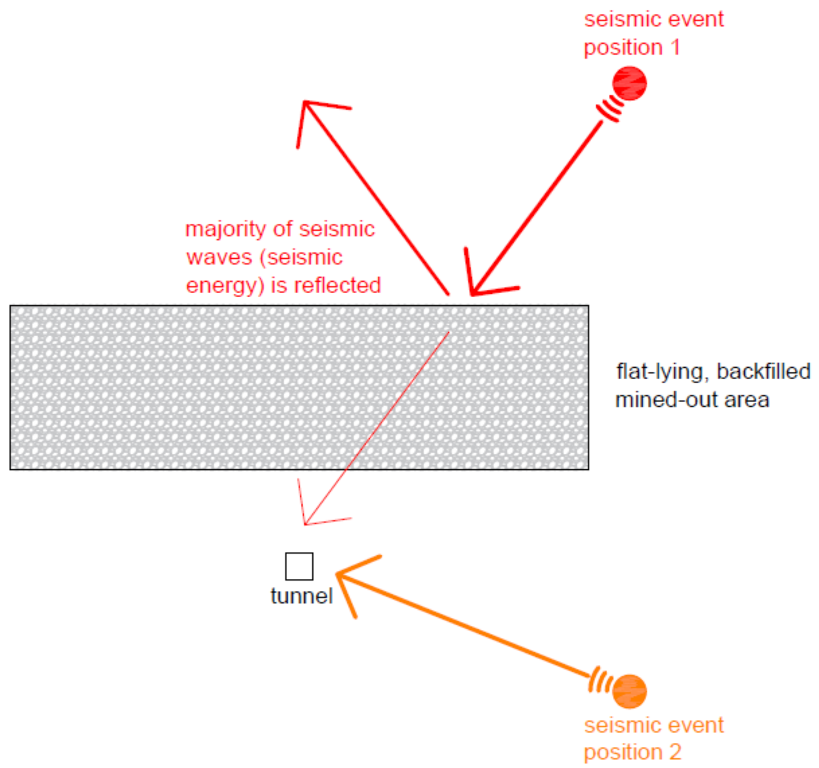


Figure 145: Effect of the indirect protection function related to the protection of a mine tunnel

7.6.2 Production aspects of the protection function

The main purpose of the protection function is related to rock mechanics, namely to protect certain rock mass portions, infrastructure etc. from high stresses and mining-induced seismicity. From a production point of view relevant aspects are the position relative to active extraction faces and time of implementation of the direct protection function. Generally, two different situations can be distinguished, namely implementing the direct protection function ahead of active extraction faces or behind active extraction faces; compare Figure 146.

- Implementation ahead: In this case the extraction face advances towards the object to be protected; compare Figure 146a. If the direct protection function is implemented ahead of the active extraction face, the stress state at the position of the protected object evolves gradually towards a potentially critical state. The behavior and stability of the protected object can be monitored and advancing the extraction face can be stopped, if monitoring indicates that the stress state at the protected object starts to become critical. A disadvantage of implementing the direct protection function ahead is that, if the protection function malfunctions unexpectedly, mining activities take place close to the failing rock mass portions or structures. Accordingly, nearby active infrastructure or other excavation can suffer significant damage resulting from this malfunction.
- Implementation behind: In this case the extraction face advances away from the object to be protected; compare Figure 146b. Therefore, the distance between the

extraction area and the protected object is fixed at the beginning and cannot be increased as mining progresses, which instance removes the possibility to adapt the distance according to the observed behavior of the protected object. The advantage of implementing the direct protection function behind an active extraction face is that a potential failure of the protected object and the corresponding release of seismic energy take place distant from active extraction faces. However, the energy changes at the active face, which result from advancing the active face, can, at least in tabular deposits, still be significant. This is reflected in mining experience, which outlines that the majority of rock bursts take place at the active face. (Salamon, 1983a)

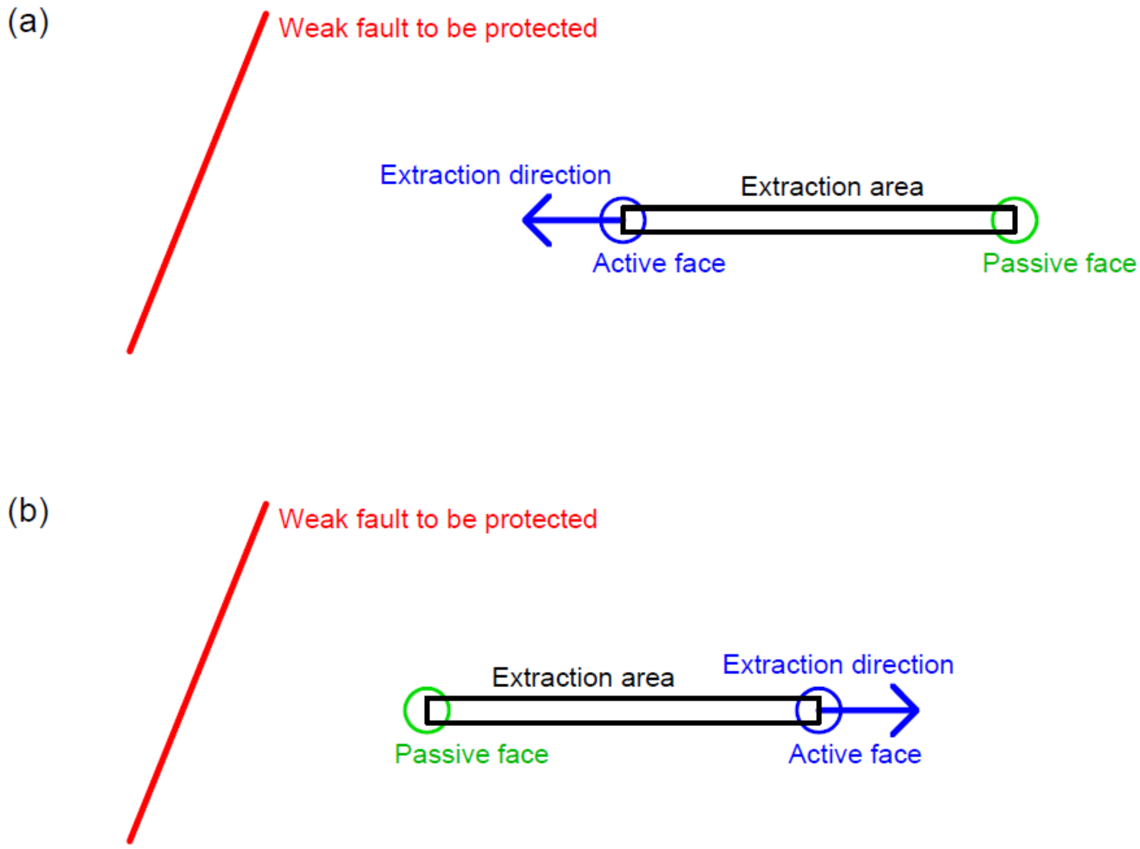


Figure 146: Implementing the direct protection function (a) ahead or (b) behind active extraction faces

7.7 Strength enhancing function

The objective of the strength enhancing function is to increase the strength of rock mass or of structures, such as pillars, comprised of rock mass. Another objective is to influence the post-peak behavior of rock mass or structures comprised of rock mass such that the rate of strain softening decreases or that a strain softening behavior is transformed to a yielding or strain hardening behavior. Therefore, the likelihood of fracture or failure decreases. Moreover, the potential for an unstable failure is reduced.

The strength enhancing function makes use of the physical effect of backfilled excavations and pillars on the resultant stress situation.

7.7.1 Rock mechanics aspects of the strength enhancing function

In order to increase the strength of rock mass, the strength enhancing function is utilized to increase the minor principal stress magnitude. Figure 147 outlines the effect of the strength enhancing function schematically on basis of a rock mass failure envelope in major and minor principal stress space. Consider the stress state at point 1, which is located above the failure envelope. The strength enhancing function increases the minor principal stress. The stress state moves to point 2, which is now located below the failure envelope. (Note that for simplification it is assumed that the major principal stress is not altered by the strength enhancing function.) Consequently, the stress state in the rock mass is moved from a point of failure to a stress state, for which rock mass failure does not occur. Additionally, the increased minor principal stress resulting from the strength enhancing function may influence the post-peak behavior positively by reducing the strain softening rate.

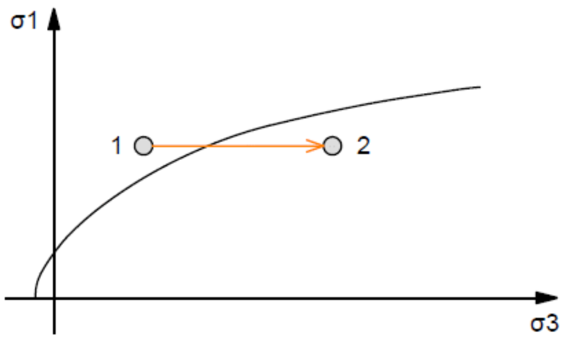


Figure 147: Effect of the strength enhancing function on the rock mass

The strength enhancing function relies on the resultant stresses caused by the creation of pillars or excavations, which are subsequently backfilled.

- In case of pillars the stresses, which are transferred through the pillar, increase the resultant stress magnitudes in the vicinity of the pillar and the influence of the pillar on the resultant stress state diminishes with distance from the pillar; compare section 6.1.2.1. These increased stress magnitudes in the vicinity of the pillar provide the strength enhancing function. Important is that the resultant stress magnitudes in the vicinity of the pillar do not exceed a certain magnitude, which can cause damage in the rock mass. In such a case the strength enhancing effect is lost and even worse it is turned into a damage accelerating effect. The stress magnitudes in the vicinity of a pillar can mainly be influenced by pillar properties; compare section 6.1.2.2.
- In case of backfilled excavations the complete excavation can be backfilled or only the parts of the excavation, where the strength enhancing function is required. As the backfill is compressed due to deformations of the excavation, it generates a reaction stress, which increases the minor principal stress in the surrounding rock mass; compare section 7.3.1.2. The backfill properties, backfill placement quality,

the excavation size and the occurring excavation deformations are important. The strength enhancing effect diminishes with distance from the backfilled areas.

The strength enhancing function seems to be similar to the regional stress transfer function, as both functions rely on the transfer of stresses through pillars or on the generation of reaction stresses due to the compression of backfill. However, the objectives of the regional stress transfer function and the strength enhancing function are different.

- In case of the regional stress transfer function regional stress transfer pillars transfer far-field stresses and the rock mass in and near regional stress transfer pillars is highly stressed; compare section 7.4.1.3. Usually, the stress magnitudes in the vicinity of regional stress transfer pillars are that high that they can cause significant damage. For this reason, the regional stress transfer function does not enhance the rock mass strength.
- In contrast, the stress magnitudes, which are transferred by pillars for the implementation of the strength enhancing function, must be significantly lower. This implies that crush pillars with a low residual strength are best suited for providing a strength enhancing function. These crush pillars must crush reliably and in a stable manner. By doing this crush pillars can ensure hangingwall stability in the working area and prevent shearing of the hangingwall at the working face. The load bearing capacity of the crush pillars must not exceed the foundation strength of the immediate hangingwall and footwall rock mass so that crush pillars do not cause damage but so that they rather increase the strength of rock mass.

Backfilled excavations have the advantage over pillars that the reaction stress magnitudes in the backfill, which provide the strength enhancing function, build up gradually and slowly. Furthermore, the backfill properties and backfill placement quality allow to control the reaction stress. Therefore, damage to the surrounding rock mass can usually be excluded. An unstable failure of backfill can principally be excluded as well. The disadvantage of backfilled excavations is though that the realizable reaction stress magnitudes and hence the strength enhancing effect are in most instances significantly lower than that of pillars and that the strength enhancing effect of backfilled excavations develops usually later compared to pillars.

7.7.2 Production aspects of the strength enhancing function

The main purpose of the strength enhancing function is related to rock mechanics, namely the increase of rock mass strength and the alteration of rock mass post-peak behavior in order to gain safety and operational benefits. From a production point of view the critical aspect related to the strength enhancing function is, whether corresponding pillars and backfilled excavations can be created without counteracting the objectives of mineral extraction. Therefore, the safety during their creation, the potential sterilization of reserves in pillars as well as potential additional cost and time have to be considered. However, the sterilization of reserves and the additional costs and time must be seen in context to later gained benefits, for example improved stress conditions or higher productivity during extraction, from the strength enhancing function, which can exceed the loss of reserves and the additional efforts by far. In summary, creating pillars or backfilled excavations providing a strength enhancing function are an investment into improved mining conditions.

7.8 Data and experience collection function

The objective of the data and experience collection function is to collect data and experience regarding the prevailing rock mass strength and behavior, the strength and behavior of pillars, the distribution of rock mass properties etc. The data and experience collection function makes use of the auxiliary monitoring and observation elements. The data and experience collection function and the subsequent structured analysis of data and experience are central for the successful implementation of the proposed stress management concept. First, they allow detecting deviations from expected behavior and critical developments at an early stage and, second, they enable to reduce the uncertainties related to the prevailing mining environment. The uncertainties comprise the distribution of rock mass properties, the strength and behavior of rock mass, the strength and behavior of pillars or the characteristics of loading systems.

Data and experience must be collected continuously throughout the lifetime of the operation. The active infrastructure and active mining areas and other areas, which are critical for stress control, such as left behind regional stress transfer pillars, must be included in data and experience collection. After data and experience were collected, they must be reviewed and analyzed on a regular basis to detect deviations from the expected behavior and to reduce the uncertainties. Furthermore, the gained improved knowledge and understanding must then be considered and implemented in the planning of future mining layouts and mining sequences as well as in adaptions of the current operation. If the analysis of data and experience is not conducted rigorously and on a regular basis, the collected data and experience is of very limited value and the costs and efforts spent in data and experience collection is lost. However, if the collected data and experience is utilized for the continuous improvement of the operation, the benefits of data and experience collection and their subsequent analysis exceed the additional costs and efforts by far.

8 Implementation of the stress management concept

The objectives of an appropriate stress management were outlined in section 2.3.1 and they aim on enabling or at least facilitating a safe, as complete as possible and profitable mineral extraction. A shortage of active stress management approaches was identified (section 2.5) and for this reason a stress management concept was proposed in the previous chapters. The proposed stress management concept is comprised of main and auxiliary elements and corresponding element functions. For the implementation of the proposed stress management concept the elements and their functions must be combined systematically and strategically to control the stress situation and energy release.

In this chapter the implementation of the stress management concept is discussed. The implementation comprises in the first step de-stressing of the deposit. In this step, which is referred to as de-stressing phase, stress shadows are created and high stresses and mining-induced seismicity are concentrated and constrained into areas and zones, where they do not have an adverse impact on the operation. Specific layouts and sequences are applied in the de-stressing phase. In the second step, which is referred to as production phase, large-scale mineral extraction takes place. Therefore, the created stress shadows are utilized. Infrastructure is developed and stopes are extracted in stress shadows, which offer more favorable stress conditions and which thus improve stability of the mine workings. Furthermore, the stress shadows enable to place mine infrastructure and stopes outside of highly stressed zones and seismically active areas. Besides utilizing the stress shadows the layout and sequence of the large-scale mineral extraction must ensure that high stresses and mining-induced seismicity remain concentrated and constrained to specific, designated areas and zones. This implementation of the stress management concept is referred to as “de-stressing strategy” subsequently.

The de-stressing strategy relies on an active stress control approach and hence the mine layout and mining sequence are central for its successful implementation; compare section 4.2. The de-stressing phase of the de-stressing strategy is principally high stress mining and hence does not provide a high production and high productivity. Instead, the de-stressing phase is an investment into an improved, favorable rock pressure situation in the production phase and throughout the remaining life of the mine. As a result, the production phase enables on the one hand a higher production and productivity and on the other hand an increased safety of the operation. In summary, the de-stressing strategy facilitates to achieve the aims of mineral extraction.

A comparable de-stressing strategy has been implemented in deep South African gold mines successfully (section 2.4.1). However, the South African de-stressing strategy is based in most situations on rather labor-intensive, non-mechanized and thus expensive stoping methods. Moreover, the South African de-stressing strategy is rather limited to the prevailing tabular gold reef mining environment. For this reason, there is a shortage of (productive) de-stressing strategies in many other mining environments and in particular in steeply dipping and massive deposits; compare section 2.5.

In order to overcome this shortage, possible layouts and sequences for the implementation of the de-stressing strategy are discussed in this chapter. An emphasis is thereby put on steeply dipping and massive deposits as well as on productive extraction methods and on methods, which allow for a high production. Therefore, the central aspects of the de-stressing strategy are highlighted and layouts and sequences are discussed on a conceptual basis. Then, relevant issues in the de-stressing phase and production phase are outlined and discussed. The demand for flexibility, which is critical for the implementation of the stress management concept, is highlighted and discussed as well. An application study for the implementation of the de-stressing strategy in a steeply dipping or massive deposit is then given in chapter 9.

8.1 Central aspects of the de-stressing strategy

8.1.1 Principle of the de-stressing strategy

The de-stressing strategy relies on de-stressing the parts of the deposit, which are extracted subsequently, and on concentrating and constraining high stresses and mining-induced seismicity to areas, where active infrastructure and stoping areas are not located. Figure 148 illustrates the general concept on basis of a horizontal cross-section of a massive deposit with a considerable vertical extent. The direction of the major and intermediate principal stress is horizontal, whilst the minor principal stress is vertical. Furthermore, the major principal stress is considerably higher than the other two principal stresses. A specifically designed de-stressing excavation, which provides a stress blocking function against the major principal stress, is created in the de-stressing phase. Consequently, the major principal stress is diverted by this de-stressing excavation and a stress shadows form in parts of the deposit, which are extracted subsequently. The extraction of the deposit can then be conducted in de-stressed ground. The prevailing stress magnitudes near stopes and associated infrastructure are considerably lower than they would be without the de-stressing excavation and the rock mechanics conditions are improved significantly. Furthermore, mining-induced seismicity is concentrated into areas distant from active stopes and active infrastructure in the production phase.

As shown in Figure 148, the creation of the de-stressing excavation does not generate a stress shadow in the whole deposit. Thus, further de-stressing excavations have to be developed at other positions. Moreover, stoping activities, which are conducted in de-stressed ground, cause further stress redistributions, which can result in the formation of additional de-stressed areas. Figure 149 illustrates such an advanced stage, where additional de-stressing excavations were created, where stoping commenced and where stoping generated additional stress shadows. Furthermore, Figure 149 highlights that the primary stress field is increasingly disturbed and that the control of the flow of far-field stresses becomes crucial. For this purpose regional stress transfer pillars are left between individual de-stressing excavations and extraction areas. Overall, the mine layout and mining sequence are decisive to provide stress shadows in the de-stressing phase and in the production phase as well as to concentrate and constrain high stresses and mining-induced seismicity to specific, designated areas.

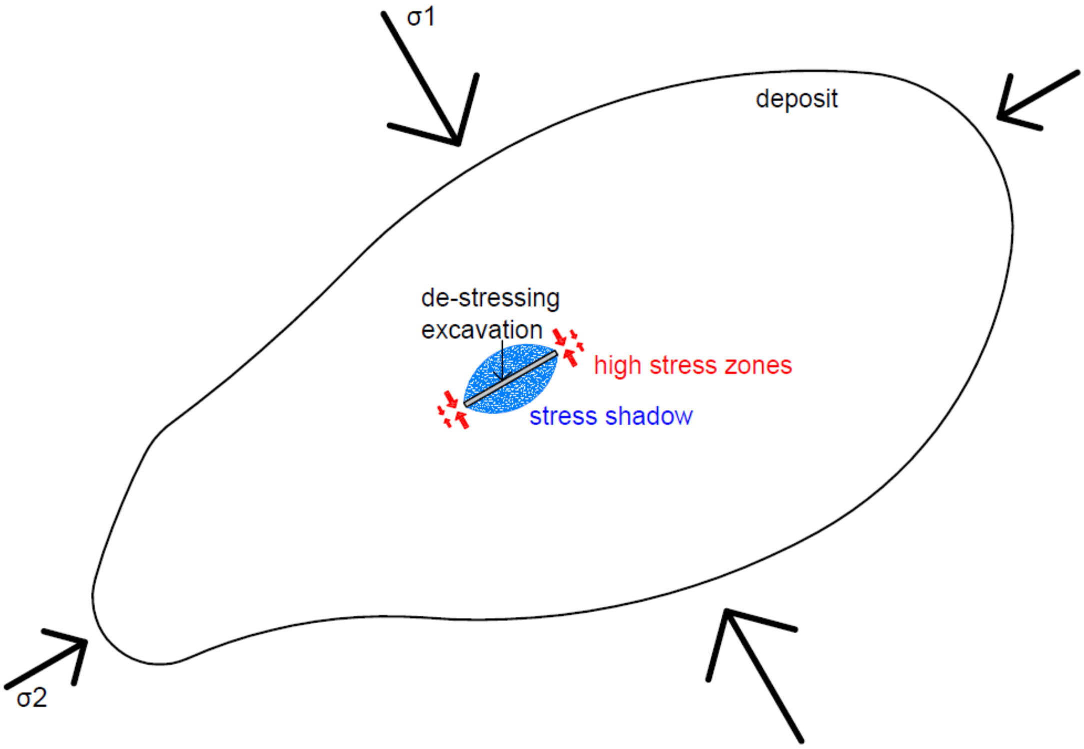


Figure 148: De-stressing strategy at an early stage illustrated in a horizontal cross-section of a massive deposit with a considerable vertical extent; the infrastructure is not shown for simplification reasons; red arrows indicate the magnitude of abutment and pillar stresses.

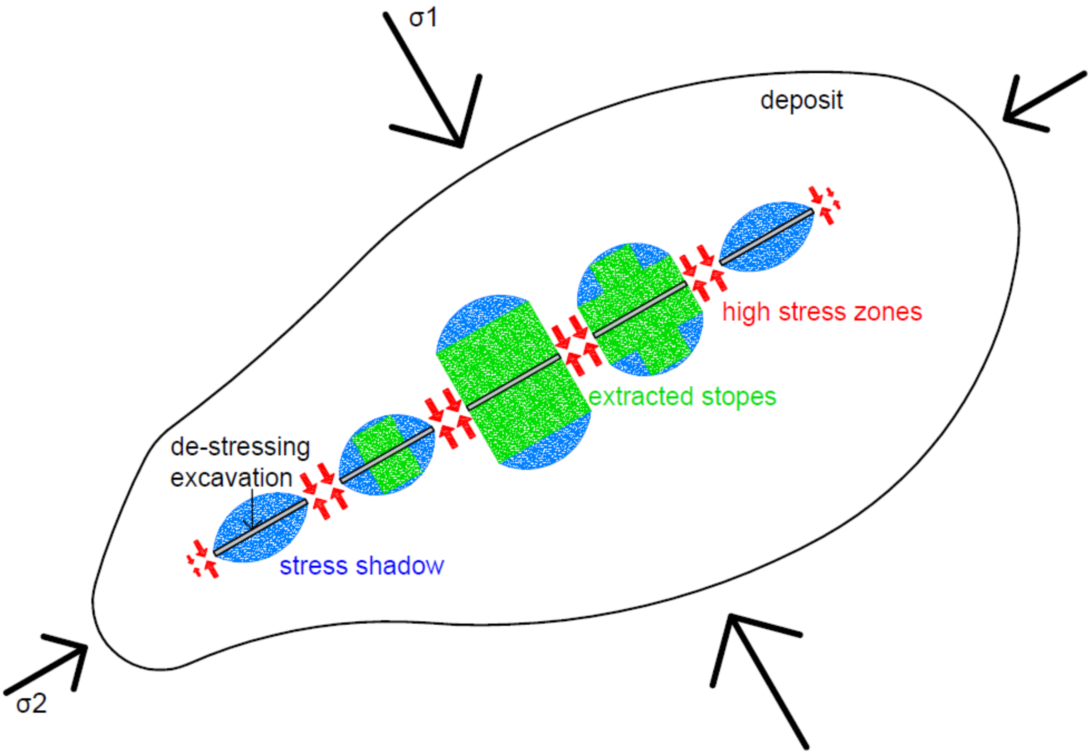


Figure 149: De-stressing strategy at an advanced stage of extraction in a horizontal cross-section of a massive deposit with a considerable vertical extent; the infrastructure is not shown for simplification reasons; red arrows indicate the magnitude of abutment and pillar stresses.

8.1.2 Advantages of the de-stressing strategy

The de-stressing strategy offers considerable advantages, which are outlined and described briefly in the following:

- Protection from high stresses and mining-induced seismicity: Active extraction areas and corresponding infrastructure are situated in de-stressed ground. The prevailing stress magnitudes can be decreased and the prevailing stress magnitudes in active extraction areas correspond mostly to stress magnitudes at shallower depths. Hence, deep mining conditions can be transformed to comparatively shallow mining conditions. However, it must be considered that certain areas in the rock mass are highly stressed as a consequence of creating de-stressing excavations. Furthermore, the de-stressing strategy enables to protect active extraction areas from mining-induced seismicity.
- Concentration of high stresses and mining-induced seismicity: Highly stressed areas and seismically active areas can be concentrated to specific locations distant from active extraction areas and corresponding infrastructure. This concentration is an integral part of the protection of production areas.
- Enabling the application of productive extraction methods: The absence or significant reduction of high stresses and mining-induced seismicity in the provided de-stressed ground enables the application of large-scale, productive mining methods, mine layouts and mining sequences. Without de-stressing these methods would not be applicable at great depths without major rock mechanics related difficulties.
- Reduction of uncertainties related to the mining environment: De-stressing excavations are created, before large-scale stoping commences. Therefore, data and experience related to the prevailing mining environment can be collected at an early stage. Consequently, the uncertainties, which are especially present for the distribution of rock mass properties and the strength and behavior of rock mass, can be reduced. The improved understanding of the mining environment can then be incorporated into the design of extraction areas.
- Reduction of the importance of flexibility in extraction areas: Flexibility for changes in the mine layout and mining sequence was identified to be critical to address uncertainties respective the mining environment. Furthermore, the flexibility is particularly important in deep mining conditions, in which an improper layout and sequence can manifest themselves in significant rock pressure problems relatively quickly. As the de-stressing phase generates a low stress environment for the subsequent production phase and as uncertainties are reduced during the de-stressing phase, the flexibility in extraction areas is not as decisive as it would be without the de-stressing phase. Indeed, a certain degree of flexibility must still be provided to control the stress situation and to concentrate high stresses and mining-induced seismicity to designated areas.
- Adaptability to the prevailing mining environment: The de-stressing strategy can be adapted to the prevailing mining environment. The position, size and orientation of de-stressing excavations can be chosen relatively freely and adapted to the local

requirements. Adaptions regarding the de-stressing excavations are normally possible at reasonable efforts, because the required amount of infrastructure in the de-stressing phase is (should be) relatively low. Furthermore, the subsequent stoping activities in de-stressed ground in the production phase are (must be) designed such that stress shadows are provided at required positions continuously throughout the lifetime of the operation.

In summary, the de-stressing strategy is effective and powerful. It enables active stress control and it is thus compliant with the proposed stress management concept. Furthermore, it facilitates the objectives of mineral extraction, namely the safe, as complete as possible and profitable extraction of deposits.

8.1.3 Critical aspects of the de-stressing strategy

Despite the offered advantages of the de-stressing strategy there are some critical aspects, which must be considered for its implementation. These aspects concern mainly the activities in the de-stressing phase. Subsequent stoping activities in the production phase benefit already from the provided stress shadows, which instance removes some of the critical aspects. Important aspects are:

- The de-stressing phase is an investment into improved mining conditions. The creation of de-stressing excavations must be conducted, before large-scale mineral extraction commences, and it can increase the time, until full production is achieved. Thus, the de-stressing strategy calls for additional costs and time at an initial stage. Furthermore, the subsequent stoping layouts and sequences, which are deployed in the de-stressed zones, may be restricted so that the implemented active stress control approach is maintained. However, the advantages gained from the de-stressing strategy pay off the additional costs and any other possible restrictions resulting from its implementation. The de-stressing strategy must therefore be considered as an investment into improved mining conditions.
- The mining activities in the de-stressing phase are high stress mining. The de-stressing excavations, which are created in the de-stressing phase, must be developed in primary stress conditions and hence mining activities in the de-stressing phase can mostly not benefit from stress shadows. This instance is particularly critical for the active infrastructure, which provides access to de-stressing excavations and which is thus situated in the vicinity of de-stressing excavations. Accordingly, high stresses and mining-induced seismicity in the de-stressing phase must be managed by concentrating and constraining them into areas distant from active infrastructure and ongoing mining activities so that the mining activities in the de-stressing phase can be conducted in a safe manner. In general, it is important to limit the mining activities in the de-stressing phase, in which high stress mining conditions are present. Hence, stress shadows should only be provided at required locations and the amount of infrastructure, which is required in the de-stressing phase, should be minimized.
- Main and some primary infrastructure are already required in the de-stressing phase. The main and primary infrastructure provide access to the deposit and they

are therefore already required in the de-stressing phase. Consequently, the upfront developed main and primary infrastructure is exposed to high stress conditions as well and they can also not be protected with stress shadows. Alternative protection measures, which rely on concentrating and constraining high stresses and mining-induced seismicity to areas distant from this main and primary infrastructure, are necessary.

- The mining activities in the production phase must ensure the continuation of the favorable rock pressure situation, which was created in the de-stressing phase. After the de-stressing phase was implemented, stress shadows are available for the subsequent production phase. However, subsequently deployed production layouts and sequences must ensure that the active stress control approach, which was implemented in the de-stressing phase, is maintained. This matter concerns on the one hand the continuous provision of stress shadows and on the other hand the continuous concentration of high stresses and mining-induced seismicity to specific, designated areas, where high stresses and mining-induced seismicity do not have adverse consequences on the ongoing large-scale mineral extraction.
- Deteriorated rock mass conditions can be prevailing in the production phase. As the de-stressing phase is high stress mining, stress induced fracturing and failure may occur in certain areas and in particular in the vicinity of de-stressing excavations. This fracture and failure often occur in typical pattern and orientations depending on the prevailing rock mass conditions and the layout and sequence in the de-stressing phase. Overall, fracture and failure deteriorate the rock mass conditions. Infrastructure and stopes of the subsequent production phase can be affected by these deteriorated rock mass conditions and the potential impact of deteriorated conditions must be considered in the design of stoping layouts and sequences.

The critical aspects are discussed further in combination with the implementation of the de-stressing strategy in the following sections.

8.2 Layouts and sequences in the de-stressing phase

In the first stage of the de-stressing strategy, which is referred to as de-stressing phase, de-stressing excavations are created. In most instances the production in the de-stressing phase is rather limited and large-scale production follows afterwards in the production phase. An exception are deposits, which are of such small dimensions that they can be extracted in the de-stressing phase completely, such as most of the deep South African gold mining operations. In this instance the de-stressing phase provides solely protection for delayed developed infrastructure.

The layout of de-stressing excavations and their development sequence, must ensure following points:

- Stress shadows of sufficient spatial extent with a sufficient stress drop are generated at required positions so that subsequent large-scale mineral extraction can commence in de-stressed ground.
- The infrastructure required for creating the de-stressing excavations is protected from high stresses and mining-induced seismicity so that the mining activities in the de-stressing phase can be conducted in a safe manner.

For the first point, the size, shape, orientation and position of de-stressing excavations is most important; compare section 6.1.1.1. However, these de-stressing excavations must be created in the (high) primary stress field. Accordingly, significant stress and energy changes take place, which can result in high abutment stresses and significant amount of seismic energy release. Infrastructure, which is required for the creation of de-stressing excavations, must be protected from these high stresses and mining-induced seismicity. Particularly critical is infrastructure, which must be placed into abutment areas of de-stressing excavations, which are typically highly stressed and associated with significant seismic activity, because of operational or logistical reasons, as this infrastructure can suffer severe damage. In order to avoid damage to infrastructure, an appropriate layout and sequence in the de-stressing phase are decisive.

As the protection of infrastructure in the de-stressing phase is central, the strategy of protecting infrastructure actively from high stresses and mining-induced seismicity allows to differentiate between two generic de-stressing layouts and sequences. The main difference of these layouts and sequences is, whether infrastructure must be exposed to highly stressed abutment areas on a regular basis. Considered layouts and sequences are:

- <u>Integrated or delayed developed infrastructure:</u> In this layout and sequence the infrastructure required for the creation of de-stressing excavations is integrated into de-stressing excavations or developed delayed inside already de-stressed zones. Hence, active infrastructure is not situated in or near highly stressed abutments. This layout is also referred to as “layout 1” in the following.
- <u>Ahead developed infrastructure:</u> In this layout and sequence the infrastructure required for the creation of de-stressing excavations is developed before the extraction of de-stressing excavations. Hence, active infrastructure is exposed to abutment stresses and corresponding mining-induced seismicity. This layout is also referred to as “layout 2” in the following.

8.2.1 Integrated or delayed developed infrastructure (layout 1)

8.2.1.1 Layouts for de-stressing excavations with integrated or delayed developed infrastructure

The principal layout of de-stressing excavations developed from infrastructure, which is integrated in de-stressing excavations or which is developed delayed, is shown in Figure 150. The de-stressing excavation provides the stress blocking function (section 7.3) and the infrastructure the access function (section 7.1). The infrastructure required for the creation of the de-stressing excavation is protected from highly stressed abutment areas, because it is either developed delayed inside the stress shadow, which is generated by the de-stressing excavation, or it is integrated into the de-stressing excavation and hence part of the de-stressing excavation and thus not exposed to abutment areas. The delayed infrastructure development is possible some distance behind the advancing face of the de-stressing excavation so that it is located inside the stress shadow. Near the advancing face the infrastructure must be integrated into the de-stressing excavation, otherwise it is exposed to the abutment area. This implies that the access to the advancing face of the de-stressing excavation is always inside the de-stressing excavation.

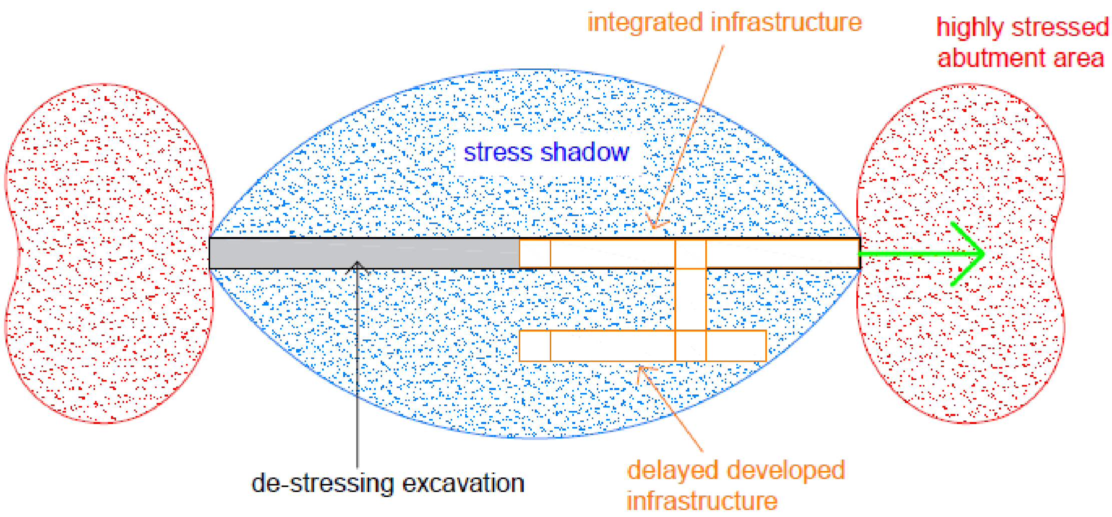


Figure 150: Vertical cross-section showing the principal layout of de-stressing excavations developed from infrastructure, which is integrated in de-stressing excavations or which is developed delayed; the green arrow shows the direction, in which the de-stressing excavation is advanced.

The need for integrating the infrastructure into the de-stressing excavation near the advancing face impacts on the design of de-stressing excavations, namely:

- The de-stressing excavation (at least at the advancing face) is an entry-type excavation and must be stable. As de-stressing excavations must in most instances be of such a size that they cannot be stabilized solely with support and reinforcement elements, an areal support in form of backfill or crush pillars is required. Hence, de-stressing excavations, where the infrastructure is integrated or developed delayed, are in most instances either completely filled (section 7.3.1.2) or partially filled (section 7.3.1.3) de-stressing excavations.
- The de-stressing excavation has to be flat-lying or slightly inclined, otherwise the integration of the access to the advancing face, which can be used by mechanized equipment, is barely possible. For this reason, de-stressing excavations, where the infrastructure is integrated or developed delayed, are mainly suitable for reducing stress magnitudes in vertical direction.

Based on these considerations two principal layouts of de-stressing excavations, which are created with delayed developed infrastructure or integrated infrastructure, can be distinguished:

- The first layout relies on the use of crush pillars, which provide areal support to the surrounding rock mass. The rooms between crush pillars are the integrated infrastructure inside the de-stressing excavation. Rooms, which are not required as infrastructure, can be backfilled to improve the stability of the de-stressing excavation.
- The second layout is a completely filled de-stressing excavation with delayed developed infrastructure. The backfill is placed directly behind the advancing face. Near the advancing face the infrastructure must also be integrated. Therefore, short inclines are developed from the delayed developed infrastructure into the de-stressing excavation.

Both layouts have been successfully applied in deep South African gold mines even though mostly in a non-mechanized and labor-intensive manner; compare section 2.4.1.

The spatial extent of the stress shadows, which are provided by the de-stressing excavations, is linked to the dimensions of the de-stressing excavations. In case of de-stressing excavations, where the infrastructure is integrated or developed delayed, the horizontal extensions of the de-stressing excavations determine the spatial extent of the stress shadow, because these de-stressing excavations are either flat-lying or slightly inclined because of operational reasons. The maximum horizontal extensions of the de-stressing excavations and thus the maximum spatial extent of the stress shadows are limited either by the stability of the de-stressing excavation itself or by the prevailing abutment stress magnitudes or mining-induced seismicity at the advancing face. The stability of the de-stressing excavation is required for the infrastructure, which is integrated into the de-stressing excavation and which provides access to the advancing face. Backfill or crush pillars as an areal support can be utilized to improve the stability of the de-stressing excavation. The abutment stresses or mining-induced seismicity can prevent that the de-stressing excavation can be advanced in a safe manner due to poor conditions at the advancing face. In order to improve the stress situation and conditions at the advancing face, regional stress transfer pillars can be used. These pillars are left between neighboring de-stressing excavations and they provide a regional stress transfer function (section 7.4); compare Figure 151. As a result, the abutment stress magnitudes at the advancing face of the de-stressing excavation are lower than they would be without the regional stress transfer pillar.

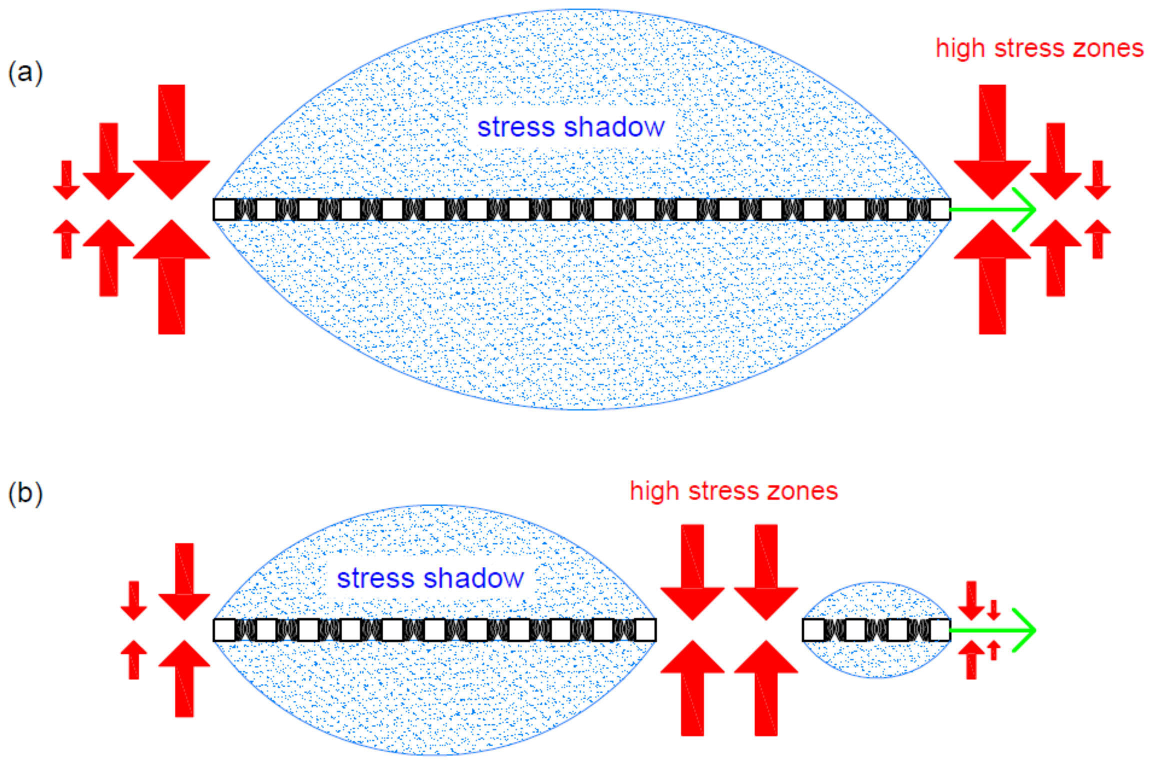


Figure 151: Vertical cross-section of flat-lying de-stressing excavations with crush pillars; (a) without a regional stress transfer pillar, (b) situation with a regional stress transfer pillar between the de-stressing excavations; the advancing face is indicated by the green arrow, the magnitude of pillar and abutment stresses are indicated by the size of red arrows.

8.2.1.2 Protection of access infrastructure to de-stressing excavations with integrated or delayed developed infrastructure

The infrastructure integrated into de-stressing excavations or in the stress shadow of de-stressing excavations is protected from high stresses and mining-induced seismicity. However, infrastructure is required to access de-stressing excavations and the infrastructure, which is already protected by the de-stressing excavations. Hence, infrastructure can be subjected to highly stressed abutments or high stress zones of regional stress transfer pillars. Exposing this infrastructure is especially critical, because the access to de-stressing excavations is usually required for the period, in which the de-stressing excavation is developed. The protection of infrastructure required for accessing de-stressing excavations and crossing regional stress transfer pillars requires specific solutions, which are discussed in the following.

- Positioning infrastructure distant from highly stressed zones: The main issue of the exposure of access infrastructure to stresses of abutments or regional stress transfer pillars arises, if the access infrastructure is situated close to the de-stressing excavation and hence it is also situated in and near highly stressed abutments or pillars. However, this issue can be resolved, if the infrastructure is moved further into the footwall and if the access into the de-stressing excavation is made central, where a stress shadow is present. Thereby, high stress zones from abutments and regional stress transfer pillars are avoided. The required distance between the infrastructure, which crosses abutments and regional stress transfer pillars, and the abutments of de-stressing excavations and regional stress transfer pillars, respectively, is given by the tolerable stress magnitudes at the infrastructure position. This distance fulfills a direct protection function (section 7.6). The disadvantage of this measure is the additional infrastructure demand, which can be significant.

- Excavating additional de-stressing excavations: As an alternative the access infrastructure can be positioned closer to the de-stressing excavations and it is then protected by additional, smaller de-stressing excavations at required positions. At positions, where access infrastructure crosses a regional stress transfer pillar, the pillar was mined-out over a small area to protect the infrastructure. Important in this case is that the access infrastructure is either integrated in the area, where the pillar was mined-out, or it is situated close to the area, where the pillar was mined-out. The pillar should be mined-out at an early stage, when the pillar is not as highly stressed as at an advanced stage. A similar approach is possible for the protection of access infrastructure in the abutment areas of a large de-stressing excavation. Therefore, a de-stressing excavation with smaller dimensions is extracted in respective abutment area. As a result the stress magnitudes at the abutments of this smaller de-stressing excavation are considerably lower than those at the abutments of the larger de-stressing excavation. The access infrastructure of the larger de-stressing excavation is put into this additional smaller de-stressing excavation or close to it so that it is protected from high abutment stress magnitudes.

Independent of the considered protection measure of the access infrastructure the de-stressing excavation should generally be developed away from the access infrastructure. First, the protection measures can be implemented at a stage, where the stress conditions can be handled easier, because of lower (abutment) stress magnitudes. Second, developing de-stressing excavations away from access infrastructure avoids that the access infrastructure is passed by highly stressed abutment areas. Third, the access infrastructure is situated at the passive face, where the seismic activity is usually lower. Illustrative examples for this are provided in section 6.1.4.

8.2.1.3 Sequences for the development of de-stressing excavations with integrated or delayed developed infrastructure

Possible sequences for the development of de-stressing excavations, where the infrastructure is integrated into the de-stressing excavations, and their advantages and disadvantages are outlined on basis of three neighboring, flat-lying de-stressing excavations, which are referred to as excavation 1, 2 and 3 from left to right. The de-stressing excavations have a larger and smaller horizontal extension. Figure 152a shows the geometry and Figure 152b-e show the considered sequences. The discussion of the sequences is based on the conducted analyses in sections 6.1.1, 6.1.2 and 6.1.4.

- The parallel development of the de-stressing excavations in direction of their larger horizontal extension is shown in Figure 152b. The regional stress transfer pillars are formed behind the advancing faces. The advantage of this sequence is that the regional stress transfer pillars are created behind the active faces. The regional stress transfer pillars control and limit the abutment stress magnitudes and released seismic energy at the advancing faces. Therefore, the regional stress transfer pillars enable to maintain acceptable working conditions at the advancing faces. Probable disadvantages of this sequence are that several de-stressing excavations are active at the same time and that production may commence later. Advancing several de-stressing excavations at the same time necessitates that they and their access infrastructure must be kept in safe and operational conditions. First, it requires that more active infrastructure and active excavations are exposed to high stress conditions and second that the exposure is over longer periods, because developing of the de-stressing excavations takes longer. A later production start in de-stressed ground can be caused, if it is necessary to develop a de-stressing excavation completely, before production can commence. A possible solution for these disadvantages is shown in Figure 152c, where excavations 1 and 2 are completely developed and excavation 3 is under development. However, this sequence could result in an (slightly) adverse abutment stress situation at the advancing face of excavation 3.

- The development of de-stressing excavations in direction of their smaller horizontal extension is shown in Figure 152d and Figure 152e. Excavations 1 and 2 are completely developed and excavation 3 is under development. In Figure 152d excavation 3 is developed away from the already created de-stressing excavations, whereas in Figure 152e excavation 3 is developed towards the already created de-stressing excavations. Accordingly, the regional stress transfer pillar is formed behind the advancing face in the sequence shown in Figure 152d and ahead of the advancing face in the sequence shown in Figure 152e. From an operational point of view the sequences shown in Figure 152d and in Figure 152e can have the advantage that only one de-stressing excavation is developed at the same time, which limits their exposure time as well as the exposure time of the corresponding infrastructure to high stresses and mining-induced seismicity. However, from a rock mechanics perspective these two sequences can have significant disadvantages, because the abutment stress situation and situation of mining-induced seismicity are generally adverse compared to the sequences shown in Figure 152b and Figure 152c. Abutment stress magnitudes increase considerably and significant energy changes and the associated release of seismic energy take place near the advancing face, as the extension of excavation 3 is increased. The abutment situation in Figure 152e is principally worse, because the regional stress transfer pillar is formed ahead of the advancing face. Forming the regional stress transfer pillar ahead of the advancing face can result in severe working conditions at the active face and the release of large amounts of seismic energy near the active face, which instances constitute a significant safety hazard. Hence, developing a de-stressing excavation towards an existing de-stressing excavation and thereby forming a regional stress transfer pillar ahead of the advancing face must be avoided.

In summary, the sequences shown in Figure 152b and Figure 152c are preferred, because they offer an improved control of the abutment stress magnitudes and of the mining-induced seismicity near advancing faces of de-stressing excavations and because regional stress transfer pillars are formed behind advancing faces.

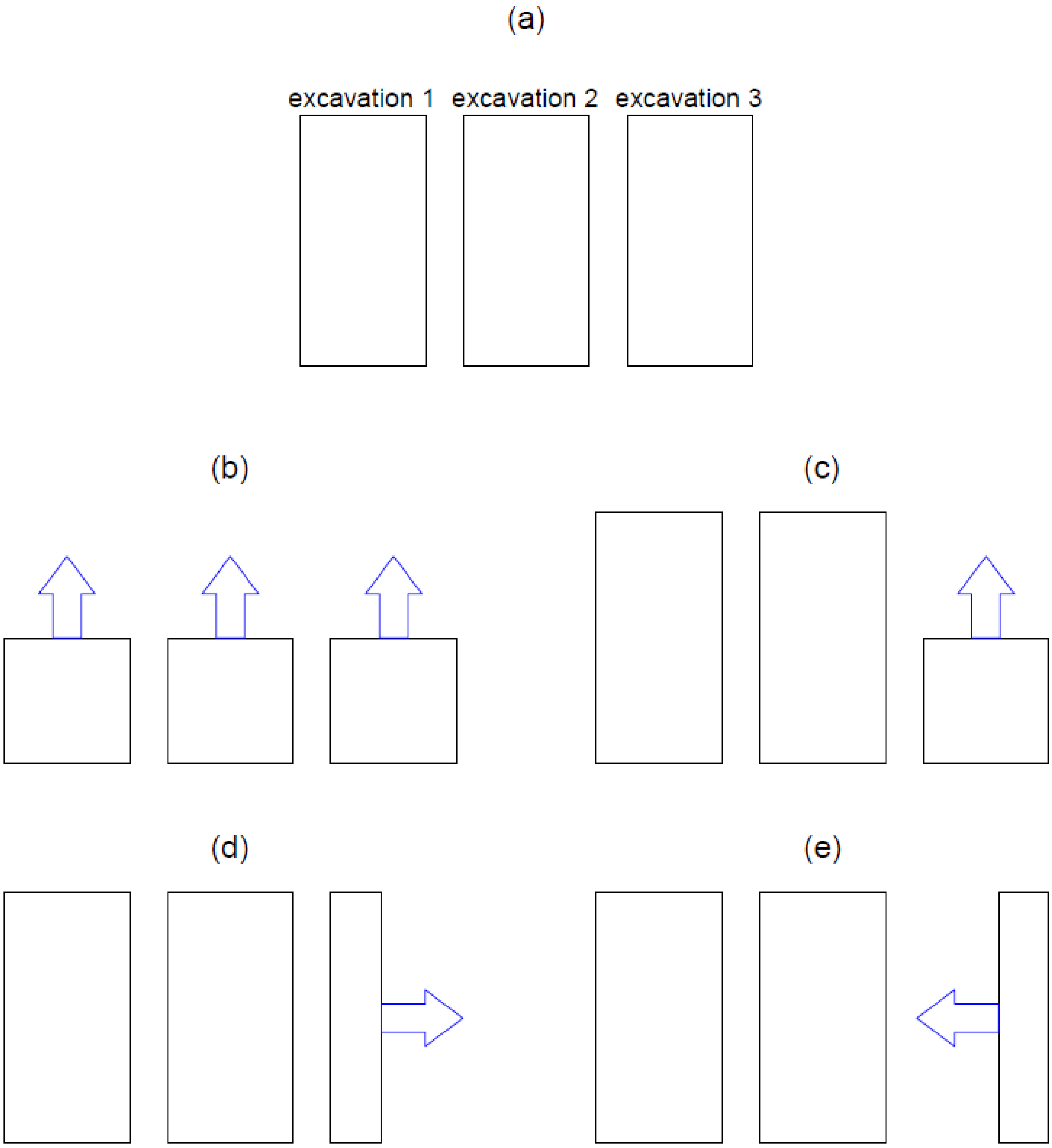


Figure 152: Plan view of three adjacent, flat-lying de-stressing excavations separated by regional stress transfer pillars; (a) final geometry; (b) – (e) different development sequences, the extraction directions are shown by the blue arrows.

8.2.2 Ahead developed infrastructure (layout 2)

8.2.2.1 Layouts for de-stressing excavations with ahead developed infrastructure

The principal layout of de-stressing excavations from infrastructure, which is developed ahead of de-stressing excavations, is shown in Figure 153. The de-stressing excavation provides the stress blocking function (section 7.3) and the infrastructure the access function (section 7.1). The de-stressing excavation is created on the retreat from the infrastructure by means of drilling and blasting and the de-stressing excavation is mostly a non-entry excavation. Accordingly, the infrastructure is situated in or near the abutments of the de-stressing excavation and the protection of this infrastructure from high stresses and mining-induced seismicity is critical. As de-stressing excavations are non-entry, a (limited) degree of instability in de-stressing excavations is normally tolerable, as long as these instabilities do not endanger the stress blocking function or the safety of work in the infrastructure utilized for their creation. Hence, unfilled, empty de-stressing excavations as well as completely filled de-stressing excavations are applicable.

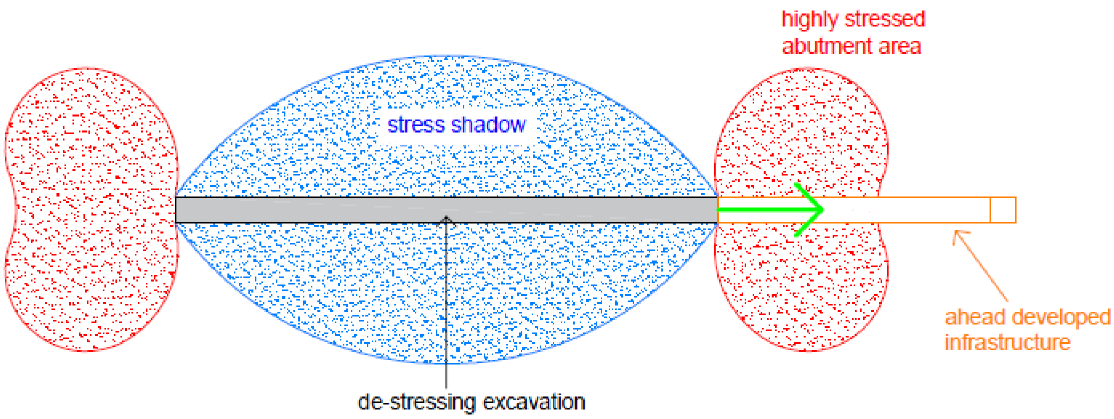


Figure 153: Vertical cross-section showing the principal layout of situating infrastructure in or near abutments of flat-lying de-stressing excavations; the green arrow shows the direction, in which the de-stressing excavation is advanced.

Two different general methods for creating de-stressing excavations with ahead developed infrastructure can be distinguished, namely:

- Creating de-stressing excavations with cut-and-fill methods: These de-stressing excavations are developed in several, small cuts, which are subsequently backfilled; similar to the cut-and-fill mining method. The individual cuts must be entered and hence the de-stressing excavation at the advancing face is an entry-type excavation and must be stable. This method of developing de-stressing excavations is not restricted in terms of the inclination, size and shape of the de-stressing excavation, as long as the de-stressing excavation at the advancing face and the corresponding infrastructure are stable and as long as safe working conditions can be ensured. Thus, this method does not limit the direction, in which stresses can be blocked. However, a major disadvantage of this method is that it is rather work-intensive and slow compared to the method of creating de-stressing excavations with stoping methods.
- Creating de-stressing excavations with stoping methods: These de-stressing excavations are developed from infrastructure with more efficient stoping methods, in which infrastructure on different levels is utilized and in which the blasted rock mass is drawn from the excavation at deeper levels. Hence, the de-stressing excavations are non-entry. After (a part of) a de-stressing excavation was mined-out, it can be backfilled. A limitation for this method of creating de-stressing excavations is that the de-stressing excavations must be steeply inclined so that the blasted rock mass can be drawn at deeper levels. Hence, this method is applicable for creating de-stressing excavations, which block stresses primarily in a horizontal direction.

8.2.2.2 Protection of infrastructure required for the development of de-stressing excavations with ahead developed infrastructure

The protection of the infrastructure, which is utilized for the creation of de-stressing excavations, is most critical. As this infrastructure is situated in and near abutments due to the required infrastructure pre-development, the abutment stress magnitudes as well as the experienced mining-induced seismicity must be kept within tolerable limits at respective locations. These limits are given by the acceptable conditions in the infrastructure and the capacities of the installed support and reinforcement. To keep the stresses and mining-induced seismicity within these limits, the control of the regional stress flow is decisive. Limiting the dimensions of de-stressing excavations is a possible and effective measure, which reduces the abutment stress magnitudes and the amount of mining-induced seismicity near active infrastructure. Regional stress transfer pillars, which provide a regional stress transfer function (section 7.4), are a further measure and can be left between neighboring de-stressing excavations. Critical for the regional stress transfer pillars is that they are normally oriented perpendicular to the major far-field principal stress direction, which instance can result in high stress magnitudes inside the pillar, because the de-stressing excavations are normally oriented perpendicular to this direction to provide an appropriate de-stressing effect. Hence, the extraction ratio of the created pillar – de-stressing excavation system should be kept low to decrease pillar and abutment stress magnitudes as well as the released seismic energy further.

A further critical aspect for the ahead developed infrastructure is that the de-stressing excavations are usually oriented perpendicular to the major far-field principal stress direction and that some infrastructure must therefore also be oriented perpendicular to the major far-field principal stress direction. This orientation of the infrastructure is least favorable from an infrastructure stability point of view. Hence, the remaining ahead developed infrastructure should as far as possible be oriented parallel to the direction of the major principal stress to improve infrastructure stability.

8.2.2.3 Sequences for the development of de-stressing excavations with ahead developed infrastructure

Besides the layout of de-stressing excavations, pillars and associated infrastructure the sequence and direction of development of de-stressing excavations are important. Principally, the same considerations regarding the sequence, which were made in the previous section 8.2.1.3, remain valid. Regional stress transfer pillars should (must) be formed behind advancing faces of de-stressing excavations and the direction of development of de-stressing excavations should (must) be away from existing de-stressing excavations. Otherwise, a highly stressed regional stress transfer pillar is created ahead of an advancing face and in an area, where active infrastructure is situated.

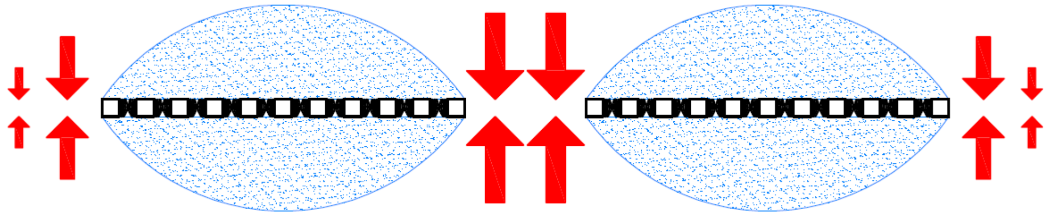
8.2.3 Comparison of layouts and sequences in the de-stressing phase

8.2.3.1 Extent of de-stressed zones

Layout 1 (infrastructure is integrated in de-stressing excavations or developed delayed in stress shadows) enables to establish larger de-stressing excavations, because the infrastructure required for their establishment is either integrated into the de-stressing excavations or developed delayed in provided stress shadows. Furthermore, fewer regional stress transfer pillars are required in layout 1 than in layout 2, because the abutment stress magnitudes for the protection of infrastructure do not need to be limited as strongly. Hence, the extraction ratio in the pillar – de-stressing excavation system is larger in layout 1 than in layout 2 and the pillar stresses in layout 1 are significantly higher. In contrast, the achievable stress shadows in layout 2 (infrastructure is developed ahead) are smaller due to considerations regarding infrastructure protection. Figure 154 illustrates in cross-sections the extent of stress shadows for layout 1 and layout 2 as well as the stress magnitudes in pillars and abutments in the same mining environment.

- The larger stress shadow of layout 1 is advantageous for subsequent stoping activities in the stress shadow, because it offers more freedom for the design of the stoping activities. The position of infrastructure and stopes inside the stress shadow and the mining sequences can be chosen relatively freely.
- On the opposite, in layout 2 the stress shadows are smaller and call for specifically designed stoping layouts and sequences so that the advantage of stress shadows can be used. The design of these layouts and sequences is more complex and more restricted.

(a)



(b)

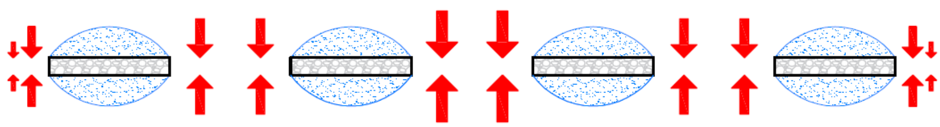


Figure 154: Extent of stress shadows (a) in a vertical cross-section of flat-lying de-stressing excavations with crush pillars in layout 1 and (b) in a horizontal cross-section of steeply dipping de-stressing excavations with backfill in layout 2; the blue areas represent the generated stress shadows and the size of red arrows indicates the stress magnitudes in pillars and abutments.

8.2.3.2 Stress and energy release control during de-stressing

The larger extent of de-stressing excavations of layout 1 results in larger abutment stress magnitudes and a higher seismic energy release in the de-stressing phase compared to layout 2. The protection of infrastructure, which is required for creating the de-stressing excavations, is critical for both layouts.

- In layout 1 the majority of infrastructure can be integrated inside the de-stressing excavations or situated in their stress shadows and thereby the infrastructure can be protected. However, the higher abutment stress magnitudes and higher seismic energy release can affect the stability of the advancing faces of the de-stressing excavations as well as the access infrastructure to de-stressing excavations. Furthermore, the pillar stresses are principally higher than in case of layout 2 because of the larger dimensions of de-stressing excavations and the comparatively smaller pillars (because of the higher extraction ratio in the pillar – de-stressing excavation system). Consequently, the failure of a regional stress transfer pillar becomes more likely in layout 1. Such a pillar failure could have an (immediate) adverse effect on the stability of the de-stressing excavations and of the corresponding infrastructure as well as an (long-term) adverse effect for the further development of de-stressing excavations.
- In layout 2 the abutment stress magnitudes and seismic energy release must be limited to ensure the stability of the infrastructure, which must be put in or near abutment areas. The abutment and pillar stress magnitudes and seismic energy release are principally lower than in layout 1, which improves the encountered conditions during the de-stressing phase. Hence, mining activities in the de-stressing phase, which are high stress mining, may be easier to conduct in layout 2.

8.2.3.3 Access to advancing faces of de-stressing excavations

The access to the advancing faces of de-stressing excavations is important for operational considerations. These access considerations limit the applicability of the layouts considerably.

- In layout 1 the access to the advancing faces must be integrated into the de-stressing excavation. First, this instance demands that de-stressing excavations are stable and that infrastructure must be maintained. Second, it increases the operational complexity particularly in case of backfilled de-stressing excavations, where the infrastructure must be integrated into the backfill, and in case of narrow de-stressing excavations, where the infrastructure inside the de-stressing excavation must be developed in an additional step. Another disadvantage of the necessity of integrating infrastructure inside de-stressing excavations is that it practically restricts layout 1 to flat-lying or slightly inclined de-stressing excavations. The reason for this is mechanization, which requires that (large) machinery has access to the advancing face. Furthermore, the utilization of machinery requires a certain minimum height of these de-stressing excavations. If layout 1 is implemented non-mechanized, then the outlined restrictions do not apply. However, the efficiency during de-stressing as well as the safety would be decreased.

- In contrast, the operation complexity and restrictions in layout 2 are lower, because the de-stressing excavations are either non-entry or only entry at the advancing face. Hence, infrastructure is not integrated in de-stressing excavations. Moreover, the inclination of de-stressing excavations is not restricted as in the case of layout 1, if cut-and-fill methods are used for the development of de-stressing excavations. However, if stoping methods are used, the de-stressing excavations must have a minimum inclination of about 50 °, which enables to transport blasted rock mass by means of gravity. Another advantage of layout 2 is that infrastructure is developed in advance and therefore the knowledge of rock mass properties and conditions is better. This improved knowledge can be used to adapt the de-stressing layout and sequence of layout 2 earlier. The smaller extensions of the de-stressing excavations enable further to adapt the de-stressing layout better to the prevailing mining conditions, such as variable directions of the deposit boundaries or variable rock mass properties.

8.2.4 Protection of main and primary infrastructure in the de-stressing phase

So far only the protection of infrastructure, which is situated near or inside de-stressing excavations, has been discussed. Main and primary infrastructure, which is already required, before the de-stressing phase can commence, and which must thus be developed, before de-stressing can commence, must be protected from high stresses and mining-induced seismicity as well.

Stress shadows are in most instances not available for the protection of this main and primary infrastructure, because they are generated in the de-stressing phase. Therefore, the stability of the main and primary infrastructure, which is exposed to primary stress magnitudes during its development, must be ensured by support and reinforcement. Furthermore, the relative position of infrastructure to each other, their position in the rock mass as well as their size, shape and orientation can be adapted to increase stability. As in the de-stressing phase additional, regional stress changes may be caused and as significant amounts of seismic energy may be released, the main and primary infrastructure must thereof be protected, which can be achieved by following options:

- The best option is usually to place the main and primary infrastructure distant from the de-stressing and subsequent stoping activities. The rock mass between the main and primary infrastructure and the extraction areas fulfills then a direct protection function (section 7.6).
- Another option is to develop the main and primary infrastructure in areas, which are subsequently de-stressed. A specifically adapted de-stressing layout and sequence are necessary to avoid damage to main and primary infrastructure. Due to its complexity the applicability of this option is limited in practice.
- Another option is to leave a protection pillar inside the deposit, in which the main and primary infrastructure is situated. This pillar fulfills a direction protection function.

However, the pillar can also sterilize significant portions of the deposit, which instance can limit the applicability of this option.

An exception arises, if the mining activities in the de-stressing phase can be conducted by utilization of main and primary infrastructure from neighboring mines or former mining areas. In this case the de-stressing phase can be implemented before the development of the (new) main and primary infrastructure, which can then be situated in the provided stress shadows.

8.3 Implications of ongoing extraction in the production phase

The de-stressing strategy relies on the creation of stress shadows in the deposit followed by the subsequent large-scale mineral extraction in the de-stressed ground. After stress shadows were created in a certain area, production can commence in respective area. Therefore, infrastructure, which is required for the large-scale extraction, is developed in the de-stressed ground and it is then utilized for the extraction of stopes. The large-scale extraction activities are referred to as the production phase or extraction phase. The mine layout and mining sequence in the production phase must ensure that the active stress control approach, which was implemented in the de-stressing phase, is maintained. In particular following points are of importance:

- Continuing the creation and provision of de-stressed zones for ongoing and future extraction in extraction areas
- Controlling the stress situation and mining-induced seismicity in extraction areas
- Enabling the creation of de-stressing excavations (the continuation of the implementation of the de-stressing phase) in other parts of the deposit
- Protecting (main and primary) infrastructure outside extraction areas from high stresses and mining-induced seismicity

The implications and effects of ongoing extraction in relation to the outlined critical points are discussed in the following sections conceptually. The discussion is based on the two different de-stressing layouts.

8.3.1 Impact on de-stressed zones and regional stress transfer

After the de-stressing phase was finished, infrastructure is developed in the provided de-stressed zones and it prepares these parts of the deposit for the subsequent extraction. This infrastructure is referred to as production infrastructure and it fulfills an access function (section 7.1). The production infrastructure benefits from the reduced stress magnitudes, which improves its stability. However, specific fracture patterns in the rock mass, which are a result of the high stress mining activities in the de-stressing phase, may be present and have to be considered in the design of production infrastructure and the corresponding support and reinforcement.

In general, the development of production infrastructure does not alter the regional resultant stress distribution, namely the position and extent of de-stressed zones and the regional stress transfer due to comparatively small excavation dimensions of infrastructure. Thus, the production infrastructure does not have a significant effect on the regional stress distribution, which was generated in the de-stressing phase. However, the resultant stress situation changes significantly, as stopes, which fulfill an extraction function (section 7.2), are extracted in the de-stressed ground. Stopes and corresponding mining panels or extraction areas tend to have large dimensions and they influence the regional stress distribution; compare sections 6.1.1.1 and 7.2.1. Furthermore, their extraction causes additional energy changes and the release of seismic energy. Figure 155 outlines the effects of stope extraction in the stress shadows of two adjacent vertical de-stressing excavations, which are separated by a regional stress transfer pillar, in a horizontal cross-section schematically. The rock mass is assumed to behave elastically in this example so that rock mass fracture and failure cannot occur. Figure 155a shows the de-stressing excavations before stope extraction and Figure 155b shows the de-stressing excavations and the extracted stopes. Before stope extraction the stress shadows are directly adjacent to the de-stressing excavations. The pillar and the abutment area are highly stressed and high stress magnitudes diminish rapidly with distance from the pillar and abutments. After stopes were extracted, the positions of the stress shadows are changed. The stress shadows are now adjacent to extracted stopes. Moreover, the abutment and pillar stress situation is altered. Both, pillars and abutments, are still highly stressed, but the spatial extent of high stress magnitudes increases.

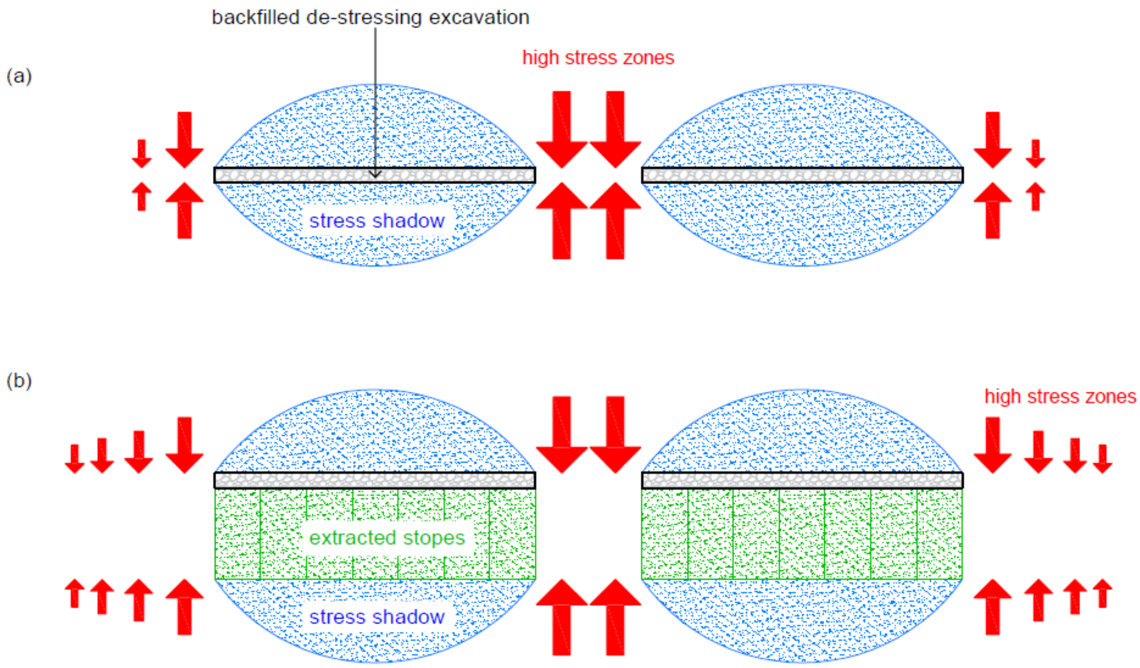


Figure 155: Effect of stoping in de-stressed ground on the resultant regional stress situation in horizontal cross-section for two adjacent vertical de-stressing excavations with backfill; (a) two adjacent de-stressing excavations separated by a pillar before stoping; (b) stopes extracted in de-stressed ground; the size of the red arrows indicates the prevailing stress magnitudes.

In Figure 155 it has been assumed that the rock mass behaves elastically. Therefore, rock mass fracturing and failure cannot take place and the pillar and abutments can withstand the high stress magnitudes. However, in-situ rock mass fracture and failure are likely to occur because of the high stress magnitudes. This is particularly important and relevant for the pillar between the adjacent de-stressing excavations, because the pillar height increases due to stope extraction and consequently the pillar width-to-height ratio and the pillar strength decrease; compare section 6.1.2.2. Potential pillar fracturing and failure affect the regional stress distribution considerably; compare Figure 156, which shows two different situations depending on the extent of pillar fracture and failure.

- In Figure 156a the pillar fracturing and failure is limited. Thus, the pillar can still transfer relatively high stress magnitudes and it still fulfills a certain, but reduced regional stress transfer function. However, the abutments become more highly stressed as a consequence. The stress shadows adjacent to the de-stressing excavations are not influenced significantly.
- In Figure 156b the pillar failed and crushed and the effect on the regional stress situation is considerable. As the pillar failed and crushed to its (relatively low) residual strength, the pillar lost its regional stress transfer function and transfers only rather small stress magnitudes. As a consequence, the abutments must take over the regional stress transfer. Abutment stress magnitudes increase drastically as well as the spatial extent of high abutment stresses. Furthermore, the spatial extent of the stress shadows increases, because the pillar does not transfer high stress magnitudes anymore. The pillar may also be extracted, because it transfers only relatively low stress magnitudes and hence the pillar is de-stressed. Despite the larger stress shadows and the possibility to extract the pillar may be beneficial, the adverse abutment stress situation must be managed. Furthermore, the stability of pillar crushing is critical and must be ensured so that a violent pillar failure does not occur. The failure and crushing of the regional stress transfer pillar can result further in significant stress and energy changes and the associated release of seismic energy.

Overall, the failure and crushing of the regional stress transfer pillar is a delicate situation. Either the design of these pillars can be such that their failure is prevented at all or such that their failure and crushing is implemented on purpose. If pillar failure and crushing is implemented on purpose, it is a remnant mining situation, which requires careful and detailed planning, additional safety measures as well as an appropriate monitoring program to detect the development of critical conditions at an early stage. The mine layout and mining sequence are decisive for a stable and safe pillar failure and crushing. A good understanding of pillar strength and behavior facilitates the design of the mine layout and mining sequence, but it is currently not available for (hard rock) pillars; compare section 6.1.2.2. An improper design for crushing a regional stress transfer pillar can impose a serious safety hazard, which vanishes the advantages of crushing the regional stress transfer pillars, such as a potential pillar extraction, a potential larger extraction ratio and an increased extent of stress shadows.

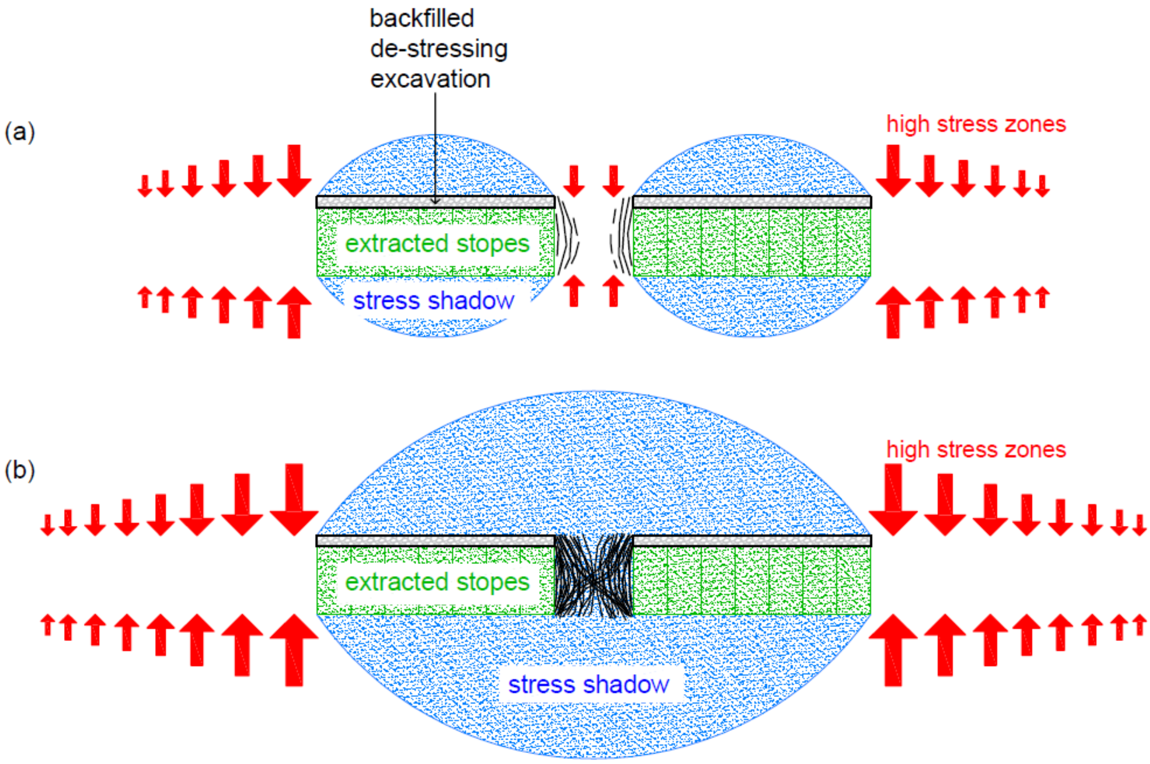


Figure 156: Effect of pillar fracturing and failure caused by ongoing stope extraction on the regional stress situation in a horizontal cross-section for vertical de-stressing excavations with backfill; (a) pillar fracturing and failure is limited; (b) pillar fractures, fails and crushes to a low residual strength; the size of the red arrows indicates the prevailing stress magnitudes.

The considerations related to the effect of large-scale mineral extraction on the regional stress situation are further discussed in relation to the two outlined de-stressing layouts in the following. Layout 1 refers to the de-stressing layout, where the infrastructure is integrated into de-stressing excavations or where infrastructure is developed delayed, and layout 2 refers to the situation, where the infrastructure is developed ahead of de-stressing excavations.

- Layout 1: As outlined in section 8.2.3.1 and Figure 154, the extent of de-stressed zones is considerably larger for layout 1 than for layout 2. Furthermore, the percentage of the de-stressed parts of the deposit is larger for layout 1 than for layout 2. These circumstances are preferable for controlling the regional stress flow in the production phase. The large extent of the stress shadows enables to conduct stoping in the de-stressed zones relatively freely. The continuous provision of stress shadows is thereby facilitated. Furthermore, there is no necessity to extract (a part of) regional stress transfer pillars, because the majority of the deposit was already de-stressed in the de-stressing phase and the losses in regional stress transfer pillars are not excessive. Thus, the stoping layout and sequence can be adapted such that the regional stress transfer pillars maintain a high strength, for example by limiting the extraction activities near pillars to avoid weakening of the pillar. The large de-stressing excavation dimensions are further positive for pillar strength. The larger de-stressing excavations enable to leave wider pillars between them. As wider pillars are stronger, the extraction ratio could be increased.

- Layout 2: In contrast, the control of the regional stress flow and the continuous provision of stress shadows in layout 2 are more difficult. First, the stress shadows, which are created in the de-stressing phase, are of smaller extent and restrict therefore the stoping activities in an early stage of the production phase. Stope layouts and stoping sequences become more complex accordingly. Second, at least some regional stress transfer pillars must be extracted to achieve an acceptable extraction ratio. Extraction of these highly stressed pillars is a remnant mining situation and requires careful planning and implementation of appropriate, additional safety measures. In order to make the extraction of a highly stressed pillar possible, the pillar must in most instances be de-stressed first. Otherwise, it is normally not possible to create infrastructure, stopes etc. inside the pillar for its extraction. The mine layout and mining sequence can be utilized to weaken and de-stress the pillar. An option is to reduce the pillar width-to-height ratio and thereby to decrease the pillar strength. Consequently, pillar crushing, which de-stresses the pillar, is triggered. The stability of pillar crushing is decisive. Moreover, the resulting regional stress changes resulting from pillar crushing and the potential considerable release of mining-induced seismicity must be considered in advance. They may affect stoping activities as well as the creation of additional de-stressing excavation adversely. Another option for de-stressing the pillar may be intensive pre-conditioning of the pillar and thereby to reduce the pillar strength and to trigger pillar crushing. In summary, the mine layout and mining sequence in the production phase become particularly important for layout 2. An in-depth design and strict implementation of the planned mine layout and mining sequence are mandatory to ensure the continuous provision of de-stressed zones, to enable the safe extraction of regional stress transfer pillars, to control the regional stress flow and to control the mining-induced seismicity.

Concluding, layout 1 provides advantages in the extraction phase, because the regional stress situation (de-stressed zones and regional stress transfer) can be controlled better and easier. Moreover, there is no need to extract at least some regional stress transfer pillars in layout 1. However, layout 1 can be more difficult to implement in the de-stressing phase and it is generally restricted to certain geometries; compare section 8.2.3.

8.3.2 Impact on de-stressing activities in other parts of the deposit

The regional stress changes resulting from stoping activities in de-stressed ground can have a significant impact on the mining activities in the de-stressing phase, namely the creation of de-stressing excavations in other parts of the deposit, in which the de-stressing phase has not been implemented. This impact is best illustrated on basis of two adjacent vertical de-stressing excavations and a third vertical de-stressing excavation, which is created besides the two existing ones, in a horizontal cross-section.

- Figure 157a shows the initial situation, where production has not started. It outlines the existing de-stressing excavations and illustrates the position of corresponding stress shadows, high pillar stresses and high abutment stresses. The third de-stressing excavation is sketched with dashed lines. As production in the stress shadows has not started yet, the stress situation, which is relevant for the creation of the third de-stressing excavation, is only influenced by the two existing de-stressing excavations. Furthermore, the third de-stressing excavation is generally situated outside the high abutment stress magnitudes of the existing two de-stressing excavations.

- Figure 157b shows the situation, where stoping was conducted in the stress shadows of the first two de-stressing excavations. The pillar is strong enough to withstand the prevailing stresses. However, the abutment stress situation was altered. The spatial extent of high abutment stresses increases. Therefore, the creation of the third de-stressing excavation, which position is again indicated with dashed lines, could be affected depending on the changes related to the abutment stresses. In case of high abutment stress magnitudes at the position of the third de-stressing excavation, the development of the third de-stressing excavation is more difficult.
- Figure 157c shows again the situation, where stoping was conducted in the stress shadows of the first two de-stressing excavations. Contrary to the previous situation the regional stress transfer pillar between the de-stressing excavations crushed. Consequently, the spatial extent of high abutment stresses as well as the abutment stress magnitudes increased considerably. The development of the third de-stressing excavation, which position is indicated with dashed lines, is affected, because the high abutment stresses, which are prevailing at the position of the third de-stressing excavation, impose rather difficult conditions for the creation of the third de-stressing excavation. The stress situation could even be such adverse that creating the third de-stressing excavation is not possible.

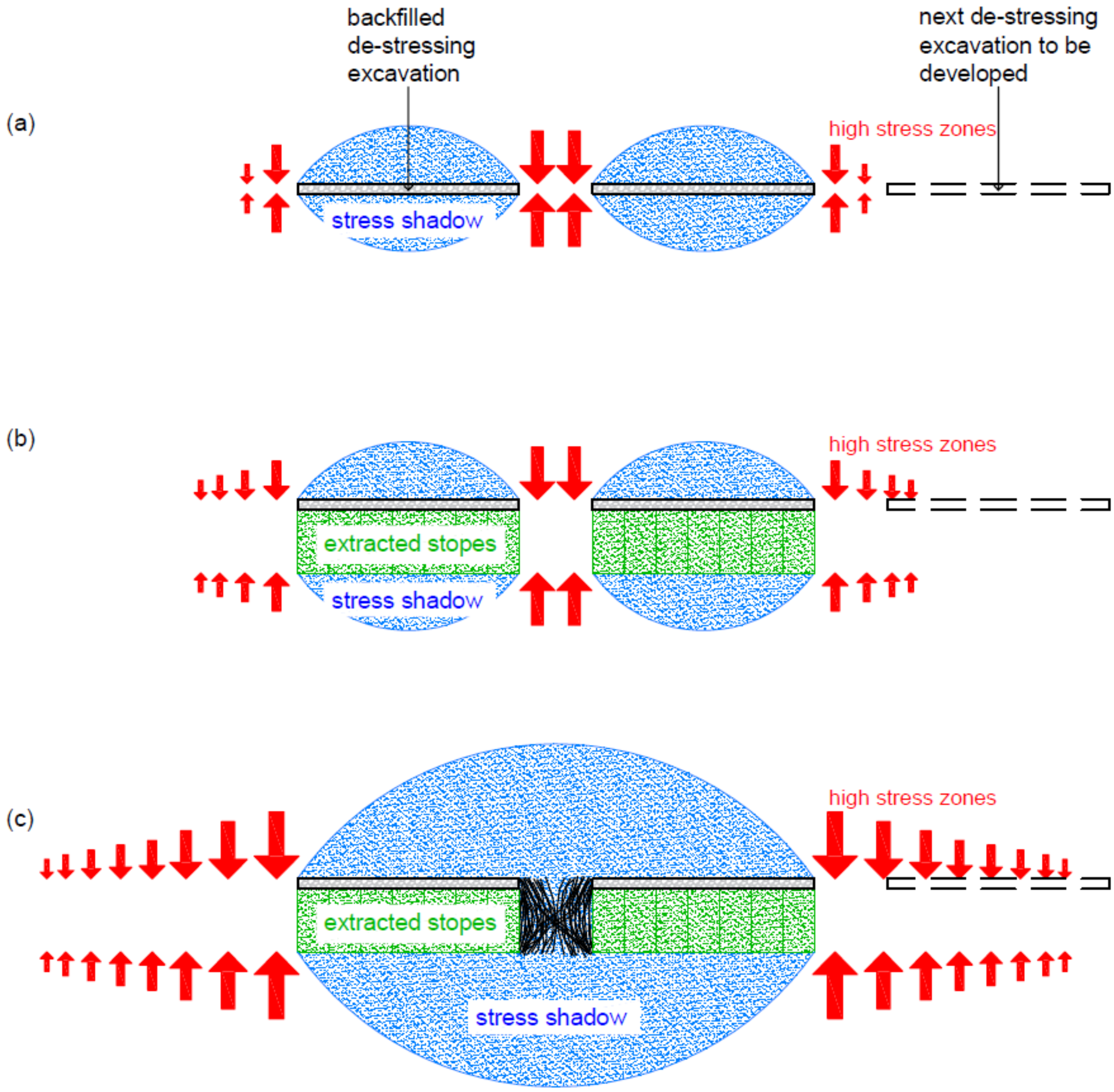


Figure 157: Schematic illustration of the impact of stoping activities on further mining activities in the de-stressing phase in other parts of the deposit in a horizontal cross-section for three adjacent vertical de-stressing excavations with backfill; (a) de-stressing excavations without production activities; (b) de-stressing excavations with production activities in de-stressed ground and a strong, intact pillar; (c) de-stressing excavations with production activities in de-stressed ground and a crushed pillar; the size of the red arrows indicates the prevailing stress magnitudes.

The impact of the ongoing production on mining activities in the de-stressing phase in other parts of the deposit can be relevant for both discussed de-stressing layouts. However, it is generally more important for layout 2, where the extraction of at least some regional stress transfer pillars between neighboring de-stressing excavations is necessary; compare section 8.3.1. A possible solution for avoiding a negative impact of production activities on the mining activities in the de-stressing phase in other parts of the deposit is to implement the de-stressing phase some distance ahead of the subsequent production.

Figure 158 outlines this solution schematically in a horizontal cross-section of vertical de-stressing excavations. Stope extraction commences a certain distance behind the development of additional de-stressing excavations. Therefore, crushing of regional stress transfer pillars in the stoping areas and the corresponding increase of abutment and pillar stresses are at a position, where they do not affect the development of additional de-stressing excavations, which position is indicated by dashed lines. At the position of the increased stress magnitudes the de-stressing excavations were already created. Additional de-stressing excavations are created distant from stoping activities and thus located outside of zones of increased stresses. Therefore, the further mining activities in the de-stressing phase are not adversely affected by stoping activities in the production phase; compare Figure 158.

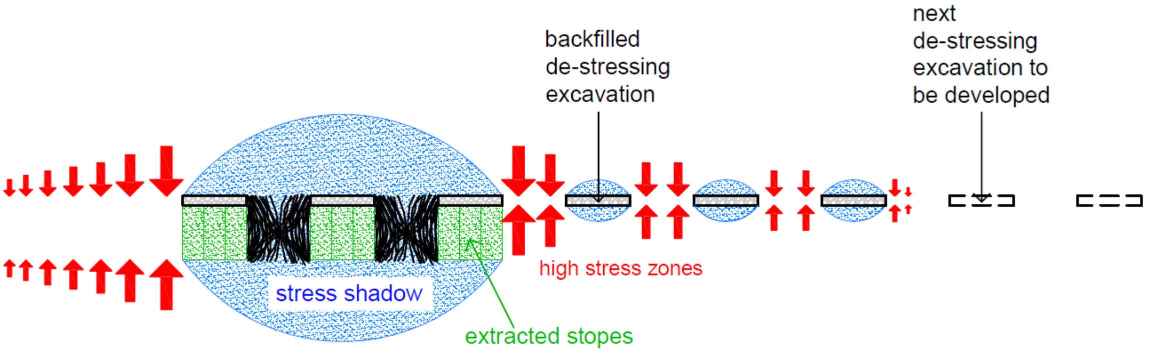


Figure 158: Horizontal cross-section of adjacent vertical de-stressing excavations showing mining activities in the de-stressing phase being conducted distant from stoping activities in the production phase to avoid an impact of stoping activities on the mining activities in the de-stressing phase; the size of the red arrows indicates the prevailing stress magnitudes.

8.3.3 Impact on main and primary infrastructure

Infrastructure must be protected from high stresses and mining-induced seismicity in the production phase. Stress shadows can provide an effective protection. However, only infrastructure, which is developed after the creation of stress shadows and which is situated inside these stress shadows, can benefit from stress shadows. This infrastructure comprises normally stope infrastructure, secondary infrastructure and primary infrastructure, which can be developed delayed inside stress shadows. In contrast, main infrastructure and some primary infrastructure must be developed before mining activities in the de-stressing and production phase can commence.

An effective protection of this main and primary infrastructure can be realized by situating it distant from the deposit or extraction areas; compare section 8.2.4. However, situating main and primary infrastructure distant from the deposit and stoping activities is not always possible. Examples are:

- Weak rock mass formations, which are prevailing distant from the deposit, may necessitate that main and primary infrastructure is situated closer to the deposit due to stability reasons. It may even be necessary to situate the main and primary infrastructure inside the deposit, if the deposit is surrounded by weak rock mass formations.

- The size, shape and orientation of the deposit prevent that the main and primary infrastructure can be situated outside of the deposit. This situation occurs particularly for deposits with considerable lateral extensions.
- Other factors, such as surface conditions and topography or boundaries of mining concessions, prevent that the main and primary infrastructure can be situated distant from the deposit.

Furthermore, some primary infrastructure must be developed from the main infrastructure to extraction areas and is therefore situated close to extraction areas.

Possible approaches to protect main and primary infrastructure in such situations were outlined in section 8.2.4 and comprise protection pillars, specifically designed de-stressing layouts and sequences near the infrastructure and utilization of existing infrastructure for de-stressing and subsequent development of the new main and primary infrastructure inside created stress shadows. Despite these measures the production activities can still have an additional impact, for which the abutment stresses of extraction areas and the energy changes and corresponding mining-induced seismicity near extraction areas are important. As extraction advances, the position of highly stressed abutments and the position of energy changes and corresponding occurrence of mining-induced seismicity change. Moreover, the abutment stresses and the energy changes become more pronounced and important with an increasing extent of extraction activities. At an early stage of extraction the abutment stress magnitudes and their spatial extent as well as the energy changes are comparatively small, but they increase significantly with increasing extent of extraction areas and maturity of extraction.

The time, at which abutments, which are highly stressed and at which position significant energy changes and the release of seismic energy take place, of extraction areas are close to and pass by the main and primary infrastructure, is decisive for the exposure of main and primary infrastructure to high stress magnitudes and mining-induced seismicity. Therefore, the regional production sequence is particularly relevant. The impact of the regional production sequence on the main and primary infrastructure is discussed on a conceptual basis for three sequences based on the investigations regarding the mining sequence, which were conducted in section 6.1.4. The sequences are different in terms of the direction, in which the production develops relative to the position of the main and primary infrastructure. The sequences are:

- <u>Center – outside sequence:</u> Production commences close to the main and primary infrastructure and develops gradually towards the outer boundaries of the deposit.
- <u>Outside – center sequence:</u> Production commences at the outer boundaries and moves gradually inwards towards the main and primary infrastructure.
- <u>Outside – outside sequence:</u> Production commences at one outer boundary of the deposit and moves gradually towards the other outer boundary of the deposit.

It is remarked that the boundaries of the deposit can also be the boundaries of a defined, regional area of the deposit, which is going to be mined. Figure 159 shows the regional production sequences schematically in a horizontal cross-section for a steeply dipping deposit.

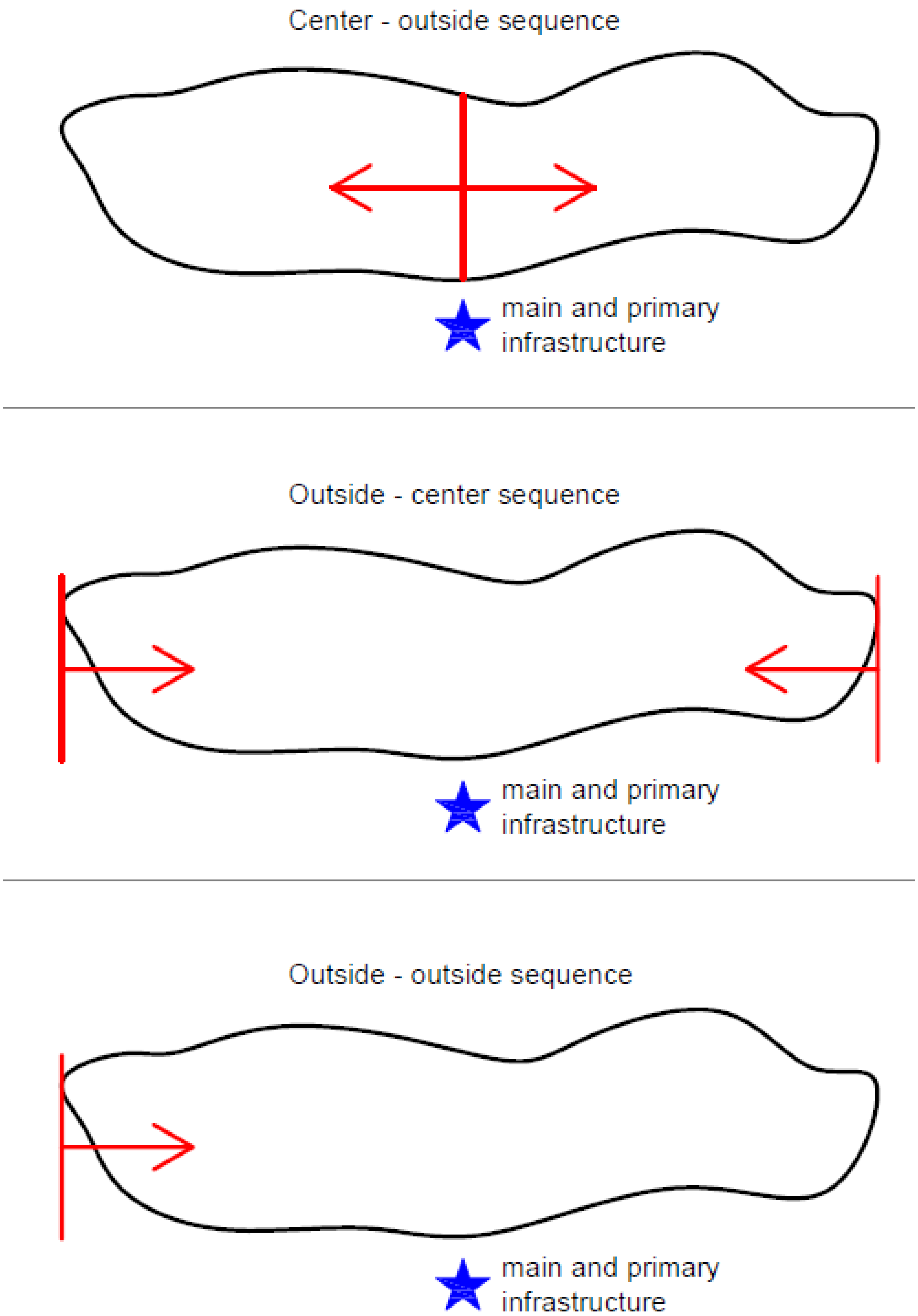


Figure 159: Possible regional production sequences relative to the position of main and primary infrastructure in a horizontal cross-section of a steeply dipping deposit; the deposit boundaries are shown as black lines; the directions, in which extraction areas advance, are outlined with red arrows.

In the examples shown in Figure 159 the production commences in the center – outside sequence close to the main and primary infrastructure. A protection pillar for the main and primary infrastructure, which would be situated inside the deposit, is not created. In this case, the abutment stresses acting at the position of the infrastructure are relatively low at the time, when abutments of advancing extraction areas pass by the main and primary infrastructure, because production just started and the extent of extracted areas is small. Moreover, the main and primary infrastructure are situated in de-stressed ground, after abutments of advancing extraction areas passed- by. In contrast, if a protection pillar is left behind in the deposit to protect the main and primary infrastructure, the abutments of advancing extraction areas do not pass by the infrastructure. However, the infrastructure is also not situated in de-stressed ground and the stresses acting at the position of the main and primary infrastructure depend strongly on the size of the protection pillar and the extent of extraction areas. Furthermore, the stress magnitudes acting at the position of the main and primary infrastructure increase steadily, but compared with other sequences slowly, with advancing production.

The outside – center sequence is principally the opposite of the center – outside sequence. Production commences at the deposit boundaries distant from the main and primary infrastructure and advances towards the main and primary infrastructure. As abutments of advancing extraction areas approach the position of the main and primary infrastructure, the stress magnitudes start to rise at respective position considerably and they are higher than in the other two sequences. Moreover, significant energy changes and the associated release of mining-induced seismicity can take place near the main and primary infrastructure. The reason for this is first that the extent of extraction areas is relatively large at the stage, where the stress situation at the position of the main and primary infrastructure is affected, and second that a highly stressed pillar is formed between the advancing production faces. Normally, the production must be stopped, once the stress state or the effects of mining-induced seismicity at the position of the infrastructure becomes critical. Accordingly, a portion of the deposit is sterilized in a protection pillar.

The outside – outside sequence is a combination of the other two sequences. Production commences at one deposit boundary distant from the main and primary infrastructure. The abutments of advancing extraction areas approach the infrastructure. Extraction can be stopped, once a critical stress state at the infrastructure position is reached, and then commenced at such a distance from the infrastructure again that the infrastructure is not affected further. Thereby, a protection pillar near the infrastructure is created. Another possibility is to continue with extraction and to pass by the infrastructure with the abutments of advancing extraction areas. However, the infrastructure can be severely damaged in this case.

In summary, the center – outside sequence offers advantages over the other two sequences. Main and primary infrastructure are not exposed to high stress magnitudes, to rapidly changing stress states and to significant amount of mining-induced seismicity. Furthermore, if a protection pillar is not left near the main and primary infrastructure in the center – outside sequence, a stress shadow at the position of the main and primary infrastructure is created at an early stage.

8.4 Demand for flexibility

Flexibility allows adapting the mine layout and mining sequence and hence stress control measures on demand and flexibly in the de-stressing phase as well as in the production phase. Providing flexibility is crucial for a successful implementation of the proposed stress management concept. The reason for this are the prevailing uncertainties related to the spatial distribution of rock mass properties, the orientation and magnitude of primary stresses and the strength and behavior of rock mass and structural elements, such as pillars. The uncertainties are particularly present at the mine planning stage. Accordingly, an exact and accurate rock engineering design of the mine layout and mining sequence is in the majority of cases not possible. Moreover, uncertainties can have a considerable effect on the performance of the implemented stress control measures. In order to decrease uncertainties an improvement of the understanding of rock mass and an increased knowledge about the spatial distribution of rock mass properties and the primary stress situation are necessary. Fundamental research can address this point; however, it is only a long-term approach. A more effective approach to reduce uncertainties for the proposed stress management concept are monitoring and observation followed by structured back analyses of collected data and experience. From a practical point of view monitoring, observation and back analyses are preferable for the proposed stress management concept, because they can be implemented relatively easily and timely. Moreover, observation and monitoring delivers data and experience related to required aspects directly. In order to benefit from the experience, data and subsequently conducted investigations and analyses, the implementation of the stress management concept must provide sufficient flexibility to adapt the mine layout and mining sequence. The flexibility is in particular required to ensure that adaptions can be implemented timely and at reasonable cost.

Within the stress management concept the flexibility must be provided first by adaptable mine layouts. Therefore, the layouts used in the de-stressing phase are in general more critical, because the mining activities in the de-stressing phase are high stress mining and the uncertainties are higher. As the de-stressing phase provides improved stress conditions for the subsequent production phase, the mining activities in the production phase are no longer high stress mining and flexibility, particularly on short notice, is not as critical as for the de-stressing phase. Furthermore, the uncertainties related to the prevailing mining environment have already been reduced in the de-stressing phase. This improved knowledge and the reduced uncertainties enable the implementation of an improved layout in the production phase. Second the flexibility must be provided in the mining sequence, which is essential for stress control as well. Similar to the flexibility of the mine layout, the flexibility of the mining sequence is in general more relevant for the de-stressing phase than for the production phase. Indeed, the extraction of regional stress transfer pillars in the production phase is a delicate issue, which requires considerable flexibility regarding the stoping layout and stoping sequence.

The time of infrastructure development is potentially the most important aspect related to the available flexibility of the mine layout and mining sequence. Infrastructure is principally required for the implementation of the elements and the element functions in the proposed stress management concept. Once the infrastructure is developed, the elements and their functions, which are implemented from this infrastructure, are largely fixed as well. Thus, the adaption of layouts and sequences call also for an adaption of the infrastructure particularly its position. After infrastructure was developed, the possibilities to adapt its position are often limited. For this reason, the time of infrastructure development is decisive for the stress management concept. Principally, the infrastructure is preferably developed as late as possible to preserve possibilities for adaptions in the mine layout and in the sequence as long as possible. Limiting factors for a late infrastructure development are the required amount of infrastructure for the implementation of certain elements and element functions and the speed of infrastructure development. Corresponding relevant issues are discussed below.

- The required amount of infrastructure should be minimized particularly in the de-stressing phase, in which infrastructure is exposed to high stress conditions. Furthermore, the de-stressing phase necessitates a larger flexibility for the control of the high stress situation. A reduced infrastructure amount decreases further the time required for infrastructure development, which improves flexibility. Moreover, the position of infrastructure can be adopted more quickly, as layouts with minimum amount of infrastructure are less complex. An adaption of infrastructure subsequent to its development is easier as well, if the infrastructure amount is minimized. The available space for additional infrastructure is larger and costs for already developed infrastructure, which is not required anymore, are lower. Finally, the reduction of the infrastructure amount results mostly in reduced mining cost.
- The speed of infrastructure development affects the time span, which infrastructure must be developed in advance. Thus, rapid infrastructure development methods are advantageous. Besides the impact of the speed of infrastructure development on the adaptability of the mine layout and the mining sequence the time of infrastructure development is essential for the protection of infrastructure. This aspect is especially relevant for infrastructure, which is developed delayed in stress shadows and mainly used for large-scale extraction. If this infrastructure is developed too early, it is not protected properly. The speed of infrastructure development and the required amount of infrastructure are again important, because they are decisive for the needed production ramp-up time in a certain area, after the de-stressing phase was finished in respective area. For infrastructure, which must be situated in high stress conditions, mainly infrastructure in the de-stressing phase, the exposure time can be limited as well, if the infrastructure is developed late.

Concluding, the required amount of flexibility depends strongly on the prevailing mining environment, the applied mine layout and the mining sequence. The larger the uncertainties related to the mining environment are, the higher is the required degree of flexibility. The proposed de-stressing strategy enables to minimize in both layouts the required amount of infrastructure in the de-stressing phase. The majority of infrastructure, which is mainly required in the production phase, can be developed delayed in the de-stressed ground. Therefore, the proposed de-stressing strategy provides in general a reasonable flexibility.

8.5 Concluding remarks regarding the implementation of the stress management concept

The outlined de-stressing strategy is split into two phases: the de-stressing phase and the production phase. In the de-stressing phase an active stress control approach is implemented. Therefore, portions of the deposit are de-stressed with minimum amount of infrastructure and the regional stress flow and the seismic energy release are controlled. The subsequent large-scale mineral extraction, which takes place in the production phase, makes use of the provided stress shadows from the previous de-stressing phase and it must ensure the continuation of the implemented active stress control approach, namely that stress shadows are provided in further parts of the deposit and that the regional stress flow and the seismic energy release are controlled. Hence, the de-stressing strategy enables an efficient, productive and safe mineral extraction in de-stressed ground.

For both, the de-stressing and the production phase, the mine layout and mining sequence are critical and require an appropriate design and an appropriate implementation of the planned design. Furthermore, flexibility in the mine layout and mining sequence is necessary to react on uncertainties. The flexibility enables to adapt the mine layout and mining sequence to the prevailing rock mass conditions and to the mining experience. Flexibility is central for a successful implementation of the proposed stress management concept.

Probably most important for the implementation of the proposed stress management concept is that the necessity for stress management must be identified first. Then, there must be a strong commitment to the stress management concept and its implementation must be strictly followed. An appropriate mine design and ongoing adaption of the design are required. In particular, the adaptations call for flexible and dynamic mine planning and scheduling, which can be difficult from an operational perspective. In this respect, the late development of production infrastructure is particularly challenging. Overall, the implementation of the stress management concept calls for specific organizational structures, which allow to incorporate rock mechanics observations, needs or adaptions into production plans on short notice. A rock engineering department, which addresses the rock mechanics aspects of the stress management concept, should be set up therefore. The collaboration of and communication between this rock mechanics department and other departments involved in the operation, especially mine planning, geology and mine management, are mandatory and crucial for the successful implementation of the proposed stress management concept.

9 Application study

The implementation of the de-stressing strategy was outlined in the previous chapter on a conceptual basis. Possible generic layouts and sequences as well as corresponding critical aspects were discussed. In this chapter the conceptual layouts and sequences are applied on a steeply dipping or massive deposit to demonstrate a possible implementation of the de-stressing strategy in practice. The layout and sequence are based on the raise mining method. The principle of the raise mining method and its advantages for the implementation of the de-stressing strategy are discussed. Afterwards, a layout and sequence for the implementation are outlined and described. The individual steps of the de-stressing and production phase are highlighted. Furthermore, the application of raise caving, which makes use of the de-stressing strategy, in Kiruna mine is investigated and the advantages and potential of raise caving are pointed out.

9.1 Raise mining method

9.1.1 Principle of raise mining

Raise mining has been applied for many decades mainly in a non-mechanized manner, which is commonly referred to as Alimak mining (e.g. Makinen and Paganus (1987), Ran and Mfula (2012)). The raise mining method, which is considered in this chapter to implement the de-stressing strategy, differs largely from the non-mechanized Alimak mining, because it is a modern, large-scale, mechanized mining method. This modern raise mining method was developed about 20 years ago in Austria and has since then been utilized in two underground mines. A similar raise mining concept, which is referred to as ROES, was suggested in Australia; see Gipps et al. (2008) and Gipps and Cunningham (2011). However, the ROES concept was not implemented.

Raises are the central infrastructure in the modern, large-scale raise mining method and utilized for the extraction of stopes. The principle of raise mining is demonstrated in Figure 160 for a vertical raise in a vertical cross-section. The raise is preferably developed by means of raise boring. Depending on the rock mass conditions and the prevailing stress situation different types of support can be installed in the raise. After the raise was drilled and supported, a hoist system is installed on top of the raise. With this hoist system a platform is lowered into the raise. On the platform different kind of machinery can be mounted to perform the work inside the raise. Creating the excavation from the raise is conducted in upwards direction. Hence, drill holes are drilled parallel to the roof of the excavation below the raise (Figure 160a). The drill hole pattern and drill hole length can be utilized to generate excavations of specific dimensions and shapes. After holes were drilled and charged with explosives, the platform is retracted to the top of the raise, where it is stored during blasting to prevent damage (Figure 160b). The simple, circular cross-section of the raise and the possibility to position the platform with the hoist system provide ideal conditions for conducting the drilling and blasting work inside the raise remote-controlled or automated. Blasting advances the excavation in upwards direction. The blasted rock mass falls into the excavation and fills it up (Figure 160c). In order to blast the next slice and to advance the excavation further, a sufficient volume of blasted rock mass must be drawn from the excavation to provide a large enough free volume for the next blast. The excavation shown in Figure 160 is schematic and it has a flat, horizontal roof. In practice the actual roof will be inclined and its shape is comparable to an open cone. The reason for this are operational considerations related to blasting as well as roof stability considerations.

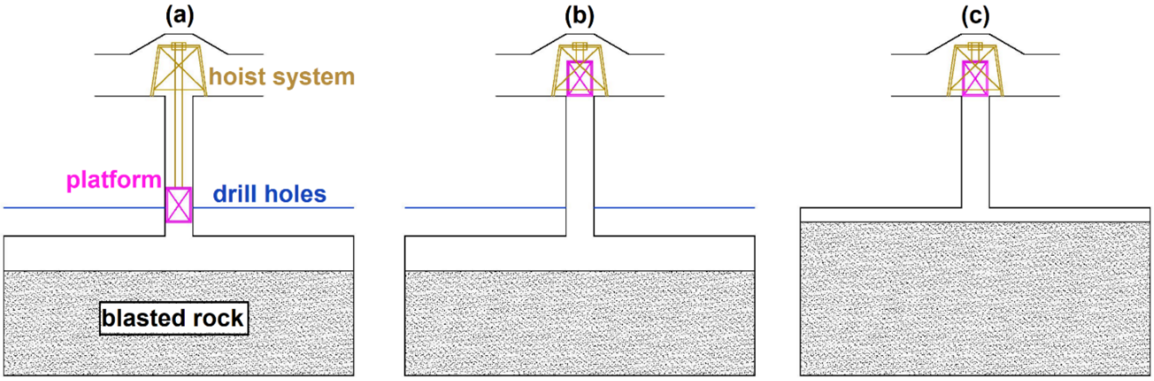


Figure 160: Principle of raise mining in a vertical cross-section; (a) drilling and loading of holes; (b) platform retracted to the top for blasting; (c) advanced excavation after blasting; details of machinery are not shown.

Figure 161 to Figure 166 display the extraction sequence of a raise mining stope and the corresponding infrastructure. The provided dimensions and stope shape are exemplary and can be adapted to the local mining environment and production requirements, such as deposit size and shape, the grade distribution and quality control, the rock mass properties and the stress conditions. For the extraction of a raise mining stope drifts are developed at a top level and at a first bottom level (Figure 161). Above the position of the raise a small cavern is created at the top drift for the hoist system. The vertical spacing of the top and bottom level is 350 m. Then a raise is bored between the bottom and top level (Figure 162). The raise has a diameter of 4 m. Additionally, drifts on a second bottom level are developed. The raise is then utilized to create a large drawbell (Figure 163). The drawbell roof has a final cross-section of 50 m x 50 m and the drawbell has a height of approximatively 50 m. The drawpoints at the first bottom level are used to draw the blasted rock mass from the drawbell during drawbell blasting. Additional drawpoints are developed into the drawbell at the second bottom level. The utilization of the large drawbell and two bottom levels with drawpoints provides advantages related to the ore flow and enables a higher production. After drawbell development is finished, the stope is extracted in upwards direction (Figure 164). The stope has a cross-section of 50 m x 50 m. The blasted rock mass is drawn at drawpoints at the first and second bottom level. During extraction the stope either can be drawn empty after each blast or only the swell is drawn after each blast so that the stope is filled with blasted rock mass, which provides support to the stope walls. Figure 165 shows a completely blasted stope, which has a height of 270 m (approximatively 320 m including the drawbell). A crown pillar with a thickness of about 30 m is left between the stope and the top level. If necessary, this crown pillar can be blasted from the drifts at the top level. After the stope was completely blasted, it is drawn empty and subsequently backfilled from the top level. Figure 166 shows a stope, which is partially backfilled. After the stope was completely backfilled, mining advances to the next stope.

The stope shown in the figures is vertical and of a regular square cross-section. In practice the shape and inclination of the raise mining stopes can be adapted well to the deposit geometry and to the deposit orientation. If stopes are inclined, the raises used for the extraction of the stopes can be inclined as well.

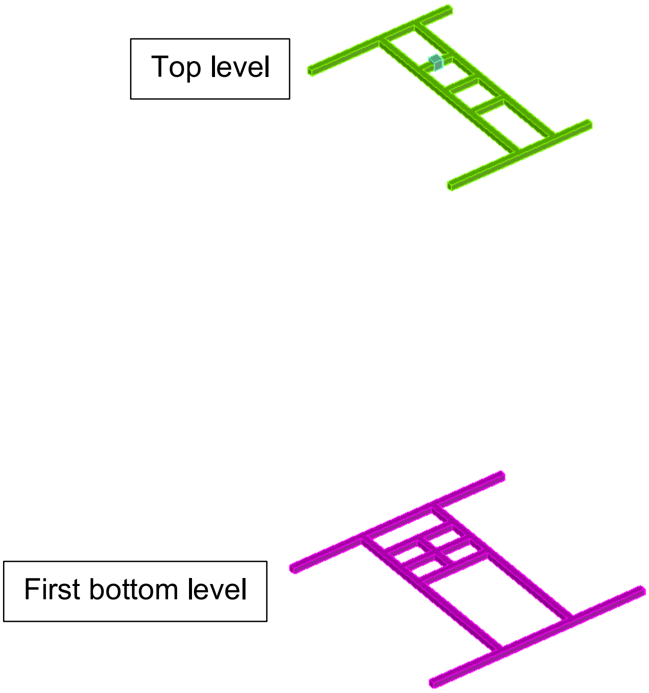


Figure 161: Development of drifts on a top and a first bottom level for the extraction of a stope

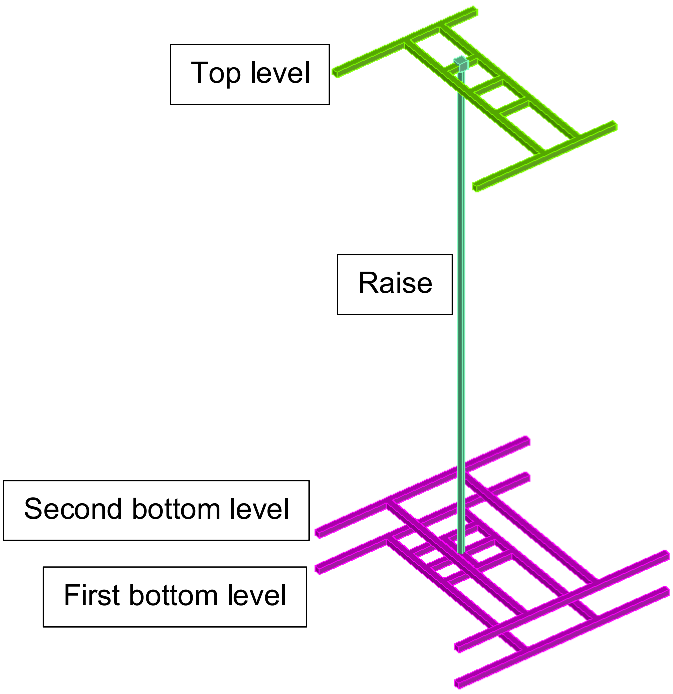


Figure 162: Development of a raise between the first bottom and the top level and development of drifts on a second bottom level

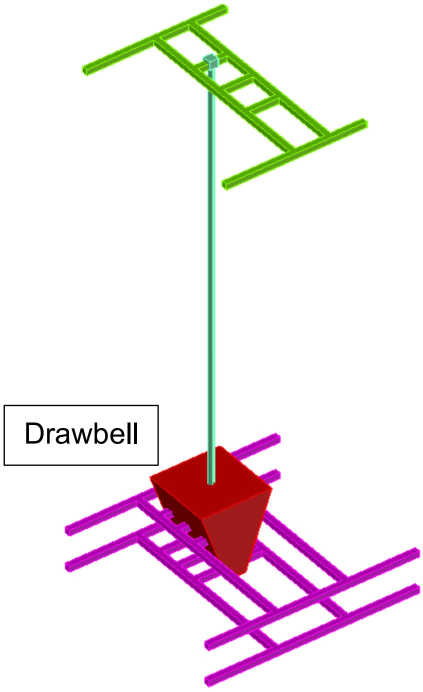


Figure 163: Creation of a large drawbell from the raise

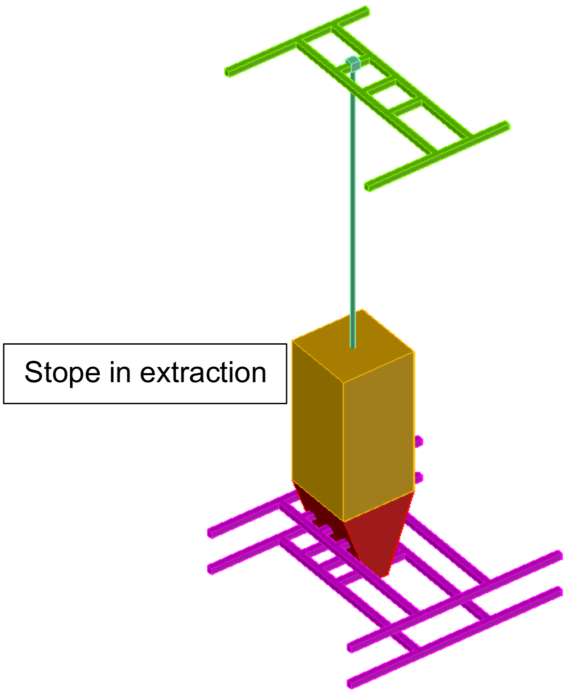


Figure 164: Extraction of a stope from the raise in upwards direction

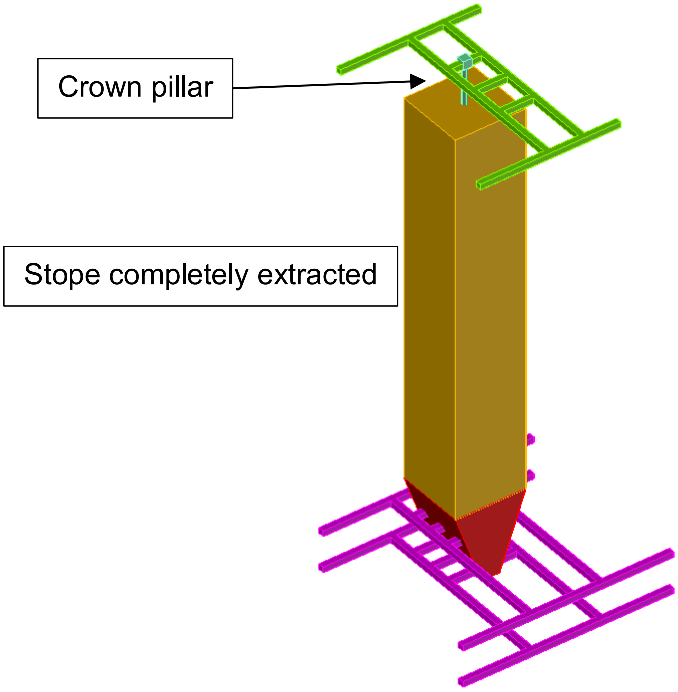


Figure 165: Completely extracted stope

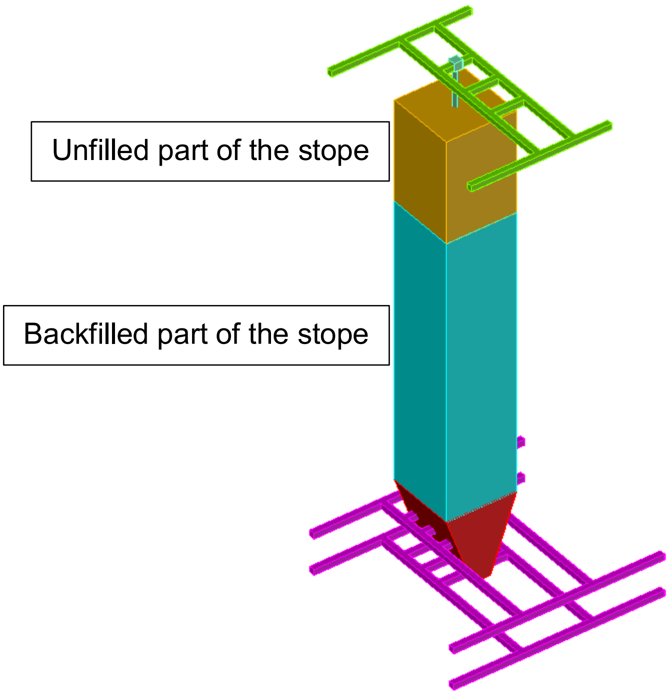


Figure 166: Backfilling of the extracted stope

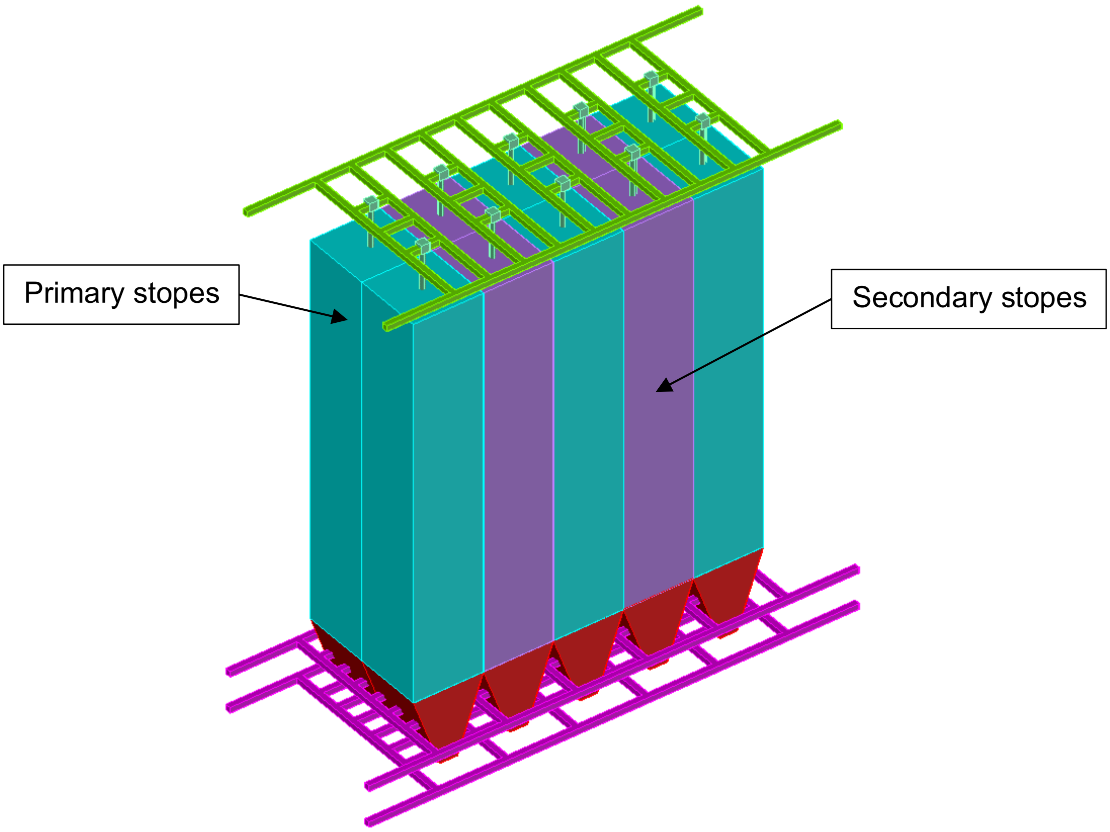


Figure 167: Mined-out panel comprised of primary and secondary stopes

Figure 167 shows a mined-out panel comprised of several adjacent mined-out and backfilled stopes. Initially pillars were left between primary stopes. These pillars were then recovered with secondary stopes. Instead of extracting pillars between stopes, pillars can be left behind between stopes to provide support to overlying and surrounding rock mass. Furthermore, Figure 167 points out well that only a low amount of infrastructure is required for the extraction of stopes. Critical for the required amount of infrastructure is the vertical spacing of the top and bottom level, or in other words the vertical extension of stopes. The larger this vertical spacing is, the lower is the required amount of infrastructure.

Backfill is a central aspect of the raise mining method. From a rock mechanics point of view the purpose of backfill is to stabilize mined-out stopes and to improve the strength of the nearby rock mass, for example abutment areas or pillars. Hence, the extraction ratio can be increased, as pillars between stopes can be smaller or as they can be extracted. Important aspects related to backfill in raise mining are outlined in the following. Different types of backfill can be applied. For the discussion it is necessary to distinguish between cemented and uncemented backfill. Cemented backfill is for example paste fill or hydraulic fill with binder and uncemented backfill is for example rock fill.

- Utilization of cemented backfill: If cemented backfill is to be applied, the stope must be drawn empty before placing the backfill. Drawing the stope empty removes the support to the stope walls, which is provided by the blasted rock mass in the stope. This implies that the stope is unsupported and that it must stand open until the backfill is placed. Depending on the stope size, the production capacity and the backfilling capacity this period can be rather long and in the range of several month or even years. Consequently, the possible stope size may be limited due to stability considerations. The advantage of cemented backfill is that the size of permanent pillars between neighboring stopes may be reduced because of the higher strength and higher initial stiffness of the cemented backfill compared to the uncemented backfill. Principally, the higher strength and stiffness of the cemented backfill can improve the strength of nearby pillars better and it can have a more beneficial effect on the post-peak behavior of pillars, namely to increase the post-peak modulus more and thereby to reduce the risk of an unstable pillar failure better. Furthermore, cemented backfill enables to extract stopes beside each other without leaving permanent pillars between stopes, because cemented backfill has a cohesive strength and it has therefore a certain free-standing height. The possible free-standing height of the backfill limits the height of stopes though. Another advantage of cemented backfill is that an efficient, continuous, large-scale placement system can be utilized. Such a system enables to fill large stopes in a comparatively short amount of time.

- <u>Utilization of uncemented backfill:</u> Uncemented backfill does not have a cohesive strength and hence uncemented backfill does not have a free-standing height. This aspect is central for the subsequent considerations related to the application of uncemented backfill. If stopes are drawn empty before the introduction of the uncemented backfill, it is necessary to leave permanent pillars between neighboring stopes, which are filled with uncemented backfill. Otherwise the uncemented backfill from neighboring stopes would flow into the mined-out stope. Furthermore, these pillars must be of sufficient strength to retain the uncemented backfill from neighboring stopes. An exception of this are stopes, which neighboring stopes were filled with cemented fill. These stopes are commonly referred to as secondary stopes and strong, permanent pillars between them and adjacent stopes, which were filled with cemented fill, are not necessary due to the provided free-standing height of the cemented backfill. Another possibility is to fill the uncemented backfill (rock fill) in parallel with drawing the stope empty. In this situation the backfill fills up the empty volume, which is created by drawing ore from the stope. A proper, continuous supply of backfill is critical and this supply may be difficult to realize, because efficient, large-scale transportation systems for uncemented backfill (rock fill) to the top of the stope may not be available. Moreover, the draw strategy and draw control are critical so that a dilution of the ore with the backfill is avoided. The advantage of this method is that the stope is not empty and thus blasted ore and introduced backfill provide throughout some support to the surrounding rock mass. Furthermore, introducing the backfill in parallel with drawing the stope empty provides the option that strong, permanent pillars between adjacent stopes are not left behind. Either pillars are not created or only small, slender pillars, which purpose is to provide a temporary barricade to already backfilled neighboring stopes and to slow down dilution with backfill from neighboring stopes, are left behind. These small, slender pillars do not have a significant strength and thus they cannot transfer large loads. An appropriate draw strategy and a strict draw control are of paramount importance to avoid dilution with backfill from adjacent stopes.
- <u>Utilization of a hybrid uncemented and cemented backfill:</u> In this case the stope is filled with uncemented backfill first, which enables to keep the stopes filled

throughout with blasted ore and introduced backfill. Afterwards, a cemented backfill is poured over the uncemented backfill. The purpose of this cemented backfill is to fill up the pore volumes of the uncemented backfill and to provide cohesive strength. The uncemented backfill must have a sufficient porosity and the cemented backfill must have good flow properties to fill up the pore volumes. A watery cement slurry fulfills these requirements. The utilization of this hybrid backfill enables to combine the advantages of uncemented and cemented backfill.

9.1.2 Raise caving

The raise mining method is a backfill type method, where extracted stopes are subsequently backfilled. However, raise mining can also be implemented in a caving variant and it is then referred to as raise caving. Principally, two different variants of raise caving can be distinguished.

- In the first variant stopes are extracted by means of drilling and blasting (as shown in Figure 161 to Figure 165). Instead of drawing completely blasted stopes empty and backfilling them, the blasted rock mass is left in the stopes. After several adjacent stopes were completely blasted, the stopes are drawn empty. Consequently, the hangingwall caves and fills up mined-out stopes. Draw control is critical to avoid dilution with caved hangingwall rock mass. The number of adjacent stopes, which must be blasted before drawing them empty, is prescribed by the caveability of the hangingwall rock mass. This variant of raise caving is particularly suitable for stopes, which are inclined so that the hangingwall can cave easier and so that caving does not take place in areas, where infrastructure is situated.
- In the second variant raises are used to create drawbells. These drawbells have also the function of an undercut and caving is initiated inside the deposit, once a sufficiently large area, which is prescribed by the caveability of the deposit rock mass, is undercut. After caving was initiated, it progresses in upwards direction and caved rock mass is drawn through the large drawbells at the bottom levels.

A description of both variants and their advantages is given by Ladinig et al. (2021).

9.1.3 Advantages of raise mining for the de-stressing strategy

The raise mining method is well suited for the implementation of the de-stressing strategy in steeply dipping or massive deposits, if steeply dipping or vertical de-stressing excavations must be created. The reason for this are the following points:

- Efficient creation of vertical or steeply dipping excavations: The raise mining method enables to create excavations, which have a large vertical extension, efficiently. The main reasons for this are that large excavations can be created with a minimum amount of infrastructure, that work can be conducted remote-controlled or automated and that machinery and other installations are stationary and do not change between work places often.

- Possibility to utilize remote-control and automation: The simple, circular geometry of the raise offers a good possibility for remote-control and automation. Hence, the personnel do not need to work inside the raise on a regular basis. Personnel must enter raises only for inspection purposes, in case of errors on the machinery or in case of work, which is not routinely conducted. As a result, personnel is mostly removed from areas, which can be highly stressed and in which energy changes take place. Therefore, the safety of the operation is improved. Furthermore, remote-control and automation enable to improve the productivity as well.
- Low amount infrastructure: The utilization of raises enables to create (large) excavations, which have a large vertical extension, with a significantly lower amount of infrastructure compared to other mining methods, such as sublevel and open stoping. For this reason, raise mining is an efficient and productive mining method in situations, where stopes with a large vertical extension are required. However, the low amount of infrastructure has also considerable advantages from a rock mechanics perspective. Namely, the amount of infrastructure, which can be subjected to high stress conditions and seismically active areas, is limited. This aspect is especially an advantage in the de-stressing phase of the de-stressing strategy. Another advantage is that the low amount of infrastructure enables to develop the infrastructure for new excavations, which are developed from raises, relatively quickly. Thus, infrastructure does not need to be developed long time in advance and the exposure time to potentially adverse stress situations is shorter. Furthermore, the quick development of infrastructure enables to utilize stress shadows better, because the infrastructure can be established inside stress shadows relatively fast, once the stress shadows were generated. Finally, the low amount of infrastructure and the short development times provide a high degree of flexibility.
- Flexibility to adapt to local requirements and experience: Due to the reasons outlined before the raise mining method provides a high degree of flexibility. This flexibility can be used to adapt the mine layout and mining sequence to the prevailing mining environment and the gained mining experience on short to medium notice. The size and shape of excavations created from raises can be adapted relatively easily by changing the drill hole length and pattern, which is drilled from the raises. Moreover, the position of the excavations created from raises can be adapted well because of the possibility to develop infrastructure (raises) late just before its utilization. In case modifications and redevelopment of infrastructure are necessary, the time and financial loss is comparatively low due to the low amount of infrastructure, which is required and which must accordingly be modified or redeveloped. As highlighted in section 8.4, providing flexibility is central for the successful implementation of the proposed stress management concept.

9.2 Implementing the de-stressing strategy with raise mining

In this section the implementation of the de-stressing strategy based on raise mining is outlined. Therefore, the required infrastructure, excavations and levels are described at the beginning. Then the application is demonstrated for an idealized, vertically dipping, thick tabular deposit. The individual steps of implementing the de-stressing strategy with raise mining are highlighted. After the implementation was shown for the idealized, vertically dipping, thick tabular deposit, the implementation is outlined for a steeply inclined, thick tabular deposit. At the end a case study of applying the de-stressing strategy based on raise mining in Kiruna mine is given. Potential advantages compared to the currently used sublevel caving are pointed out.

9.2.1 Infrastructure, excavations and levels

The de-stressing strategy with raise mining requires the following infrastructure, excavations and levels. The abbreviations in the brackets are used for the description in figures. The outlined dimensions of excavations and infrastructure are exemplary and for demonstration purposes in Figure 170 to Figure 193. The actual dimensions need to be based on and adapted to the prevailing mining conditions and production requirements.

- Slot raise (SR): Slot raises are utilized for the construction of slots and have thus an access function (section 7.1). Slot raises are developed by means of raise boring between individual raise levels and the slot development level, respectively. The slot raise diameter is primarily determined by the size of the machinery, the thickness of the installed support and expected deformations of the raise. The slot raise length is influenced by the raise boring capabilities, the possible unsupported stand-up time of the raise, because the support can only be installed in the raise, after boring was finished, and the regularity of the ore body. The shown slot raises have a diameter of 4 m, a length of about 200 m and their spacing along strike is 100 m.
- Production raise (PR): Production raises are utilized for the extraction of stopes and the construction of large drawbells. Hence, they have an access function (section 7.1). Production raises are also developed by means of raise boring between the raise levels and the production levels, respectively. Production raises are positioned in stress shadows and thus they are protected from high stresses. The production raise diameter is primarily determined by the size of the machinery, the thickness of the installed support and expected deformations of the raise. The production raise length is influenced by the raise boring capabilities, the possible unsupported stand-up time of the raise, because the support can only be installed in the raise, after boring was finished, and the regularity of the ore body. The shown production raises have diameter of 4 m and they are situated centrally behind slots and stopes at a distance of 25 m.
- Slot (SL): Slots are created in the de-stressing phase from slot raises by means of raise mining. Slots are elongated tabular excavations. The slot width is a function of the required spatial extent of the stress shadow behind slots, whereas the slot

thickness is primarily determined by ore flow considerations, namely preventing of hang-ups, and drilling and blasting capabilities. The slot length depends on the deposit geometry and deposit regularity. Furthermore, slot stability considerations may limit the slot dimensions, particularly the slot width and thickness. The shown slots have a width of 50 m, a thickness of 10 m and a length of several hundred meters. Figure 169 shows the definition of the used dimension terms. The slot roof is slightly inclined to improve the stability of the roof and blasting of the roof. The purpose of slots is to provide a stress shadow for infrastructure, which is developed or utilized in the production phase. Their elongated tabular shape is therefore best suited. Hence, slots are de-stressing excavations and fulfill a stress blocking function (section 7.3). In order to improve slot wall stability, slots are throughout filled with blasted rock mass. As slots are situated inside the ore body in the given application example, they have an extraction function (section 7.2) as well. However, the majority of extraction is still conducted in stopes. Neighboring slots are separated by massive pillars.

- Start slot (STSL): In their lower area slots are increased in width and they are then referred to as start slot. Accordingly, pillars are not left between neighboring start slots and start slots form a continuous, persistent slot. The purpose of start slots is to provide a continuous stress shadow for (later developed) production levels and to avoid stress concentrations of pillars and significant stress changes, which result from pillar extraction in the production phase, near production levels. Hence, start slots have a stress blocking function (section 7.3). The start slot width depends on the slot and pillar width, the start slot thickness is determined by ore flow and drilling and blasting considerations and the start slot length depends on considerations related to the protection of production levels from high stresses and mining-induced seismicity. The width of shown start slots is 100 m, the thickness is 10 m and their length is approximatively 100 m. Start slots are always filled with blasted rock mass. As they are in the deposit as well, they fulfill also a minor extraction function (section 7.2).
- Production level (PL): Drifts and other infrastructure are developed at production levels and utilized for the development of production raises as well as for the extraction of blasted rock mass from slots and mainly stopes. Infrastructure at production levels is developed inside stress shadows, which are provided by the start slots, and production levels can thus be protected from high stresses. Infrastructure at the production levels has an access function (section 7.1). Due to the usage of large drawbells two production levels are required. The ore, which is drawn at the production levels, is subsequently transferred to the main haulage system and main haulage infrastructure.
- Raise level (RL): Drifts and other infrastructure are developed at raise levels and utilized for the development of slot and production raises. The raise levels are the top levels of raises. Infrastructure, which is required to operate the machinery inside the raise, is located at raise levels. Hence, the infrastructure at raise levels provides an access function (section 7.1). Furthermore, additional drawpoints can be developed into slots at raise levels. The vertical spacing of raise levels depends on

the possible length of slot and production raises and the deposit inclination. The shown vertical spacing of raise levels is about 200 m.

- Slot development level (SDL): Drifts are developed at the slot development level. These drifts are utilized for the construction of slot raises and the creation of start slots and slots at an early stage in the de-stressing phase. At a later stage of the de-stressing phase the slot development level is abandoned. The infrastructure at the slot development level provides an access function (section 7.1). The slot development level is situated about 40 m below the production levels. The purpose for this is that the start slots extend below the production levels so that the production levels are not near a highly stressed abutment, which forms below the bottom of the start slots.
- Intermediate draw level (IDL): Intermediate draw levels and corresponding infrastructure are developed, if additional drawpoints are required at elevations above the production levels. This can be the case, if inclined stopes are extracted. Hence, the infrastructure at intermediate draw levels fulfills an access function (section 7.1). Intermediate draw levels can be developed in the production phase and thus either benefit from provided stress shadows or be protected from high stresses, which are prevailing in abutments of extraction areas. Moreover, former raise levels can be converted to intermediate draw levels. The required positions of intermediate draw levels are governed by ore flow considerations and the deposit shape especially the deposit inclination.
- Pillar (PI): Massive pillars are situated between adjacent slots and stopes, respectively. In the de-stressing phase the purpose of pillars is to control the regional stress situation and the mining-induced seismicity. Thus, the pillars have a regional stress transfer function (section 7.4). The pillar dimensions are governed by the pillar function, which calls for strong pillars in the de-stressing phase. The pillar length and pillar height are prescribed by the slot length and slot thickness. Thus, only the pillar width can be adapted to create pillars of certain properties and behavior. The shown dimensions of pillars between slots in the de-stressing phase are 50 m in width, 10 m in height and several hundred meters in length. Figure 169 shows the definition of the used dimension terms. In the production phase pillars provide initially still a regional stress transfer function. However, in the production phase the height of pillars is increased and depending on stoping layouts the pillar width may be reduced. Hence, pillars are gradually weakened and finally extracted in the production phase. This implies that regional stress and energy changes occur in the production phase and that stress concentrations are shifted into the abutments of extraction areas. Weakening and extracting regional stress transfer pillars is a delicate task, which requires a careful and detailed rock engineering design.
- Stope (ST): Stopes are utilized for the large-scale mineral extraction and have therefore an extraction function (section 7.2). Stopes are mined-out from production raises in the production phase. The stope dimensions are limited by drilling and blasting capabilities, which is conducted from the production raises, ore flow considerations and stope stability considerations. Cross-section of shown stopes is 50 m x 50 m and the stopes are several hundred meters high. Stope roofs are inclined to improve their stability and the blasting of subsequent slices in the roof. During their extraction stopes are always filled with blasted rock mass, which

provides support to the stope walls. Furthermore, stopes continue to provide stress shadows for the ongoing, further production. Hence, stopes have a stress blocking function (section 7.3) as well.

- Drawbell (DB): Drawbells are developed from production raises and utilized for the large-scale mineral extraction in stopes. Thus, drawbells have an extraction function (section 7.2). As drawbells are developed inside stress shadows of start slots, they can be protected from high stresses. The drawbell dimensions are governed by ore flow considerations and the dimensions of corresponding stopes. The dimensions of shown drawbells are about 50 m in height and the final drawbell roof cross-section is 50 m x 50 m. The drawbell roof is inclined as well to improve the stability and blasting work. The large drawbell dimensions enable first to construct several drawpoints into the drawbell and thus to increase the possible production and second the large drawbells can improve the ore flow inside stopes. Using two production levels allows to adapt the drawpoint position such that an improved and more equal spacing of adjacent drawpoints can be achieved. Furthermore, the large drawbells and their inclined sidewalls may improve the ore flow characteristics too. These ore flow considerations are particularly important, if the operation is conducted as caving operation.
- Drawpoint (DP): Drawpoints are developed into drawbells, slots and start slots. They are situated at the slot development level, production levels, raise levels and intermediate draw levels. Except of the drawpoints, which are situated at the slot development level, the drawpoints can be developed in stress shadows provided by slots, start slots and stopes.
- Ore pass (OP): Ore passes are developed by means of raise boring between intermediate draw levels and production levels to transport the drawn ore to the main haulage infrastructure. Ore passes can be developed in the production phase and thus either benefit from provided stress shadows or be protected from regional abutments of extraction areas and associated high stress magnitudes.

Besides the outlined (rather specific) infrastructure other infrastructure, such as hoisting shafts, ramp systems, ventilation raises, main haulage drifts to shafts, workshops etc., is required. As this (main and primary) infrastructure is required in any mining method, it is not further discussed or shown in following sections and application examples. Measures to protect this main and primary infrastructure were outlined in foregoing chapters.

9.2.2 Application in a vertically dipping, thick tabular deposit

The individual steps for the implementation of the de-stressing strategy with raise mining are outlined on basis of an idealized, vertically dipping, thick tabular deposit, which enables to discuss the implementation of the de-stressing strategy with relatively simple layouts and sequences. Backfill is central for the application of raise mining and thus central for the implementation of the de-stressing strategy based on raise mining. Different backfill types and considerations regarding their application were outlined in section 9.1.1.

Figure 168 shows the deposit geometry. The tabular deposit shape and the vertical orientation of the deposit cause a considerable disturbance and redistribution of the primary horizontal stresses perpendicular to the strike direction of the deposit, whereas the primary horizontal stresses parallel to the strike direction of the deposit and the primary vertical stresses are not influenced as strongly. Hence, the horizontal stresses perpendicular to the strike direction of the deposit are critical and the de-stressing strategy must address the stresses in this direction. As this impact is a consequence of the deposit geometry and the deposit orientation, the magnitude and orientation of the primary stresses have only a minor influence and they do not change this critical stress direction in general.

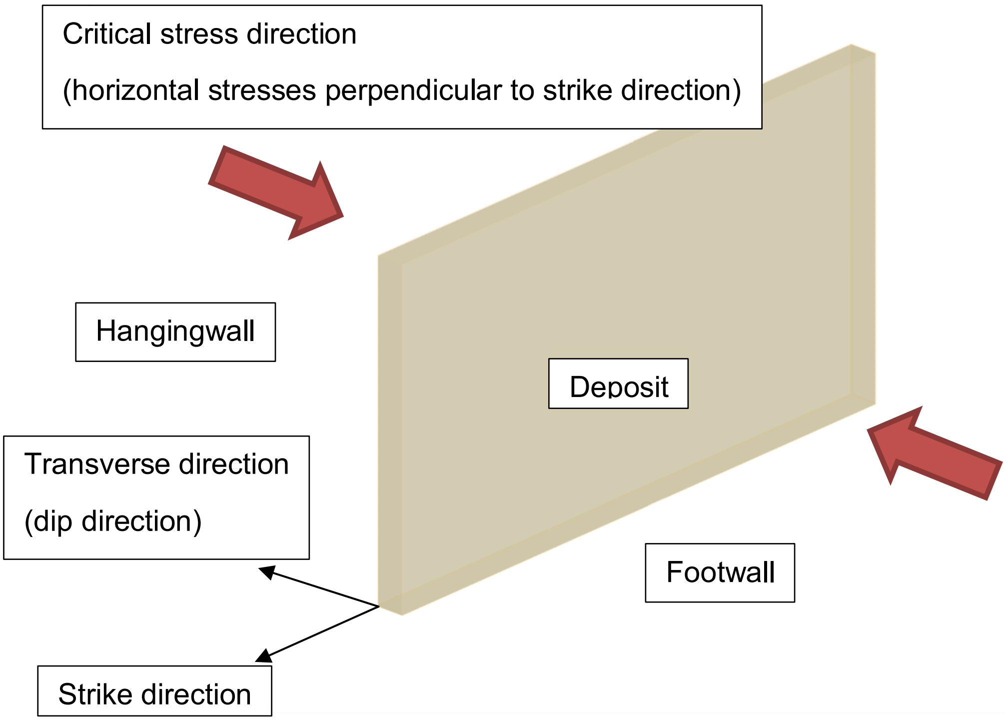


Figure 168: Idealized, vertically dipping, thick tabular deposit; the critical stress direction is indicated by the red arrows.

For demonstration purposes it is assumed that the deposit has very large extensions in strike and vertical direction so that the extraction can extent over large areas and so that the dimensions of the area, for which the implementation of the de-stressing strategy is shown, is not limited by the deposit geometry. This assumption simplifies the outlined layout and sequence further, because constraints resulting from a limited deposit size are not present. The main and primary infrastructure is situated in the footwall and outside the zone of influence of large-scale mineral extraction. Thus, the main and primary infrastructure is not shown and further discussed. Furthermore, as the main and primary infrastructure is in the footwall, extraction commences at the hangingwall contact and advances towards the footwall contact. Therefore, the de-stressing excavations, which are created in the de-stressing phase, are located at the hangingwall contact. The individual steps for the implementation of the active stress control approach (de-stressing phase) and the subsequent large-scale mineral extraction (production phase), which must ensure the continuation of the implemented active stress control approach, are shown in Figure 170 to Figure 191 for a part of the deposit. The figures show each an isometric view and a side view perpendicular to the strike of the deposit from the slots, stopes etc., which are on the left side of the panel. The provided layouts in these figures are schematic and highlight important points. Details about the design are not considered in these layouts for simplification and to keep the focus on the relevant aspects of the de-stressing strategy.

9.2.2.1 De-stressing phase

In the de-stressing phase a slot pillar system is created at the hangingwall contact. Slot raises are utilized for the creation of slots, which provide a stress shadow for later developed infrastructure. The purpose of pillars is to control the stress situation and mining-induced seismicity near active infrastructure and slots. As the deposit dips vertically, the long axis of slots and pillars are oriented vertically as well. The layout and development sequence of the slot pillar system in the de-stressing phase are a layout and sequence, where the infrastructure is developed ahead; compare section 8.2, in which relevant rock mechanics aspects of this layout and sequence are outlined.

Before demonstrating the individual steps of creating the slot pillar system, the terminology, which is used for describing slot and pillar dimensions, is outlined. Figure 169 shows a horizontal cross-section through slots and pillars, which are oriented vertically.

- The term slot width refers to the longer extension of the slot in the horizontal direction, which is in strike direction in the given example of the vertically dipping, tabular deposit.
- The term slot thickness refers to the shorter extension of the slot in the horizontal direction, which is in transverse direction in the given example of the vertically dipping, tabular deposit.
- The term slot length is the slot extension in vertical direction.
- The term pillar width refers to the extension of the pillar between adjacent slots in the horizontal direction. In the given example of the vertically dipping, tabular deposit the pillar width is the pillar extension in strike direction.
- The term pillar height refers to the extension of the pillar in the horizontal direction, which is perpendicular to the direction of the pillar width. In the given example of the vertically dipping, tabular deposit the pillar height is the pillar extension in transverse direction. Thus, the pillar height corresponds to the slot thickness in the de-stressing phase. This definition of the pillar height may be confusing, because it does not refer to the pillar extension in vertical direction, which is normally called pillar height. The reason to still use the term pillar height to describe the pillar dimension in horizontal direction perpendicular to the direction of pillar width is that for pillars, which long axis is oriented vertically, this pillar dimension acts as pillar height functionally, namely it has a similar effect on the pillar strength and pillar behavior, as the pillar height for pillars, which long axis is oriented horizontally.
- The term pillar length is the pillar extension in vertical direction.

In case the slots and pillars are not oriented vertically but instead oriented steeply inclined, the terms remain the same, but in this case they refer to the slot and pillar dimensions in a cross-section, which is perpendicular to the long axis of slots and pillars (perpendicular to the slot and pillar extension in direction of their length).

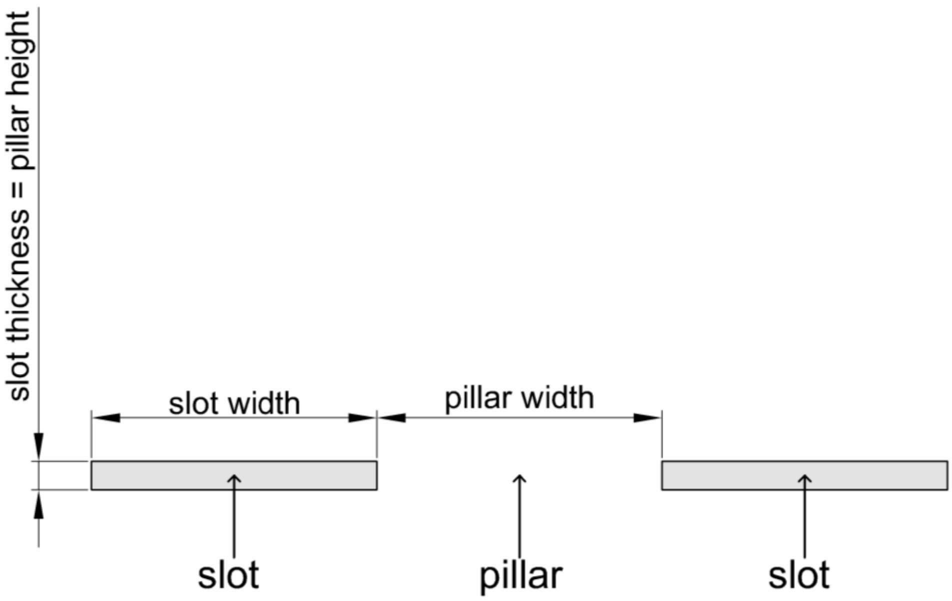


Figure 169: Definition of terms for slots and pillars in a horizontal cross-section in the de-stressing phase; slots and pillars are oriented vertically.

9.2.2.1.1 *Step 1*

Figure 170 and Figure 171 show an isometric and side view of step 1. Drifts are developed at the slot development level and the first raise level. At the slot development level drawpoints for the subsequent creation of the first slot and start slot are developed. The first slot raise is bored between the slot development level and the raise level. The raise is at the hangingwall contact of the ore body.

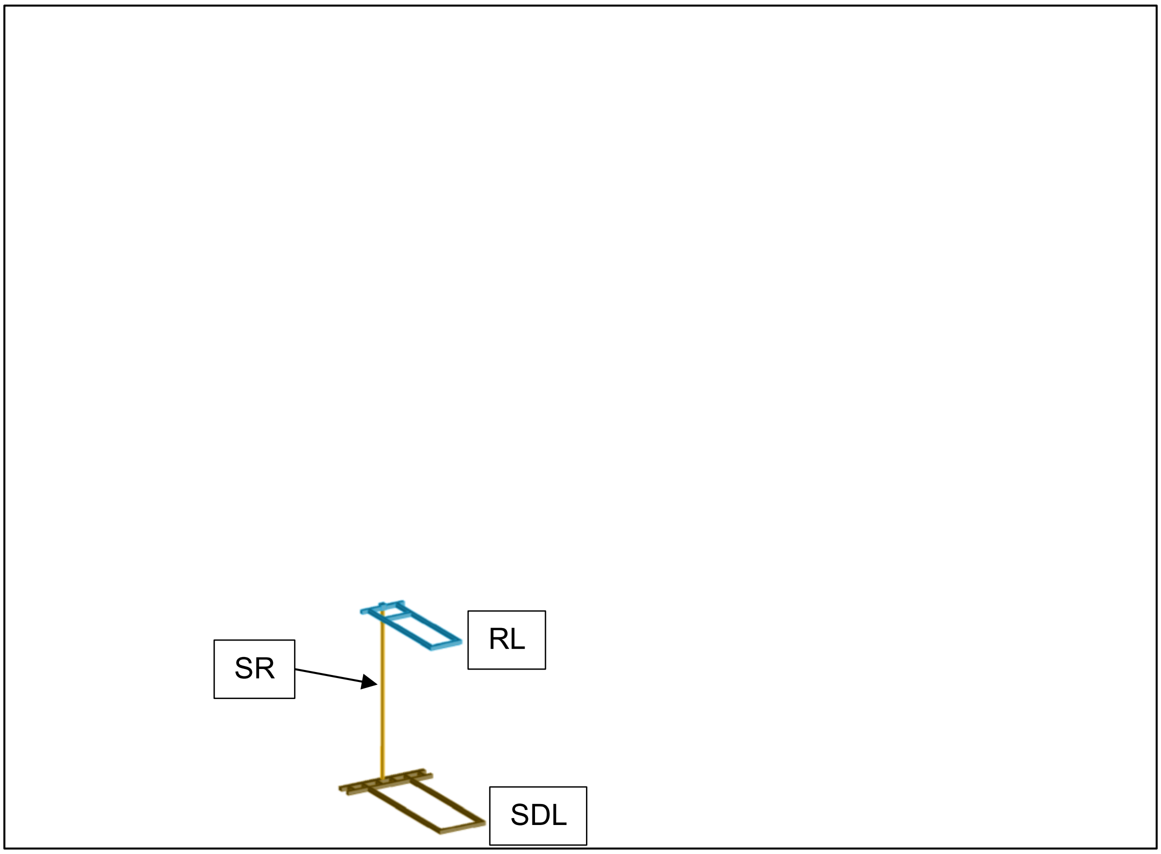


Figure 170: Isometric view of step 1

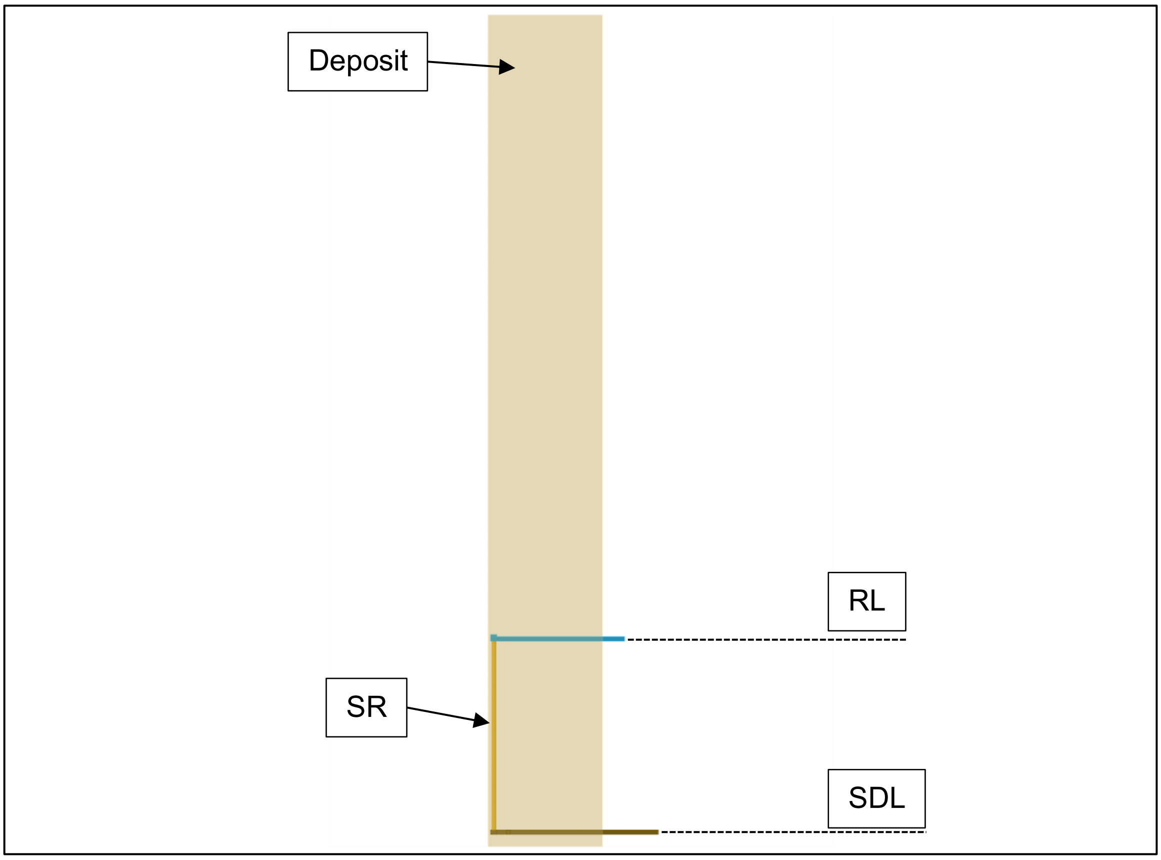


Figure 171: Side view of step 1

9.2.2.1.2 Step 2

Figure 172 and Figure 173 show an isometric and side view of step 2. The slot development level and the raise level are extended and a new raise level, which is situated above the first raise level, is developed. The extension of existing levels and the development of new levels are made in preparation for the creation and extension of slots. Furthermore, the creation of the first start slot commenced. Therefore, the first part of the start slot is blasted with fans at the slot development level on the retreat from the slot raise. The purpose of these retreating fan blasts is to widen the drift at the bottom of the start slot to the thickness of the start slot, which is done to improve the ore flow inside the start slot and to avoid the formation of hang-ups. Furthermore, the retreating fan blasts increase the free volume for subsequent blasts of the start slot, which are conducted from the slot raise.

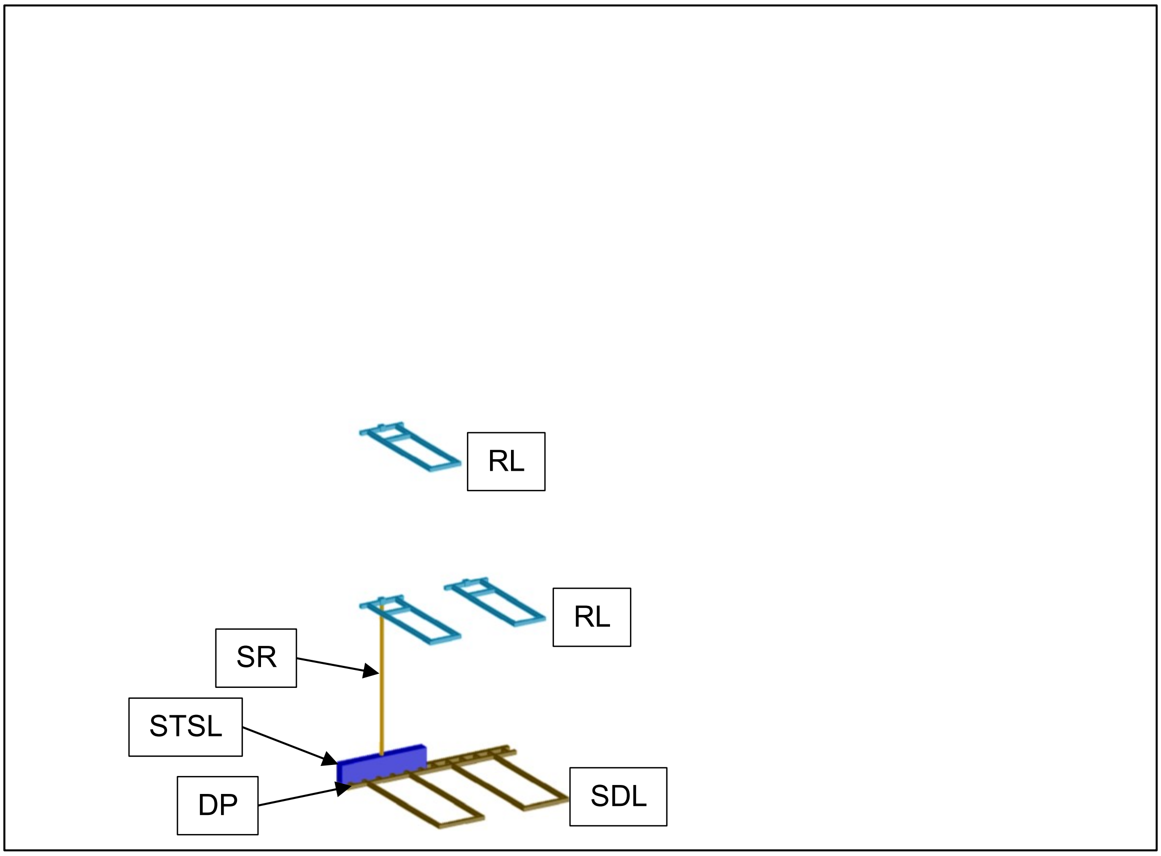


Figure 172: Isometric view of step 2

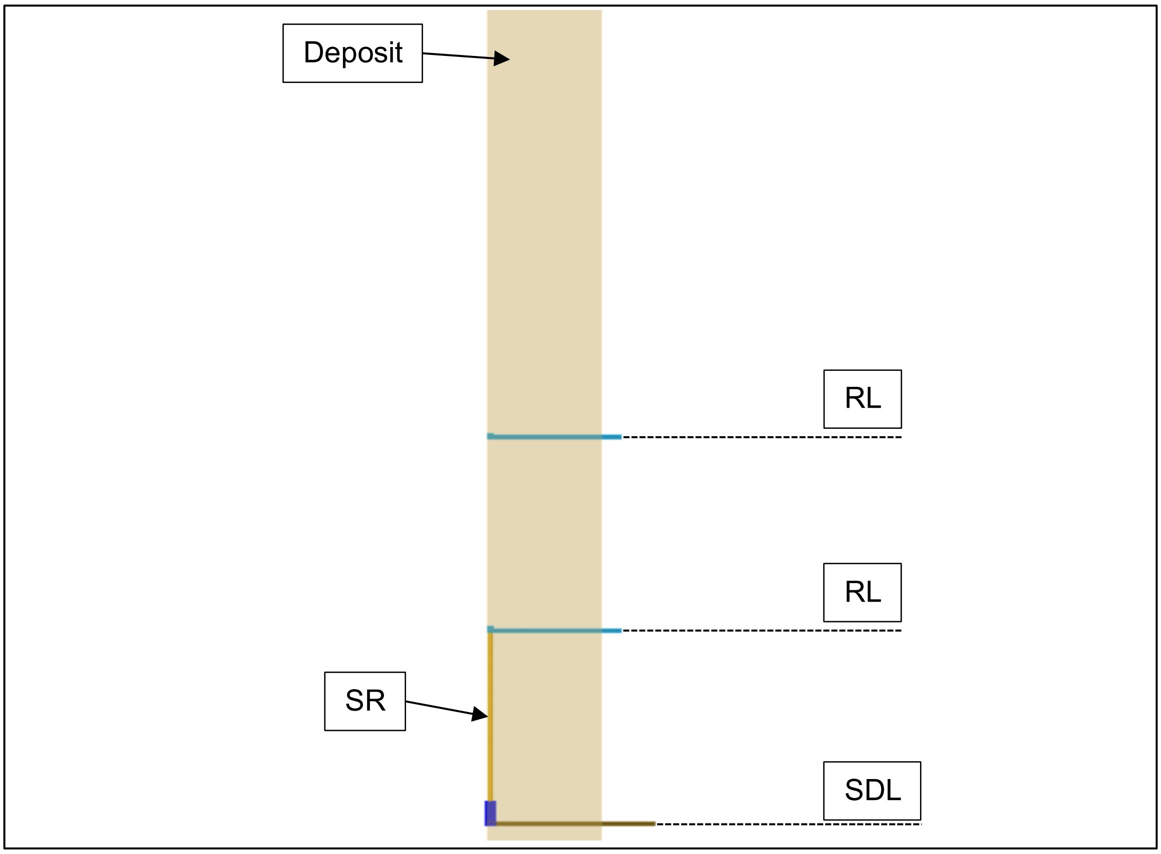


Figure 173: Side view of step 2

9.2.2.1.3 Step 3

Figure 174 and Figure 175 show an isometric and side view of step 3. Development of infrastructure required for creating slots and start slots continues. The slot development level and raise levels are extended, new raise levels are developed and additional slot raises are developed. Slot raises, which are developed between raise levels are positioned such that the slot, which is developed from the slot raise below, can be extended with the additional slot raise, which is developed between raise levels. The start slot is created from the corresponding slot raise. The roof of the start slot is blasted with rings in upwards direction. The swell of each blast is mucked at drawpoints at the slot development level, before the next blast is made. Hence, the start slot is always filled with blasted rock mass, which provides support to the sidewalls of the start slot. The remaining blasted rock mass is left in the start slot and it is later drawn from the start slot, when the stope behind the start slot is extracted and drawn empty. The creation of the next start slot commenced as well. It can further be seen that a pillar between adjacent start slots is not formed.

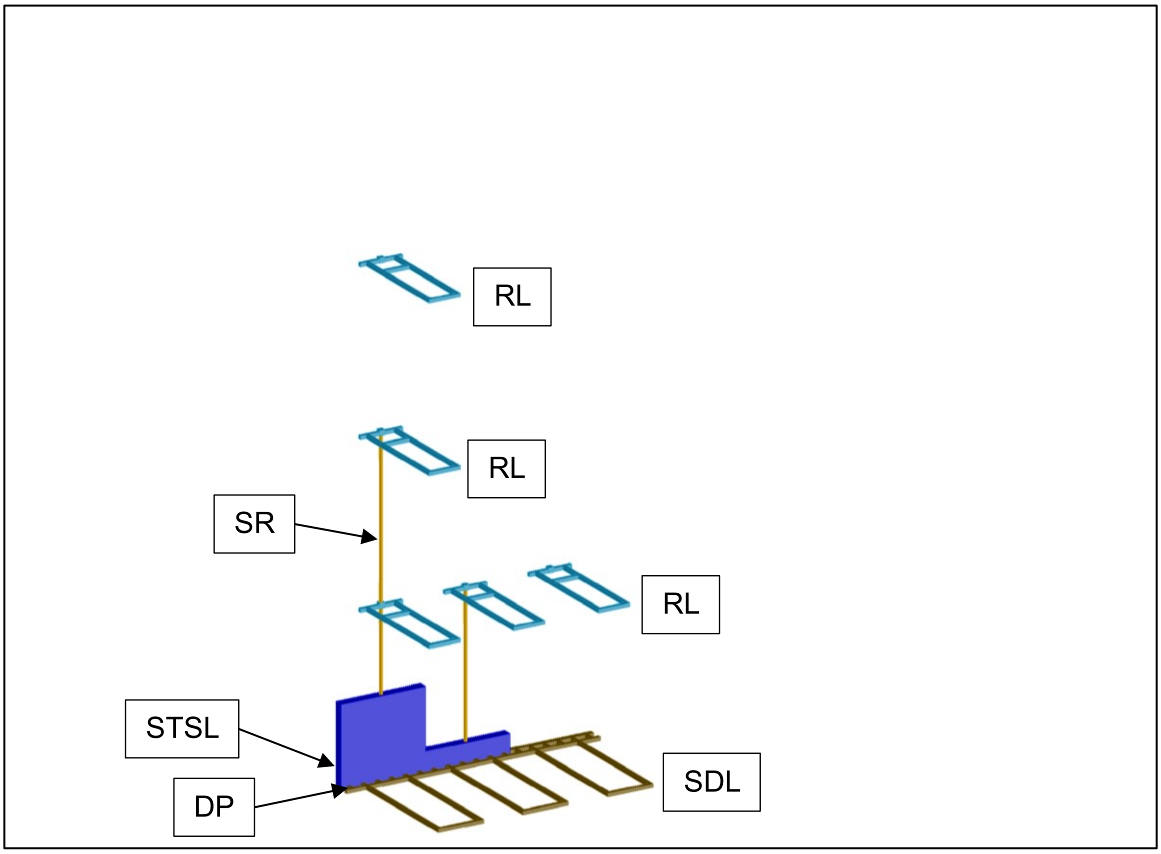


Figure 174: Isometric view of step 3

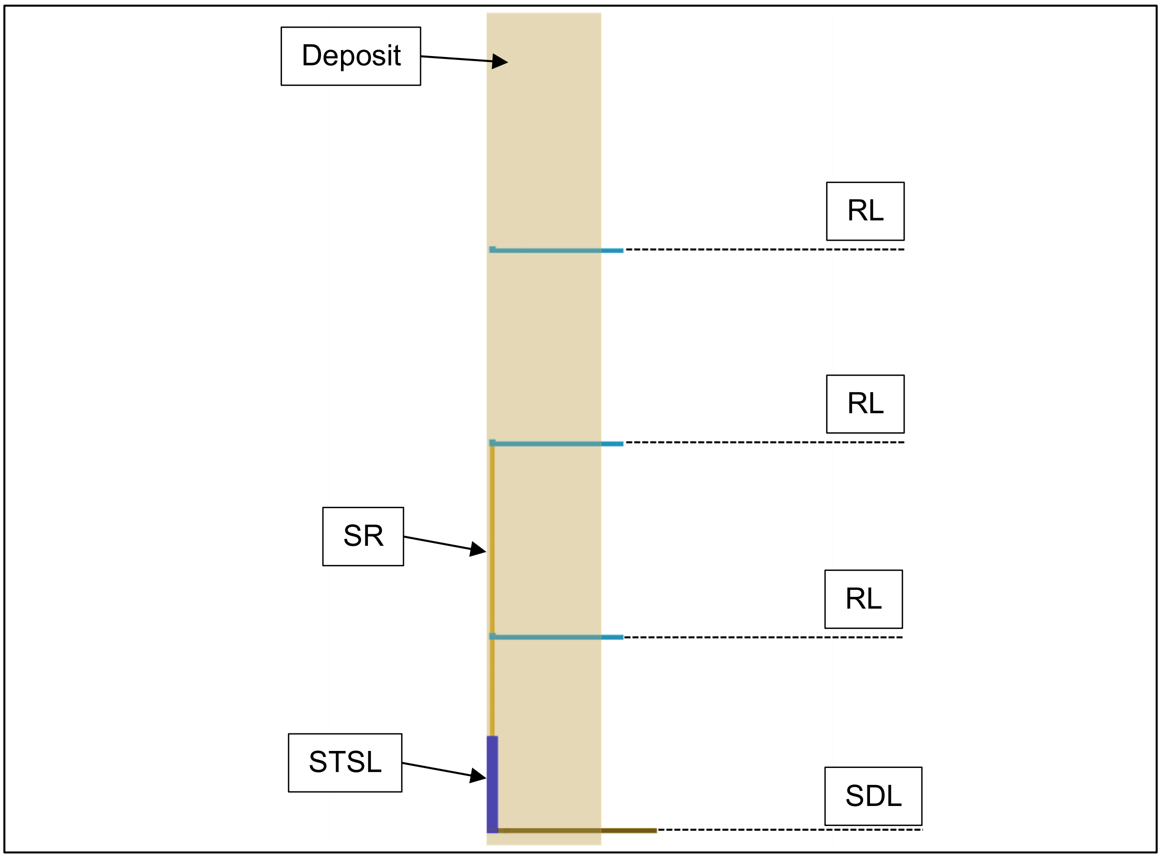


Figure 175: Side view of step 3

9.2.2.1.4 Step 4

Figure 176 and Figure 177 show an isometric and side view of step 4. The mining activities in the de-stressing phase commence. Additional infrastructure at the slot development and raise levels is developed, additional slot raises are developed and the creation of slots and start slots continues. The first two start slots were developed to their final length and then their width was narrowed to form slots. Accordingly, a massive pillar was created between the adjacent slots. The pillar is created behind the advancing slots and controls the stress situation and mining-induced seismicity. In case the actual pillar behavior deviates from the planned behavior, the pillar dimensions can be adapted on short notice by changing the slot dimensions (drill and blast layouts) in slots, which are under development.

The first slot was also developed above the first raise level. At this raise level additional drawpoints were developed into the slot to facilitate the flow of blasted rock mass inside the slot. Slots are same as start slots always filled with blasted rock mass and only the swell is mucked after every blast. The blasted rock mass inside slots provides some support to the slot walls but also to the pillar adjacent to the slots. The remaining blasted rock mass is left in the slot and it is later drawn from the slot, when the stope behind the slot is extracted and drawn empty.

Furthermore, it can be seen that drifts were developed at the production level, which has been de-stressed and which is protected from high stresses by the start slots. At the production level drawpoints were developed into start slots. Thus, the slot development level is no longer needed for drawing blasted rock mass from slots in areas, where the production level and drawpoints at the production level were developed, and it can be abandoned in these areas. Overall, the two figures demonstrate well that the de-stressing phase can be implemented with a minimum amount of infrastructure and that the majority of the infrastructure can be developed short before its utilization, which circumstance provides a significant degree of flexibility.

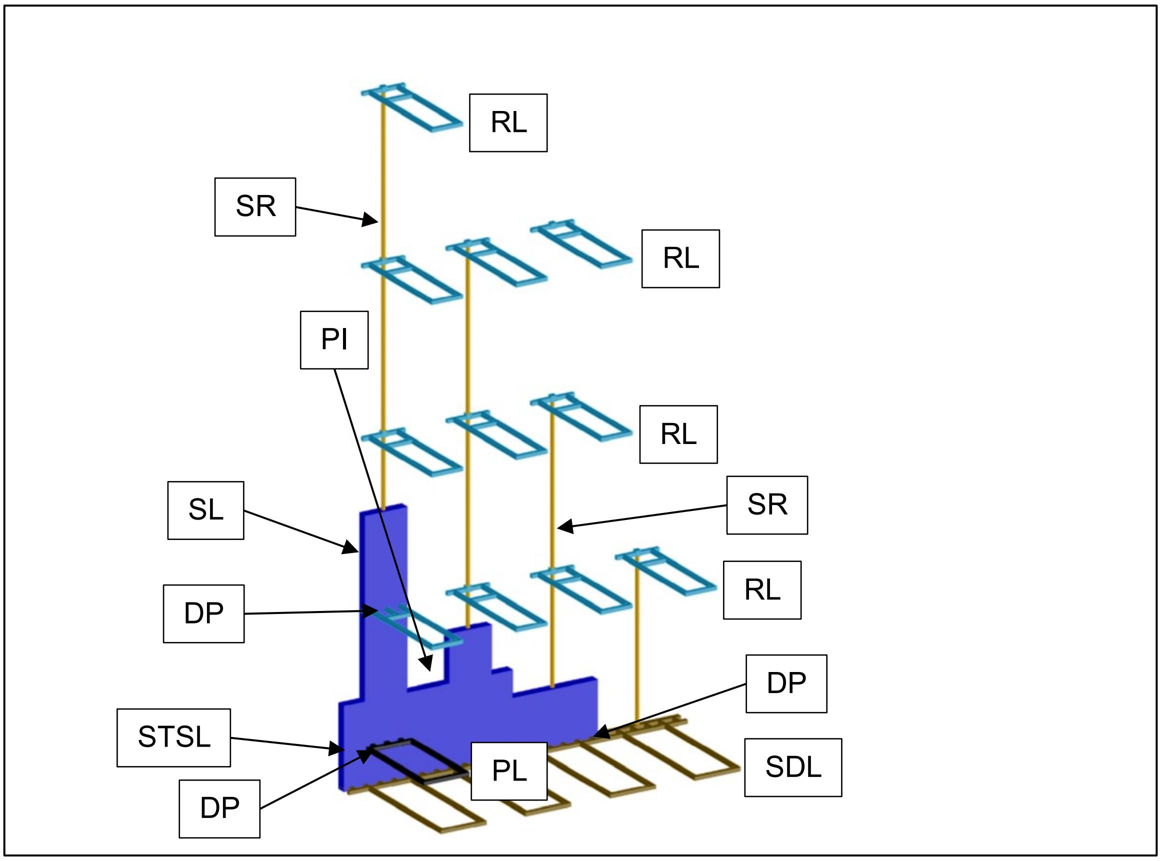


Figure 176: Isometric view of step 4

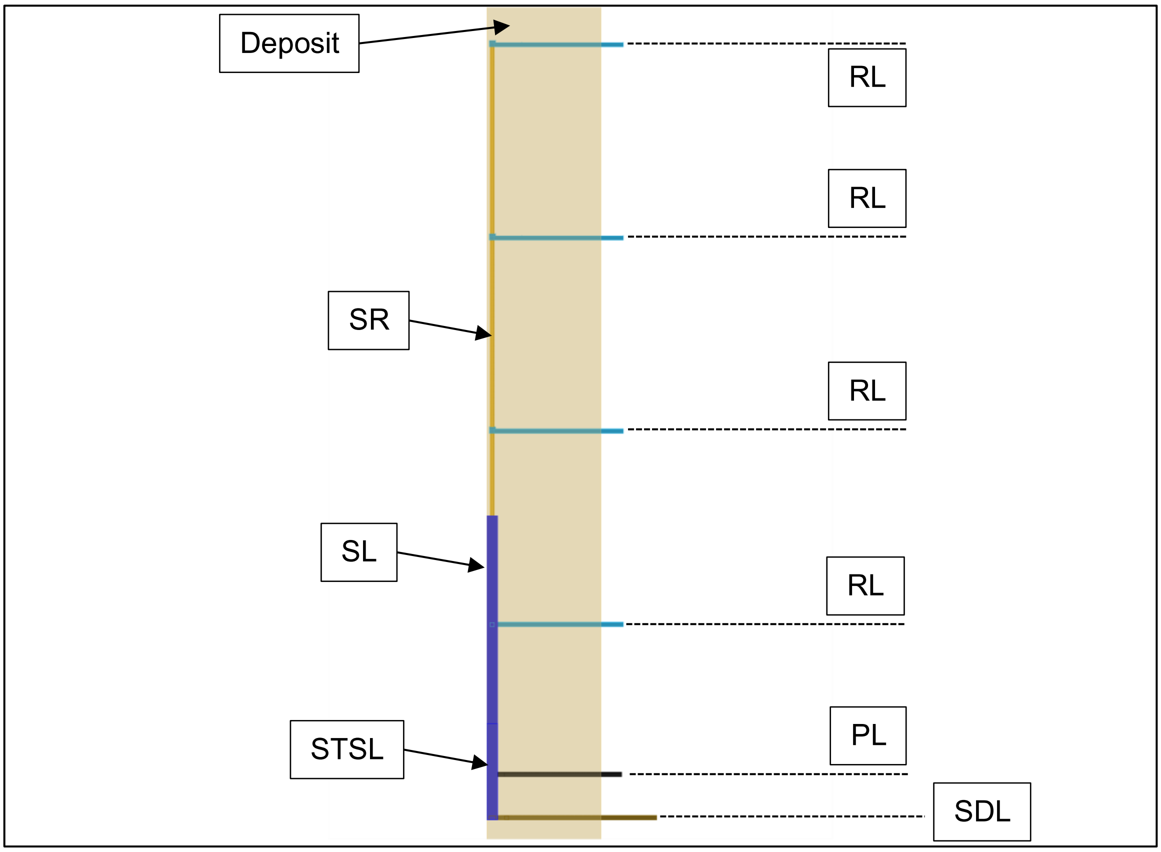


Figure 177: Side view of step 4

9.2.2.1.5 Step 5

Figure 178 and Figure 179 show an isometric and side view of step 5. The mining activities in the de-stressing phase continue. Start slots, slots and corresponding infrastructure are developed. The first slot reached its final length and is thus not extended further.

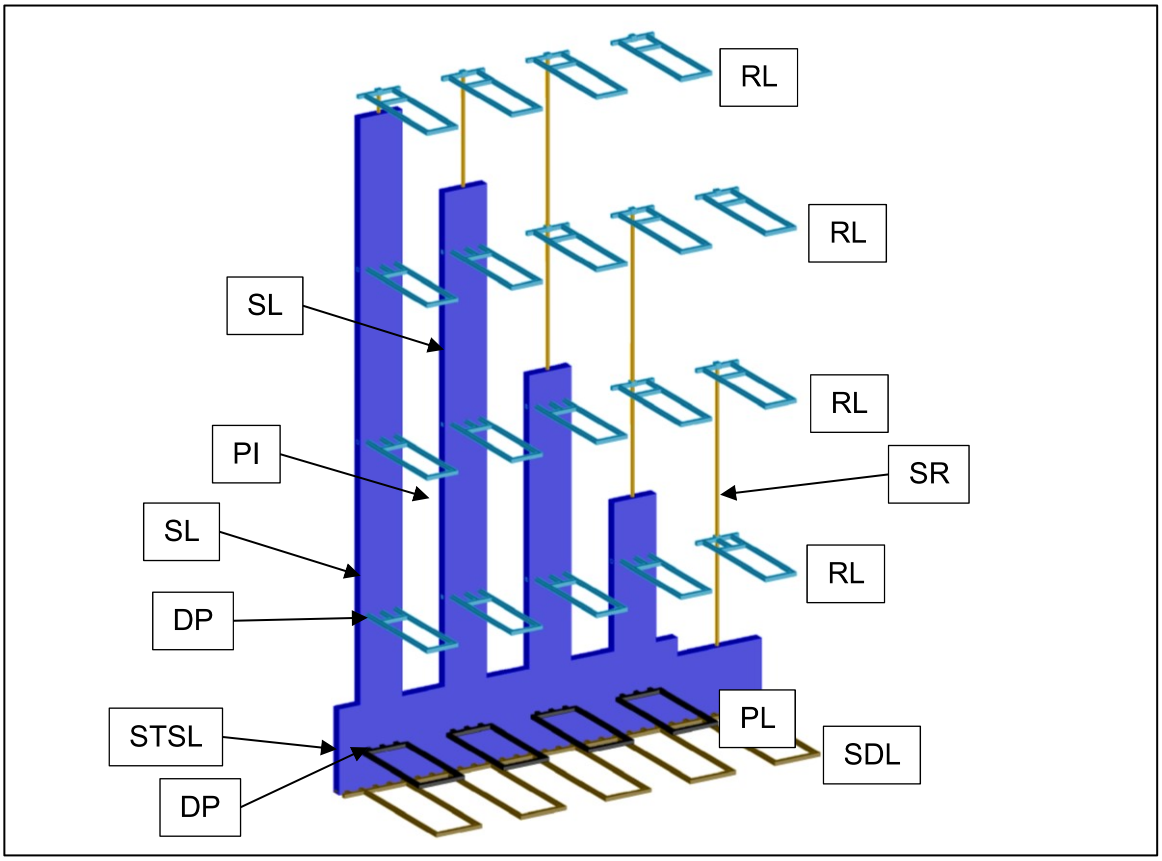


Figure 178: Isometric view of step 5

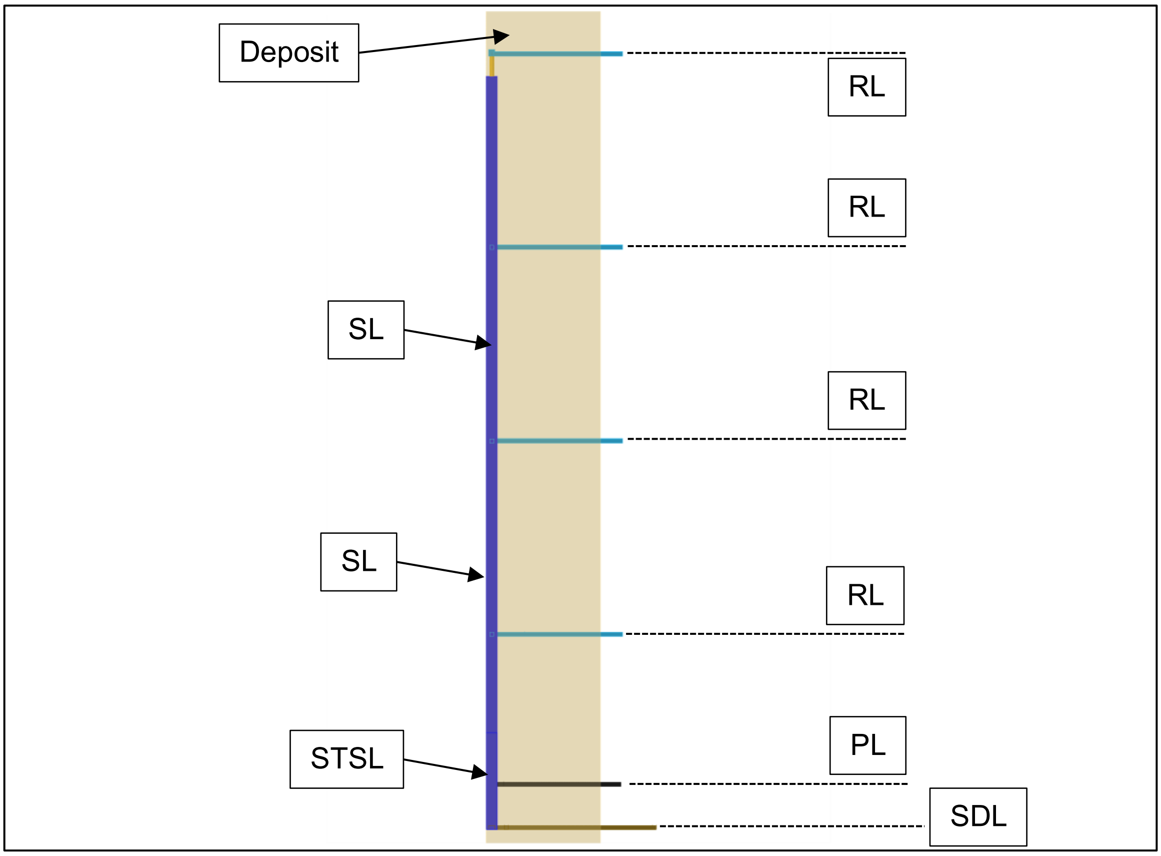


Figure 179: Side view of step 5

9.2.2.1.6 Step 6

Figure 180 and Figure 181 show an isometric and side view of step 6. All slots were developed to their final length. Hence, the mining activities in the de-stressing phase were finished and respective part of the deposit is ready for the large-scale mineral extraction, which takes place in the production phase.

The two figures show the final state of the de-stressing phase in a part of a vertically dipping, thick, tabular deposit. The slots and start slots provide de-stressed ground for the subsequent mining activities in the production phase. The slots and start slots are oriented such that they block the stresses in the critical stress direction, which is horizontal and perpendicular to the strike direction of the deposit. The pillars control the stress situation and mining-induced seismicity in the de-stressing phase, which is high stress mining. Furthermore, it can be seen that the slot pillar system can be established with a minimum amount of ahead developed infrastructure.

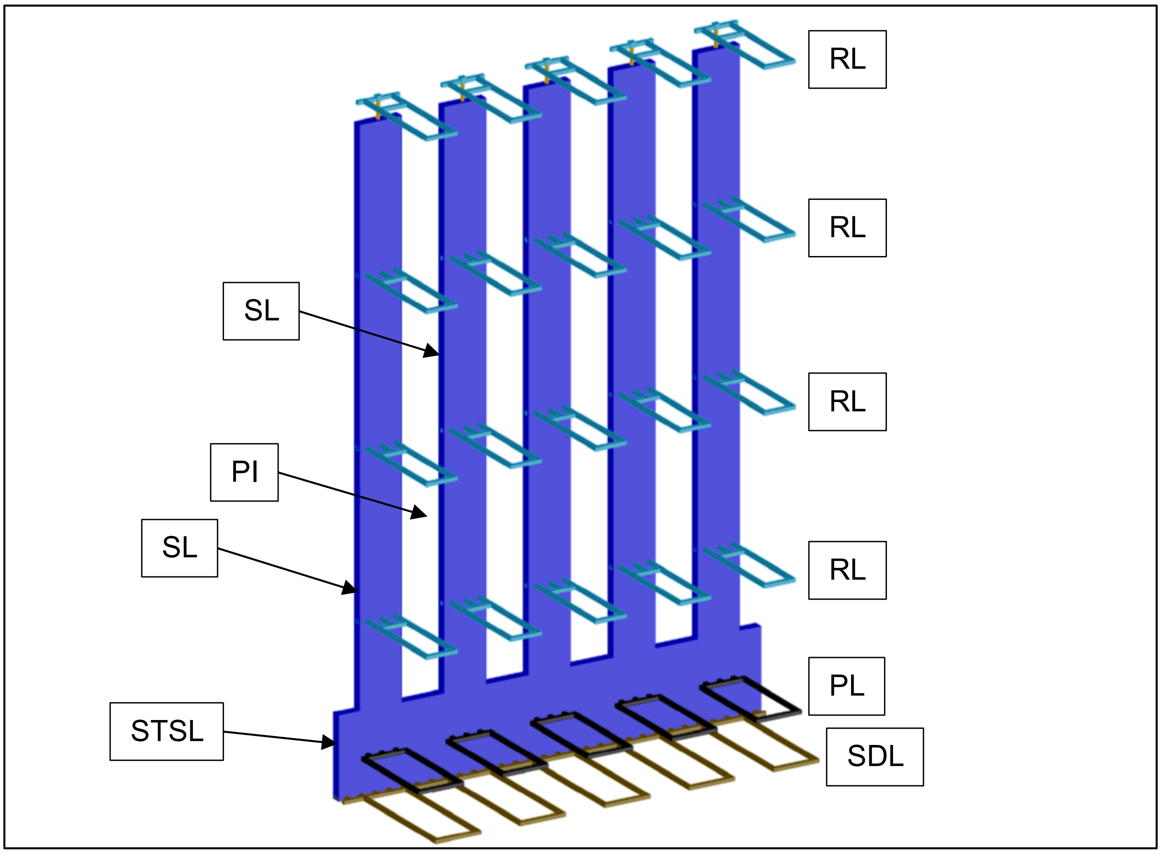


Figure 180: Isometric view of step 6

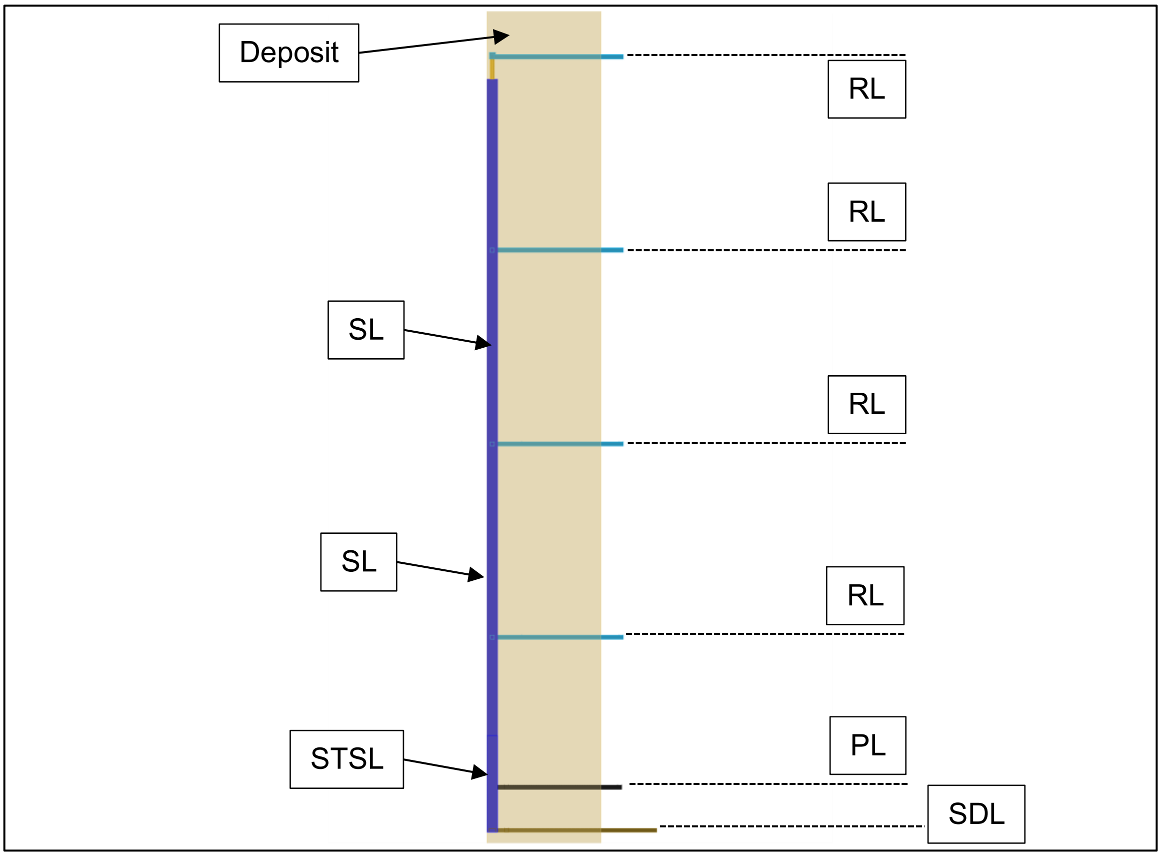


Figure 181: Side view of step 6

9.2.2.2 Production phase

In the production phase the large-scale mineral extraction commences. Infrastructure for mining activities in the production phase is developed in the de-stressed ground and stopes are extracted in the de-stressed ground. Furthermore, the mining activities in the production phase must ensure that the active stress control approach, which was implemented in the de-stressing phase, is maintained. Relevant rock mechanics aspects in the production phase of the present layout and sequence, which is based on ahead developed infrastructure in the de-stressing phase, are outlined and discussed in section 8.3. The steps of the production phase are shown in the following. The step number is continued from the de-stressing phase. Hence, the first step of the production phase is step 7.

9.2.2.2.1 Step 7

Figure 182 and Figure 183 show an isometric and side view of step 7. The infrastructure at the production level is extended to prepare for the large-scale mineral extraction. Furthermore, production raises are developed between the production level and raise levels. It can be seen that major adaptations or extensions to the infrastructure for subsequent production are not necessary and that the infrastructure is situated in de-stressed ground.

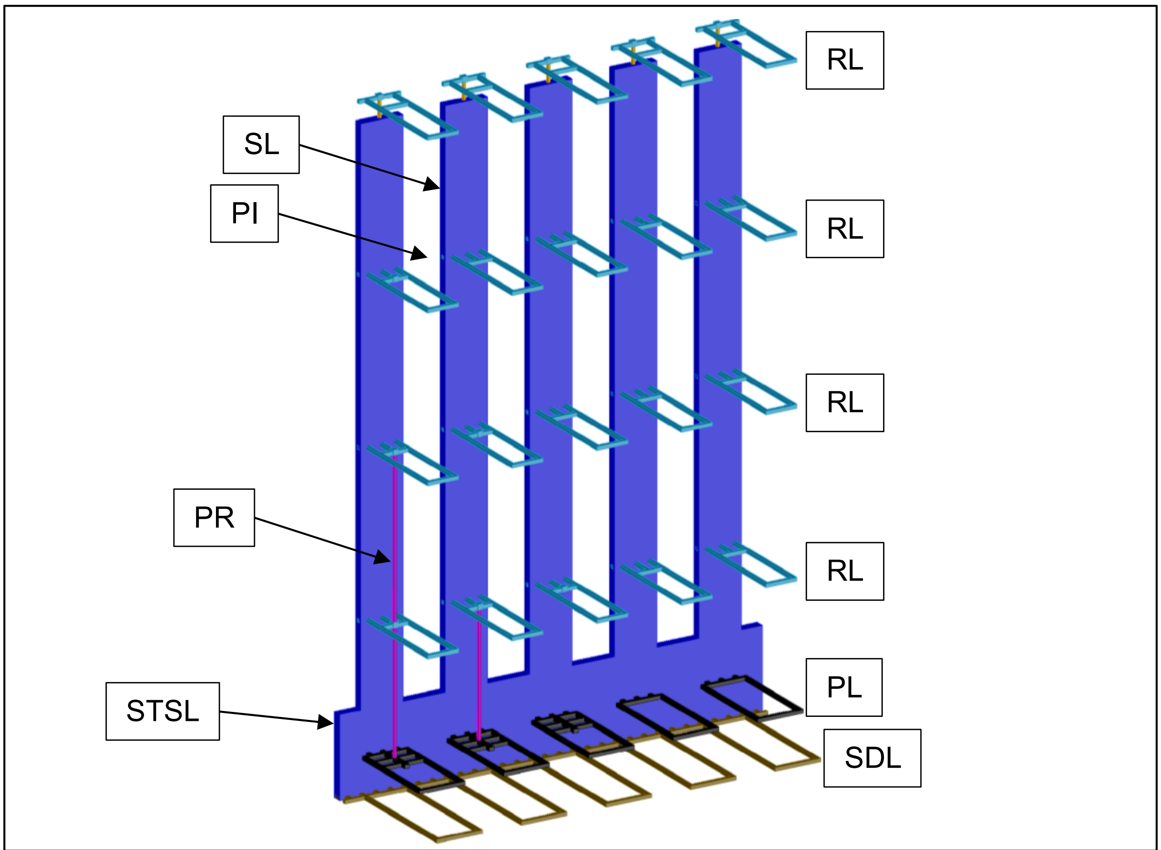


Figure 182: Isometric view of step 7

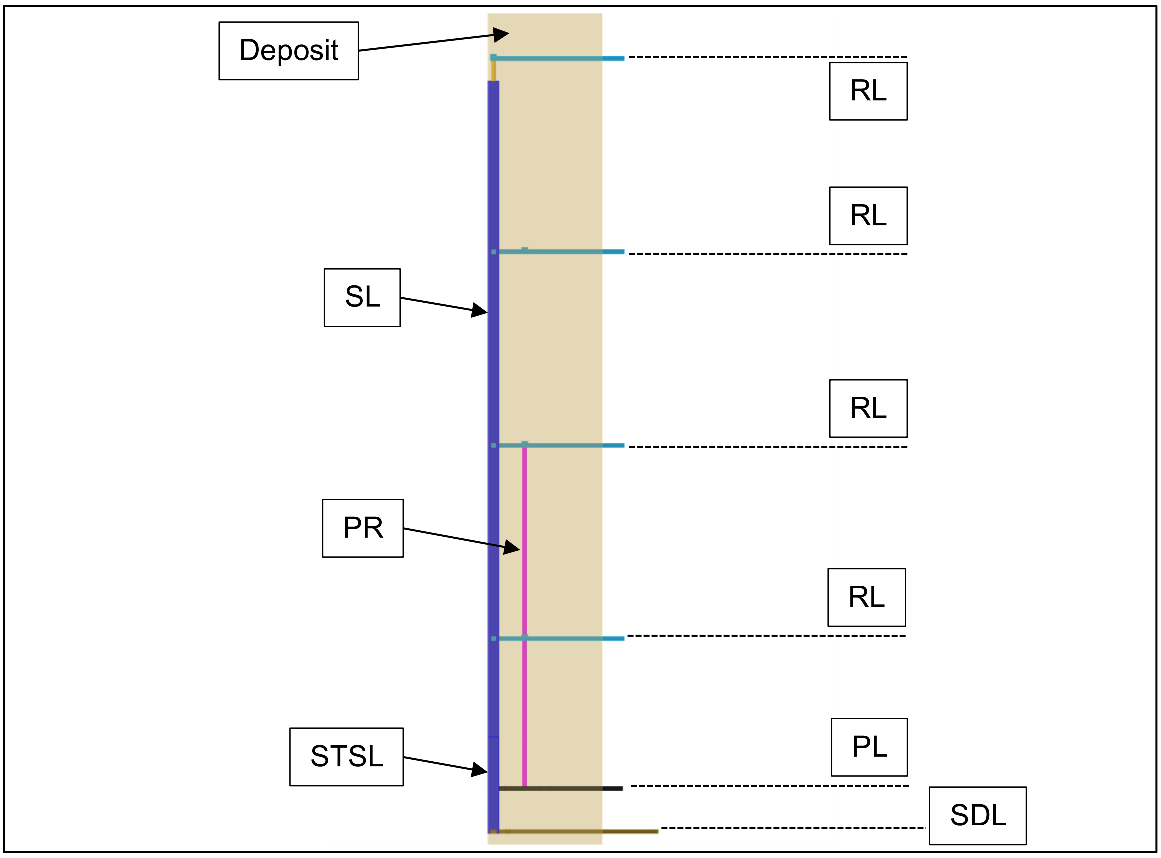


Figure 183: Side view of step 7

9.2.2.2.2 Step 8

Figure 184 and Figure 185 show an isometric and side view of step 8. The production raises and infrastructure at the (first) production level are utilized to develop large drawbells. Therefore, rings are blasted from production raises and the swell of the blasted rock mass is drawn at drawpoints at the first production level. As only the swell is drawn, the drawbells are filled with blasted rock mass, which provides support to the drawbell walls. Moreover, an additional (second) production level is developed. This second production level is situated above the first production level and utilized to develop additional drawpoints into the drawbell. As the swell from blasting the drawbell can be drawn at the first production level due to the inclined drawbell walls, the second production level and corresponding drawpoints can be developed delayed, after the development of the drawbell commenced.

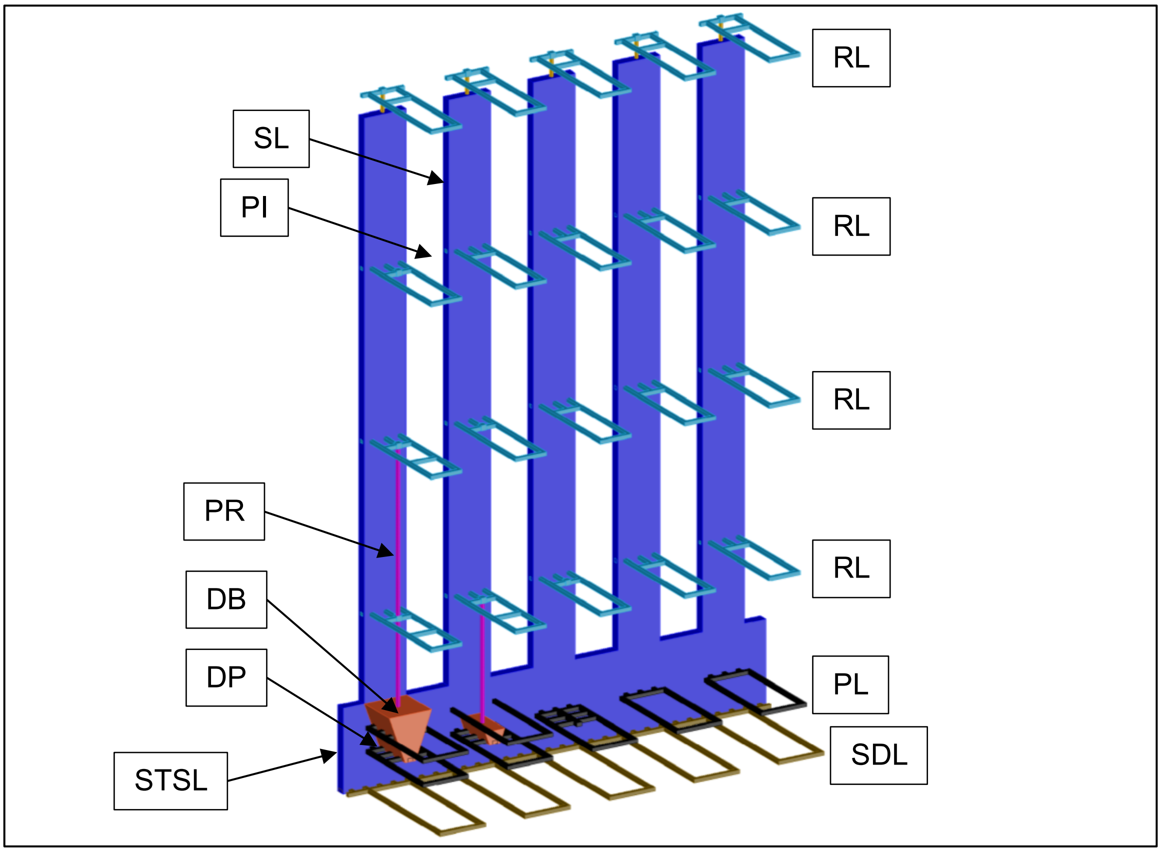


Figure 184: Isometric view of step 8

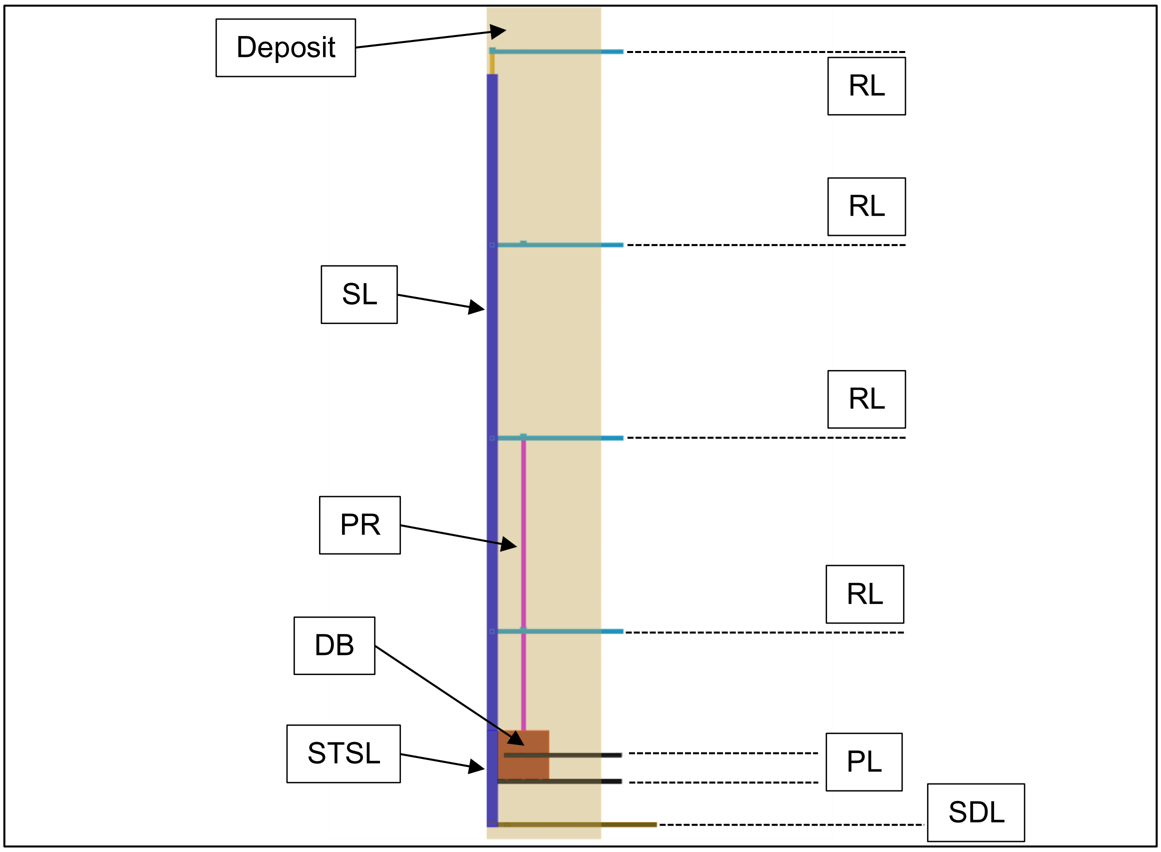


Figure 185: Side view of step 8

9.2.2.2.3 Step 9

Figure 186 and Figure 187 show an isometric and side view of step 9. Additional infrastructure and drawbells for stope extraction have been developed. The extraction of stopes behind slots has commenced. During blasting subsequent slices of the stope roof from raises only the swell is drawn after each blast so that the stopes are filled with blasted rock mass, which provides support to the stope walls and which prevents the occurrence of an air blast. After blasting of stopes finished, stopes are drawn empty and simultaneously backfilled with rock fill from the uppermost raise level. A proper draw strategy and draw control are required to avoid dilution of blasted ore with the rock fill. The first three stopes were already completely mined-out and backfilled.

Large quantities of rock fill and an efficient backfill system are required in the outlined layout and sequence. If rock fill in required quantities or an appropriate backfill system are not available, paste fill may be used. However, in this case the stope must be drawn empty before paste fill can be placed. The stope height and cross-section may be limited by stope stability considerations and thus an adapted mine layout may be necessary.

The completely extracted stopes extend up to the same elevation as completed slots. The last raise level and the last production raise are therefore situated above mined-out stopes in a highly stressed abutment area. In order to protect this infrastructure from high abutment stresses, the slots must extend above the last raise level, from which production raises are bored. This aspect is not shown in the figures for simplification and overview purposes.

Extraction of the stopes impacts further the pillars between slots (and stopes). The pillar width-to-height ratio is decreased and crushing of pillars is triggered. Consequently, pillars become de-stressed and regional stress and energy changes take place. Thus, the extraction of stopes continues to provide de-stressed ground for the infrastructure, which is required to extract next stopes and pillars. If pillars do not crush by changing the pillar width-to-height ratio, additional measures, such as hydraulic fracturing or pre-conditioning blasting, may have to be applied inside the pillar. Overall, stable crushing and the associated de-stressing of pillars are critical and decisive for a successful application of the outlined mine layout and mining sequence.

From these figures it can be seen that the extraction of stopes requires only a minimum amount of infrastructure and that the infrastructure can be developed short before its utilization, which circumstance adds a considerable degree of flexibility. Furthermore, the stope shape and dimensions can be adapted on short notice, if pillar behavior (pillar crushing) deviates from the actual design.

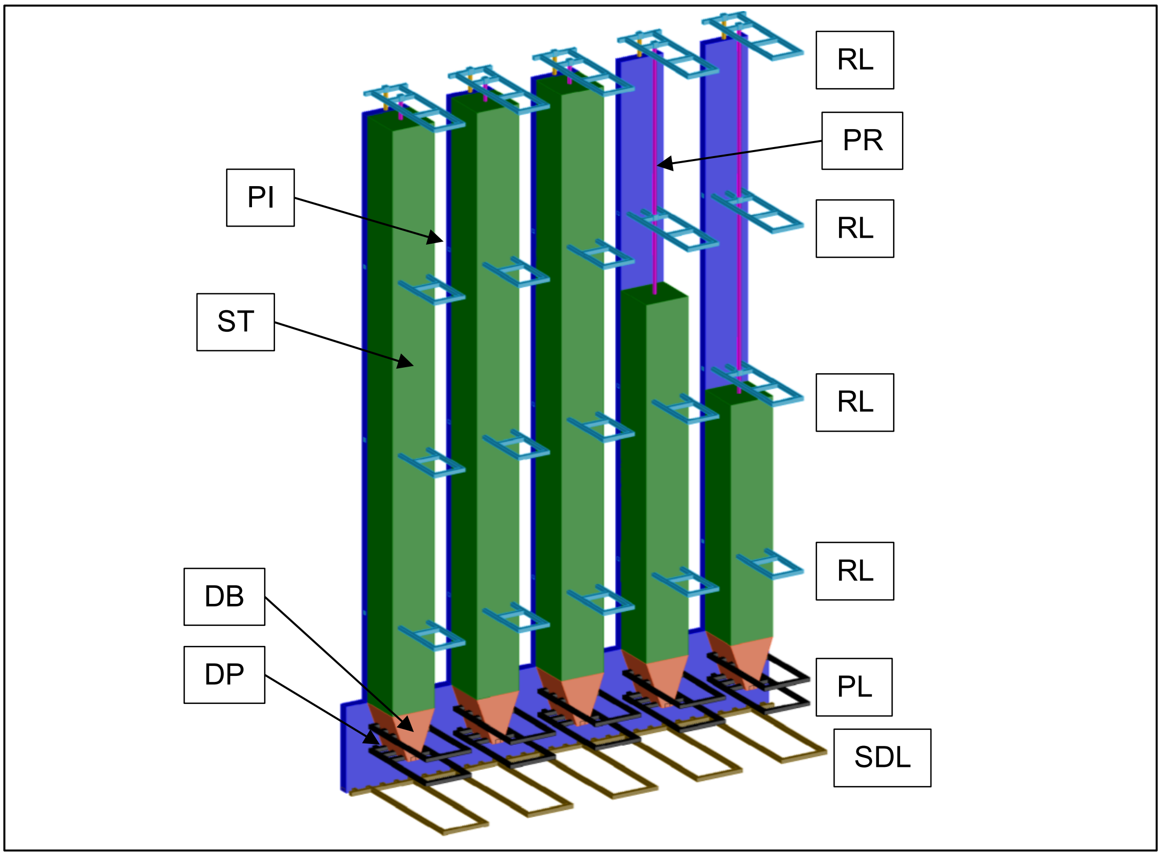


Figure 186: Isometric view of step 9

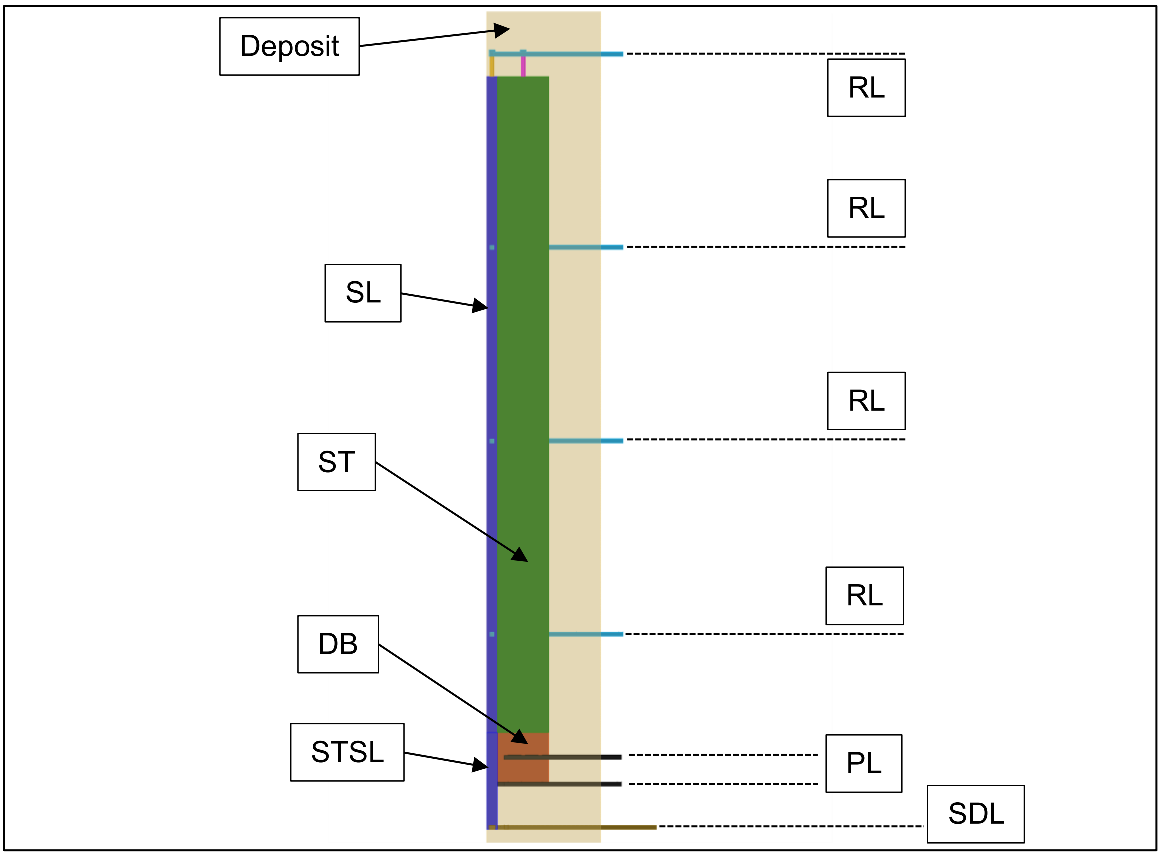


Figure 187: Side view of step 9

9.2.2.2.4 Step 10

Figure 188 and Figure 189 show an isometric and side view of step 10. Additional stopes were extracted and backfilled with rock fill behind the first stopes and stopes are under extraction in former pillars. The required infrastructure and sequence of stope extraction is the same as for the first stopes. For stopes inside pillars raise levels and production levels need to be extended, whereas for the next stopes behind already mined-out stopes only some additional drifts and drawpoints need to be created. Small, slender pillars can be left between adjacent stopes. (These small, slender pillars are not shown in the figures for simplification and overview purposes.) The small, slender pillars have such dimensions that they do not have a significant strength and hence that they cannot transfer high stress magnitudes. The purpose of these small slender pillars is to retain rock fill and to prevent inflow of rock fill from adjacent mined-out stopes. However, as these small, slender pillars have only a very low strength, they do most likely not prevent the inflow of rock fill from adjacent mined-out stopes completely. Rather, the small, slender pillars do slow down dilution with rock fill. Besides these slender pillars the draw strategy and draw control are decisive to minimize the dilution with rock fill.

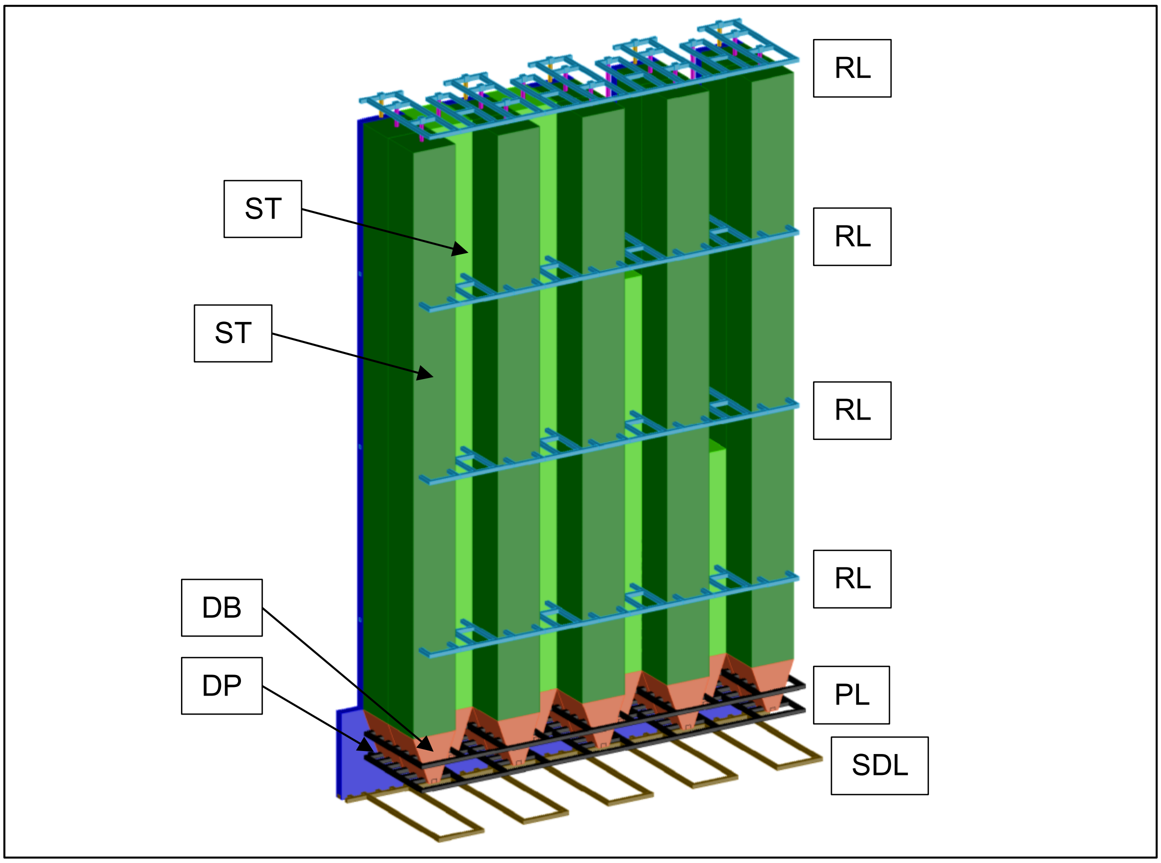


Figure 188: Isometric view of step 10

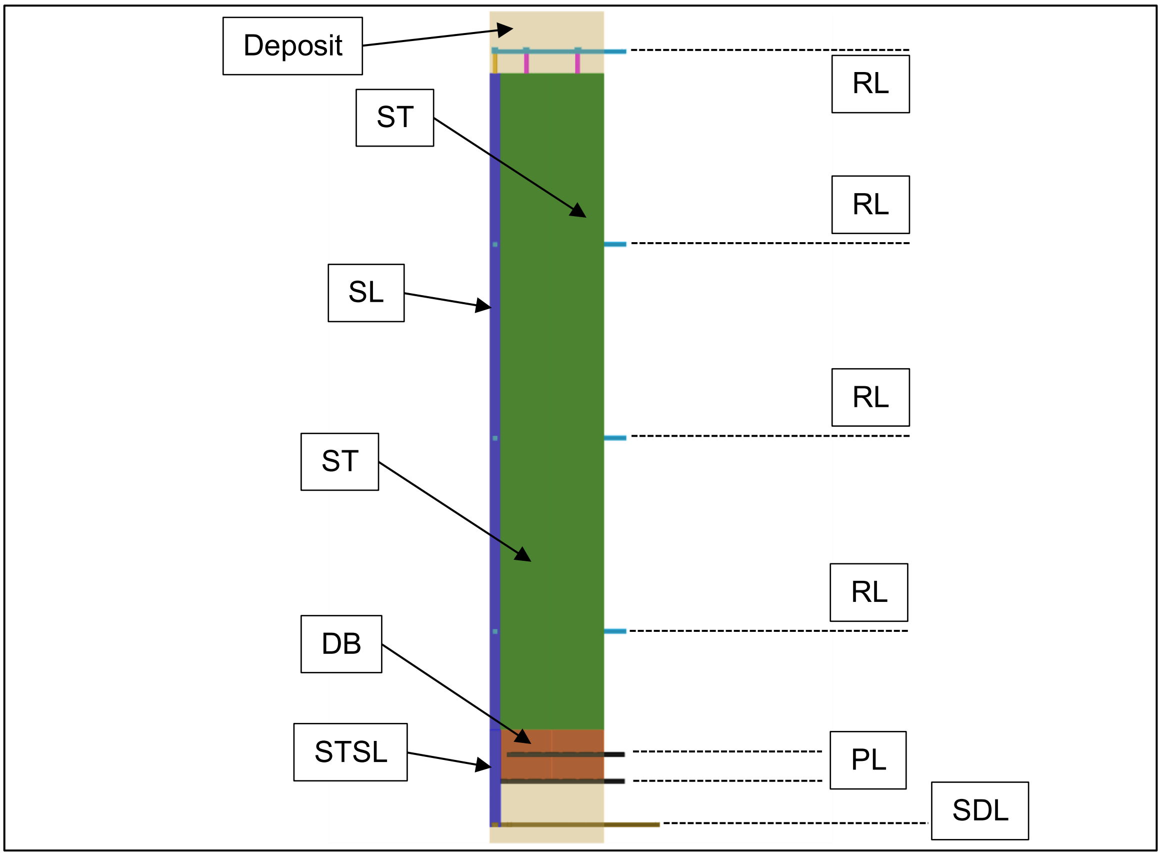


Figure 189: Side view of step 10

9.2.2.2.5 *Step 11*

Figure 190 and Figure 191 show an isometric and side view of step 11. Stopes behind slots and in former pillars were completely extracted and backfilled. Hence, the mining activities in the production phase in the considered part of the deposit finished.

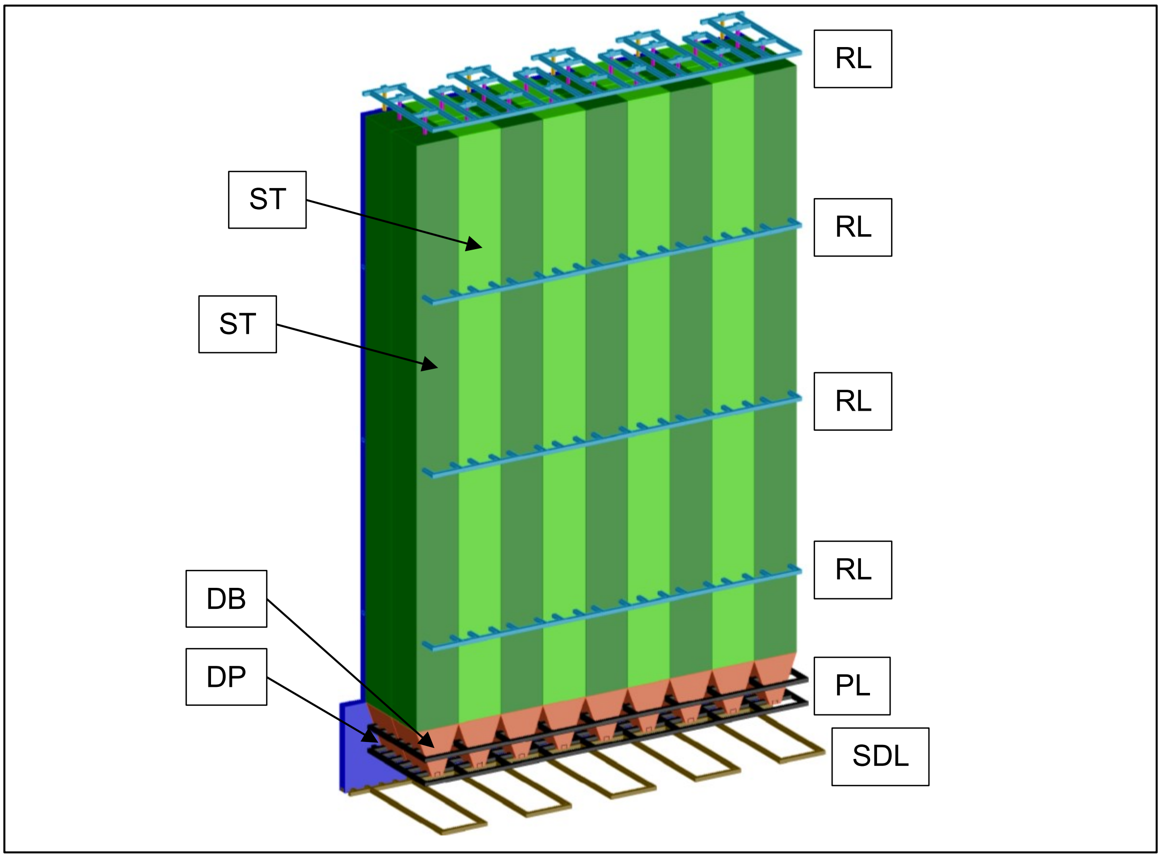


Figure 190: Isometric view of step 11

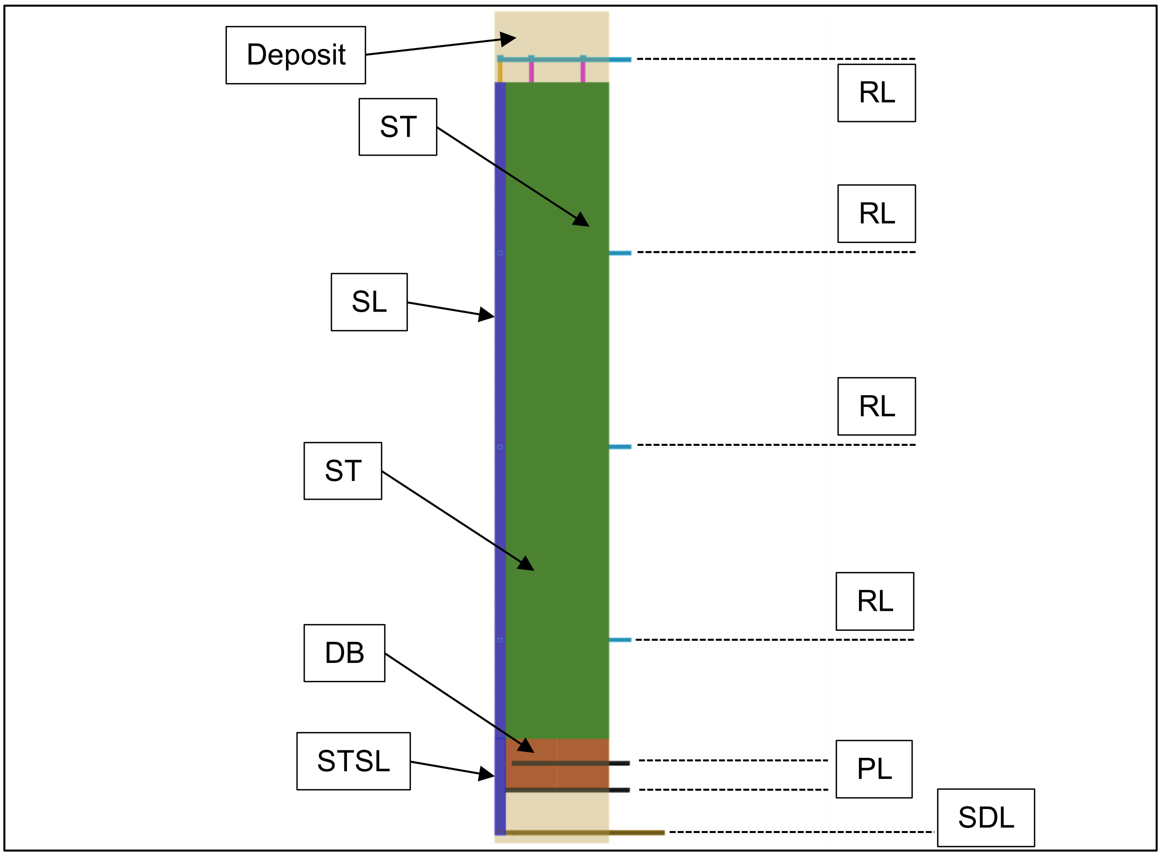


Figure 191: Side view of step 11

9.2.2.3 Parallel implementation of the de-stressing and production phase

In the explanation of the individual steps of the de-stressing and production phase the de-stressing phase was finished in the considered part of the deposit completely, before the production phase in the respective part commenced. However, as shown in Figure 192 both phases can be conducted in parallel in different parts of an extraction area (parts of the deposit). The mining activities in the de-stressing phase must be conducted first and the large-scale mineral extraction in the production phase follows the mining activities in the de-stressing phase some distance behind. The required distance between the mining activities in the de-stressing phase and the commencement of large-scale mineral extraction in the production phase is determined by the regional stress and energy changes caused by the large-scale mineral extraction. The distance between the mining activities in both phases must be sufficiently large such that the mining activities in the de-stressing phase are not affected adversely by the regional stress and energy changes resulting from the mining activities in the production phase. Thus, the de-stressing phase must lead a number of slots; compare Figure 192.

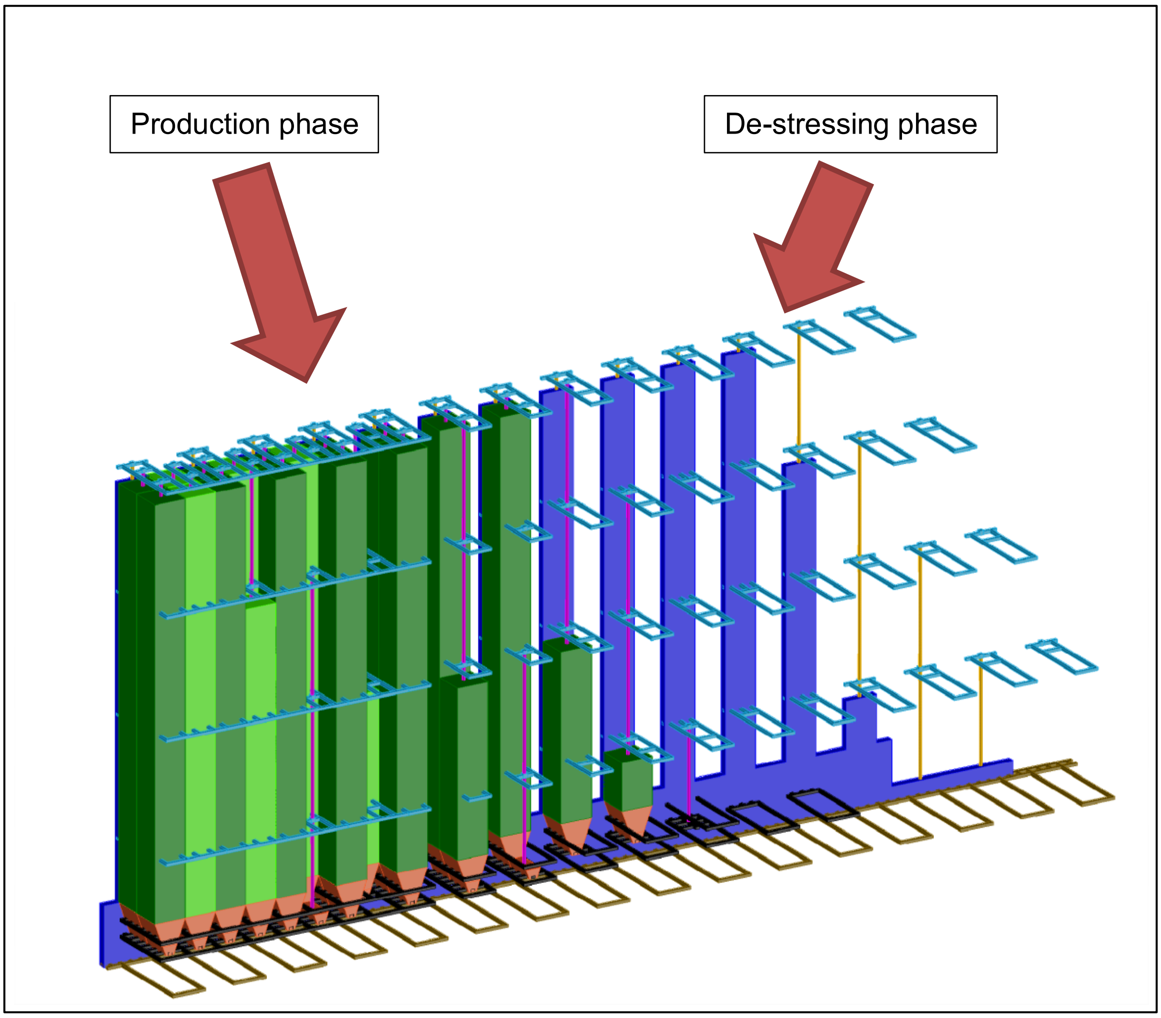


Figure 192: Parallel implementation of the de-stressing and production phase in a vertically dipping, thick, tabular deposit; mineral extraction advances from left to right.

9.2.3 Application in a steeply dipping, thick tabular deposit

The application of the de-stressing strategy based on raise mining in an idealized, steeply dipping, thick, tabular deposit is outlined in Figure 193. The de-stressing phase and production phase are conducted in parallel. The de-stressing phase leads the production phase some slots to avoid adverse impacts of the regional stress and energy changes of the production phase on the mining activities in the de-stressing phase. Principally, the steps of implementing the de-stressing strategy are the same as in case of a vertically dipping, thick, tabular deposit; compare section 9.2.2. A difference is though that intermediate draw levels and ore passes are required, because the blasted rock mass in stopes cannot be entirely drawn at the drawbells, which are at the bottom of the stopes, due to the inclination of the deposit. Moreover, the stopes should have an inclination of at least 50 ° to ensure the flow of blasted rock mass to the drawpoints. The outlined intermediate draw levels and corresponding drawpoints into stopes are located at former raise levels. Ore passes are used to transport the ore, which is drawn at intermediate draw levels, to the production level. Important for the de-stressing strategy is that ore passes and intermediate draw levels can be developed delayed in the production phase and short before their utilization. Consequently, intermediate draw levels and ore passes can either be positioned in de-stressed ground or protected from high stresses and mining-induced seismicity. If necessary, additional intermediate draw levels can be developed between raise levels. Such intermediate draw levels are not shown in Figure 193 for simplification and overview reasons.

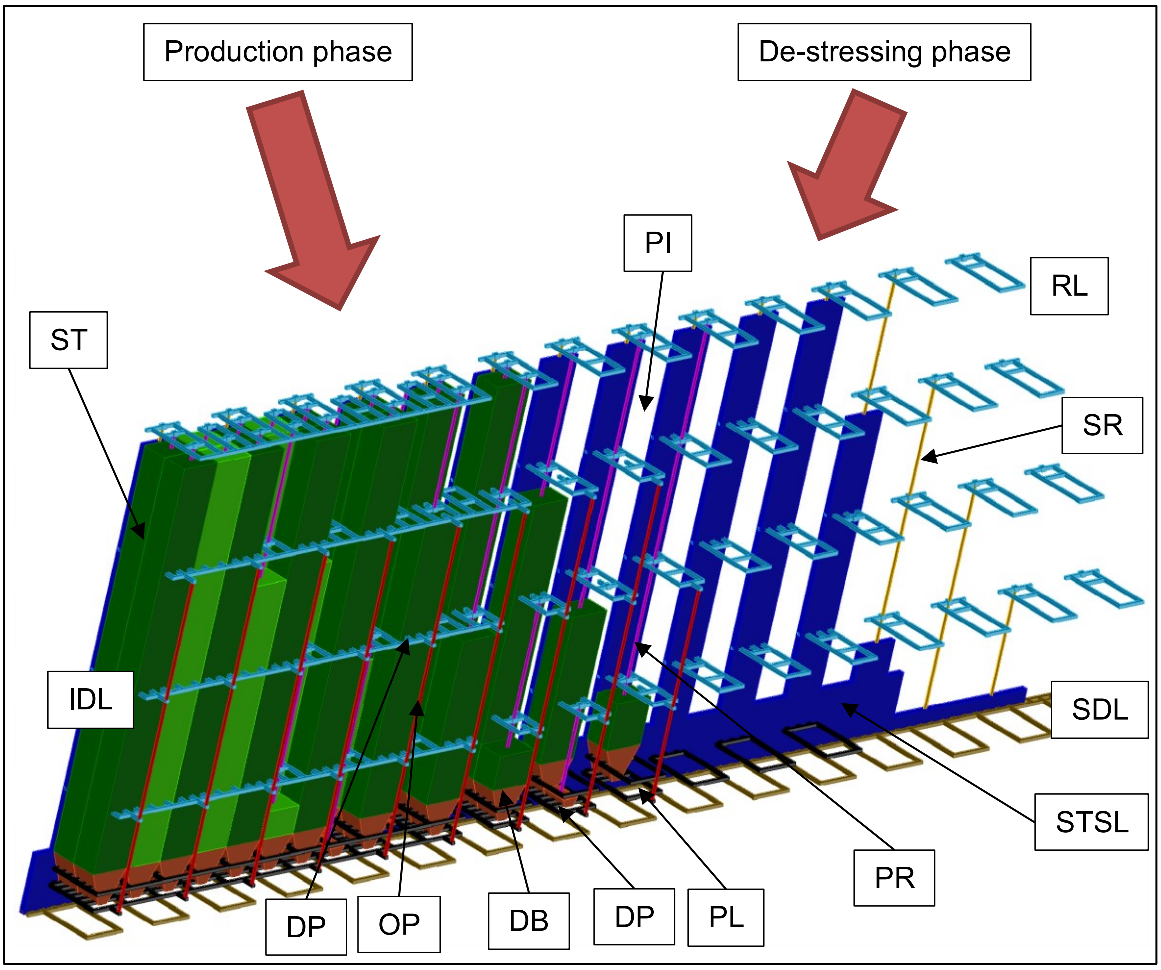


Figure 193: Application of the de-stressing strategy in an idealized, steeply inclined, thick, tabular deposit

The provided example of applying the de-stressing strategy based on raise mining in a steeply dipping tabular deposit demonstrates its adaptability, which is available on short to medium notice because of the provided flexibility of raise mining. Furthermore, this adaptability can be utilized in deposits, which are not idealized, to adapt to local conditions. For example, the position, size, shape and orientation of slots and the size and dimensions of stopes can be adapted based on the needs of rock mechanics, production logistics and ore body boundaries. Limitations regarding the adaptability are present. These limitations result from rock mechanics, such as stability of excavations or requirements for the implementation of the active stress control approach, mining technology, such as drilling and blasting or machinery, ore flow and production requirements.

9.2.4 Case study in Kiruna mine

Kiruna mine is a deep sublevel caving operation with an extraction depth of around 900 m to 1100 m and operated by LKAB. Increasing rock pressure problems, in particular rock bursts, have been experienced for several years. (Dahnér et al., 2012) In order to overcome the encountered rock pressure problems, the application of the stress management concept and the corresponding de-stressing strategy was investigated. The following sections provide an overview of the conducted investigations and advantages, which an active stress management approach offers. Details are provided in Ladinig et al. (2019).

9.2.4.1 Background

Sublevel caving has been applied for several decades and constantly developed further, large-scaled and optimized to increase the productivity, to enable a high yearly production of close to 30 million tons per year and to keep mining costs low. (Wimmer and Nordqvist, 2018) The steeply dipping, thick deposit is totally extracted over the full strike length, which is about 4 km. Regional stabilizing pillars are not left behind and the hangingwall is allowed to cave. The extraction takes place in so-called production blocks, which have a strike extension of about 400 m. Figure 194 shows the typical layout of a sublevel in a production block. A drift in striking direction is normally developed about 20 m to 40 m from the deposit in the footwall. From this striking footwall drift cross-cuts are developed in transverse direction to the hangingwall contact. The spacing of the centerlines of the cross-cuts is about 25 m. The ore is blasted and mucked ring by ring from the hangingwall towards the footwall. Ore passes, which are accessed from the striking footwall drift and which are typically situated about 40 m to 60 m from the deposit in the footwall, are used to transport the ore to the main haulage level, which is situated at a depth of 1365 m. Trains are operated at the main haulage level and they transport the ore to shafts, which are used to hoist the ore to the surface. The ore passes follow the dip of the ore body and each production block has several ore passes. Individual sublevels have a vertical spacing of 29 m.

In order to achieve the required high production, the striking footwall drifts and cross-cuts at sublevels are developed one to two years in advance below the currently producing sublevel. The ore passes and other main and primary infrastructure, such as hoisting shafts, main haulage tunnels, ramps or vent raises, were developed together with the main haulage level at 1365 m.

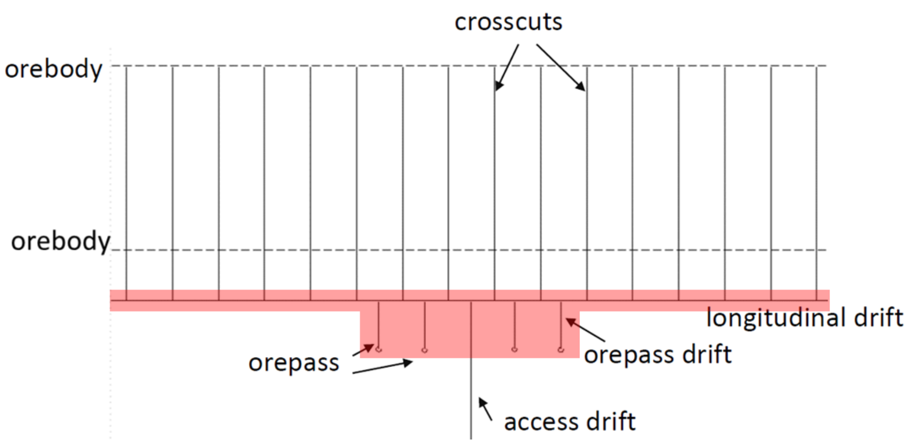


Figure 194: Schematic layout of a sublevel in Kiruna mine (Quinteiro, 2018). Infrastructure, which has been suffering from rock pressure problems, is marked red.

Rock pressure problems have been encountered for more than ten years. (e.g. Sjöberg et al. (2011), Dahnér et al. (2012), Edelbro et al. (2012), Dahnér and Dineva (2020)) The rock pressure problems concentrate on the striking footwall drifts and ore passes in the active mining area (Figure 194), namely the currently producing sublevel and the sublevels below, which are under development. High stresses result in the formation of fracture zones and seismic events cause rock burst damage to striking drifts in the footwall and ore passes. Thus, rock pressure problems have been imposing a safety risk and have been causing operational difficulties. The high abutment stresses, which are encountered below the mined-out areas, are considered to be the main reason for the rock pressure problems. Furthermore, large geological structures, namely faults and dykes, are prevailing and these structures may cause large, damaging seismic events. In the highly stressed and seismically active abutment area the majority of mining activities takes place. Addressing rock pressure problems relies strongly on a passive support strategy. Heavy dynamic support and reinforcement systems are installed in vulnerable areas routinely. (Jacobsson et al. (2013), Krekula (2017)) Additionally, opening and closing criteria have been developed and used on a routine basis (Dahnér and Dineva (2020), Nordström et al. (2020)) and a recently developed comprehensive seismic risk management plan, which is specifically designed on basis of Potvin et al. (2019a), is in an implementation phase. (Wimmer, 2021)

9.2.4.2 Depth extension in future

In future it is planned to deepen the Kiruna mine further to a depth of about 1800 m to 2000 m. The geometry of the ore body changes with depths, in particular the strike extension becomes considerably smaller. (LKAB, 2018) Due to the rising primary stress magnitudes the control of the stress situation and of the mining-induced seismicity will be crucial for a successful depth extension. The severity of the currently experienced rock pressure problems for deepening the sublevel caving operation is investigated by means of numerical simulations and well-established design criteria in the following.

9.2.4.2.1 <u>Abutment stress situation</u>

The abutment stress situation at the current mining depth is calculated with FLAC3D (Itasca, 2013). The geometry of the extracted deposit is replicated and a caving angle of 65 ° is assumed. In a first approximation the broken, caved rock is not modelled. Instead, the deposit as well as caved hangingwall is removed completely. This simplification is a conservative approach, because it does not allow transferring stresses through the cave. The rock mass is modelled linear elastic and primary stresses are taken after Sandström (2003). Rock and rock mass properties are taken from existing studies (Berglund and Andersson (2013), Björnell et al. (2015), Vatcher et al. (2016), Winell et al. (2018)). Simulations yield abutment stresses in the range of 70 MPa to 85 MPa at a depth of about 1000 m. For comparison, the primary maximum principal stress at this depth is about 35 MPa. Due to the circumstance that primary stresses increase approximatively linear with depth abutment stresses of 140 MPa to 170 MPa have to be expected at 2000 m depth for a sublevel caving operation. Although intact rock strength in footwall and ore is relatively high, namely in the range of 150 MPa to 300 MPa, abutment stresses are reaching and exceeding the strength of intact rock. The magnitude of resultant stresses around infrastructure, such as drifts or ore passes, is significantly higher than abutment stress magnitudes. An inherent disadvantage of sublevel caving is that active infrastructure is situated in this highly stressed abutment area.

9.2.4.2.2 Infrastructure stability

Rock bursts are the main cause for infrastructure damage and subsequent rehabilitation. However, deformation and fracturing around drifts and especially ore passes are detectable at current mining depths due to high (static) stress magnitudes as well. For this reason, a rockwall condition factor (RCF) analysis (Wiseman, 1979) of striking footwall drifts and ore passes is conducted. The derived RCF values for typical rock mass conditions are approximatively 1 for ore passes and 1.1 for striking footwall drifts. Figure 195 outlines determined RCF values. The observed drift and ore pass conditions correspond with calculated RCF values and installed support types. A heavy support system comprising grouted rebars, dynamic rock bolts, shotcrete and mesh is used in striking footwall drifts. In contrast to drifts ore passes are usually unsupported. Fracturing or deformation in the surrounding striking footwall drifts is not visible or of limited extent. However, ore pass cross-sections can widen considerably due to rock fracturing and rock flow.

At a depth of 2000 m primary stresses are doubled. As the same rock mass formations are expected at greater depths and as rock mass strength is not increasing with depth, RCF values double as well. In case the same infrastructure and mine layout are used at greater depths, the unsupported ore passes are barely stable and rather poor drift conditions have to expected, even if a heavy fully integrated support is installed; compare Figure 195.

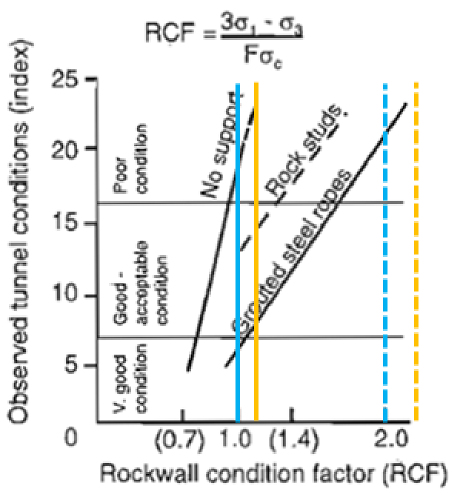


Figure 195: Excavation conditions in ore passes (blue) and in striking footwall drifts (orange); solid lines mark conditions at 1000 m and dashed lines mark expected conditions at 2000 m in the currently used sublevel caving layout; diagram after Jager and Ryder (1999)

9.2.4.2.3 Seismicity

Mining-induced seismicity is evaluated by comparing the energy changes resulting from mining activities (blue line) with the released seismic energy (red line); compare Figure 196. The energy changes from mining activities are approximated by the tons mined multiplied by the depth of mining. This approximation is a simple measure and a back analysis with data from 2014 on showed a good correlation; compare Figure 196. Furthermore, the analysis shows that a lack of seismic energy release, which can be seen by the deviation from the released seismic energy from the energy changes from mining activities, is compensated by larger seismic events with magnitudes up to and larger than 2.5. The outlined May 2020 event had a magnitude above 4. A similar correlation between energy changes from mining activities and the released seismic energy were found in deep South African gold mines; compare Dempster et al. (1983) and Gay et al. (1984).

If the mining depth is increased to 2000 m and if the production remains constant, it can be assumed that the energy changes from mining activities will approximatively double (green line); compare Figure 196. Consequently, the released seismic energy will increase considerably as well. The determination of the actual increase of the released seismic energy requires further analysis and must consider potential changes in the rock mass and the mine layout and mining sequence. However, for a first estimation and under the assumption of comparable rock mass and mining conditions the released seismic energy will at least approximatively double.

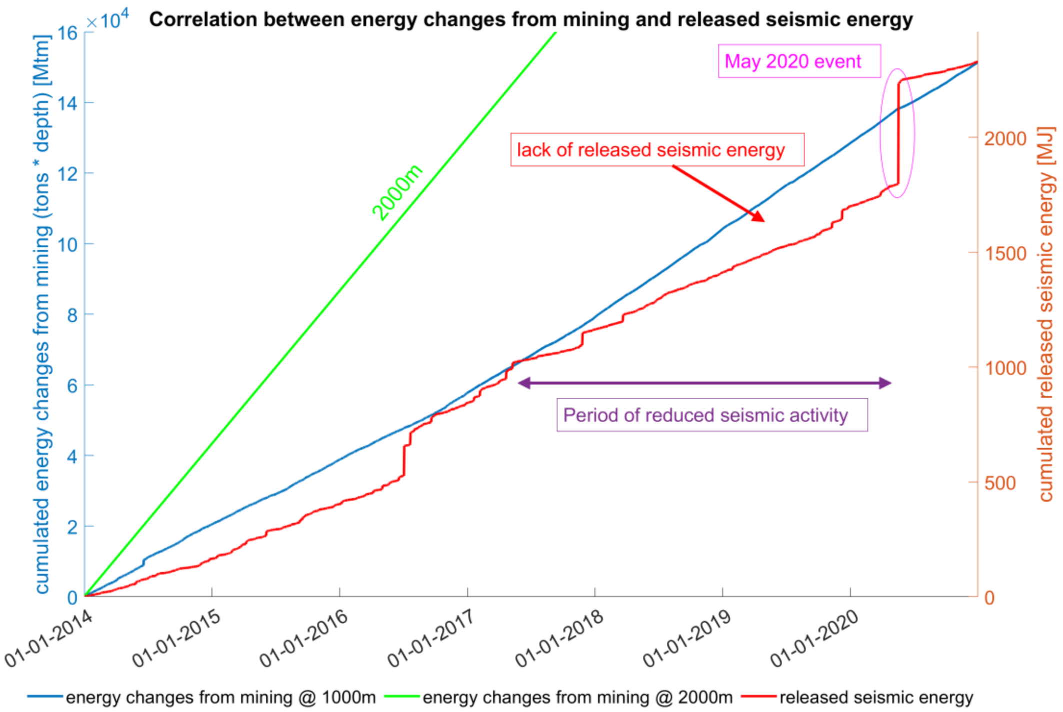


Figure 196: Correlation between energy changes from mining activities and the released seismic energy

9.2.4.2.4 <u>Concluding remarks to the depth extension</u>

Summing it up, mining experience at a depth of around 1000 m has highlighted the impact of rock mechanics on the current sublevel caving operation. Abutment stresses cause infrastructure damage and trigger rock bursts. The circumstance that active infrastructure in sublevel caving must be situated in abutment areas aggravates rock mechanics issues further. The outlook to greater depth indicates that the severity of rock mechanics issues will increase significantly in the currently applied mining layout and mining sequence. This assessment applies to the next sublevel as well as to a possible extension of sublevel caving to greater depths. The considerably smaller strike extension at greater depths does not change this assessment noticeably, because the strike extension of the deposit is still large compared to its thickness and hence the general characteristics of the resultant stress situation are not changed significantly. Concluding, the assessment shows that an appropriate control of stresses and mining-induced seismicity will be decisive for a successful extraction at great depths.

9.2.4.3 Addressing rock pressure problems with raise caving

Due to the rising importance of the control of the rock pressure situation LKAB has started intensive investigations and developments related to mining methods, mine layouts and mining sequences for mining at greater depths. Therefore, an upscaling of sublevel caving in combination with an adaption of the sublevel caving design (Quinteiro (2018), Quinteiro (2020)), inclined caving and block caving (Hoffmann, 2019) are considered. Furthermore, the application of raise caving in combination with the de-stressing strategy is investigated (Ladinig et al. (2019), Ladinig et al. (2021)).

In raise caving the de-stressing strategy is implemented by means of a slot pillar system, which is established at the hangingwall contact with raise mining technology. Other means for the development of slots are in consideration too and under investigation. The individual steps of the de-stressing phase based on raise mining were outlined in section 9.2.2.1. Afterwards, the large-scale mineral extraction commences in the production phase in the provided stress shadows. The production is based on raise mining and the individual steps of the production phase were outlined in section 9.2.2.2. Instead of backfilling mined-out stopes the hangingwall is allowed to cave and thereby to fill up mined-out stopes. Thus, the mining method is referred to as raise caving. The general layout and sequence, which are considered for raise caving in Kiruna mine, are very similar to the layout and sequence shown in Figure 193.

9.2.4.3.1 <u>Investigation of the application potential of raise caving</u>

The application potential of raise caving for a depth extension in Kiruna mine is investigated. Accordingly, the analyses are preliminary and simplifications are made. The emphasis is on rock mechanics key issues and on addressing the experienced rock pressure problems, namely infrastructure, slot and stope stability, pillar behavior and seismicity. Therefore, three-dimensional numerical simulations in FLAC3D are conducted and well-established design criteria mainly from deep South African gold mines are applied. The utilized design criteria have further been calibrated on mining experience in the current sublevel caving operation. The numerical model represents an idealized layout of raise caving and comprises six slots, five pillars, stopes behind slots and stopes in pillars; compare Figure 197. The dimensions of slots, stopes and pillars are in the range of the dimensions outlined in section 9.2.1. Slots, stopes and pillars can be removed individually to model different mining sequences. Moreover, the dimensions are varied and different mining sequences are considered. Drifts are not modelled explicitly and represented as lines. Due to the circumstance that their influence is small compared to regional effects of slots, pillars and stopes this approach is deemed acceptable. Large geological structures, such as faults or dykes, are not modelled explicitly to reduce the complexity and parameter uncertainty in the simulations.

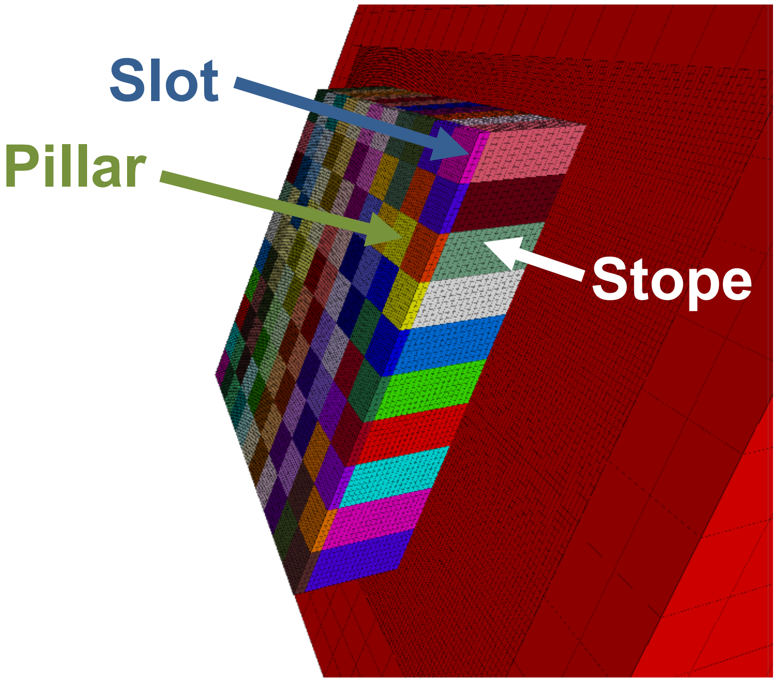


Figure 197: Numerical model for the investigation of rock mechanics issues of raise caving in Kiruna mine; the hangingwall rock mass and the remaining deposit rock mass are not shown in the figure. (Ladinig et al., 2019)

Rock mass is modelled linear elastic and rock mass properties are taken from Berglund and Andersson (2013), Björnell et al. (2015), Vatcher et al. (2016) and Winell et al. (2018). The primary stress state is taken from Sandström (2003). In the model the stress gradient with depth is neglected and primary stresses at a depth of 2000 m are considered, which is a conservative approach, because stress magnitudes are largely overestimated. The primary stress magnitudes at a depth of 2000 m are 72 MPa (major principal stress), 56.5 MPa (intermediate principal stress) and 54 MPa (minor principal stress). The major principal stress is horizontal and approximatively perpendicular to the deposit strike, the intermediate principal stress is vertical and the minor principal stress is horizontal and approximatively parallel to the deposit strike.

Overall, the model represents the raise caving layout and sequence in a simplified manner. Pillars are infinitely strong and local pillar crushing is not modelled explicitly. Instead crushing of pillars is conservatively modelled by removing the pillar completely in areas, where the pillar is expected to crush. The influence of blasted or caved rock mass in slots and stopes is neglected. Details of the mining sequence, such as complex interactions of local pillar crushing or the advance of slots and stopes in small steps, and hangingwall caving are not considered. Moreover, influences of sublevel caving activities at current mining depths on raise caving are not considered. The reason for the simplifications is to reduce the complexity of investigations and to determine the principal application potential of raise caving. Despite these simplifications the model is suited to study the applicability of raise caving, because the important characteristics of the resultant stress situation in areas, where mining activities take place and where active infrastructure is situated, are maintained and represented appropriately.

In the following sections an overview of the results of the conducted investigations regarding the applicability of raise caving in Kiruna mine is provided. Details of the calculations and results can be found in Ladinig et al. (2019).

9.2.4.3.2 Infrastructure stability

Infrastructure stability is determined by means of RCF calculations. Infrastructure in the de-stressing phase, which is required for the slot development, is exposed to similar static stress conditions as current infrastructure situated in the abutment of sublevel caving at a depth of around 1000 m. Experience in the current sublevel caving operation and RCF analysis show that these stress magnitudes are well manageable with support, but an early support installation can be necessary. This issue could be critical for raises, which are developed by raise boring, because the support can only be installed, after raise boring finished. Hence, it can limit the possible length of raises. A possibility to overcome this issue may be the development of new machinery, which enables the installation of some preliminary support directly behind the reamer head. As slot development progresses, stresses near slot roofs increase significantly. However, analysis show that these areas are local and can be managed. Moreover, the slot roof shape, for example an inclined roof, can influence the stress situation positively, which influence has not been investigated so far. In contrast to sublevel caving seismicity and associated dynamic loading conditions for de-stressing infrastructure are different and expected to be considerably lower to negligible compared to the experienced seismicity in sublevel caving.

The investigations show that infrastructure, which is utilized in the production phase for the extraction of stopes, can be situated in de-stressed zones. As mining progresses, stress shadows increase in size, because pillars crush, because pillars are mined-out and because stopes block stresses in the second horizontal direction as well. RCF values range from 0.6 to 1 for infrastructure in the production phase at a depth of 2000 m. These RCF values are remarkably lower than in sublevel caving. Investigations show also that the timing of infrastructure development is critical. If infrastructure is built in advance in areas, which have not been de-stressed, it would suffer significant damage. Figure 198 illustrates this issue for ore passes. RCF values for ore passes situated behind stopes are lower than 0.6 depending on the distance of ore passes into the footwall. In contrast, RCF values would exceed 1.1, if ore passes are developed ahead of stopes. The sudden increase of RCF values in the area of the stope roof, where the de-stressing effect of stopes diminishes, is visible as well. Moreover, the area above stopes may be seismically active.

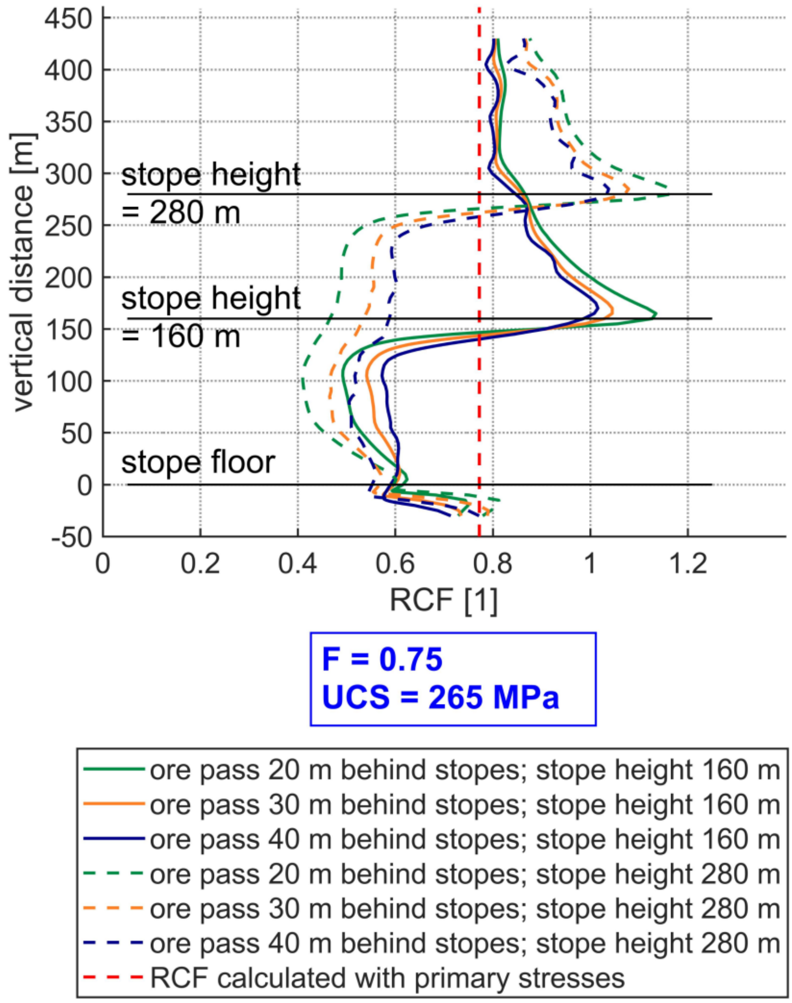


Figure 198: RCF values for ore passes located behind stopes in footwall for stress conditions at a depth of 2000 m; full lines represent a stope height of 160 m and dashed lines a stope height of 280 m; RCF calculated with primary stresses is shown as red dashed line. (Ladinig et al., 2019)

9.2.4.3.3 Slot and stope stability

The Matthew's stability graph method is applied for slot and stope stability analyses (Potvin (1988), Mawdesley et al. (2001)). Results indicate that slots and stopes of required dimensions can be excavated with acceptable probability of failure. However, at this point it has to be noted that the applicability of the Matthew's stability graph method is limited in the prevailing situation. Reasons are uncertain meanings of definitions such as failure or major failure and neglecting of the positive effect of broken rock inside slots and stopes.

9.2.4.3.4 Pillar strength and behavior

The pillar behavior is investigated by means of calculating the average pillar stress numerically and comparing the derived average pillar stress with pillar strength, which is calculated after available pillar strength equations. For the conducted preliminary investigations, the pillar strength is calculated based on the pillar strength equations of Salamon and Munro (1967) and Hedley and Grant (1972) and the influence of the present long and squat pillars is considered by the approaches after Wagner (1980) and Wagner and Madden (1984). The site-specific rock mass conditions are considered for the application of the pillar strength equations.

Calculations outline that in the de-stressing phase pillars with a width-to-height ratio larger than five can withstand the exposed loads. Consequently, pillars can control the stress situation and mining-induced seismicity in the de-stressing phase effectively. However, local pillar crushing, for example due to weakness zones in the rock mass, cannot be excluded. Accordingly, an appropriate mine design, which is able to handle local pillar crushing, is required. An advantage is that pillars are formed behind slot roofs, as slots are advanced upwards. The calculations show further that in the production phase pillars are overloaded and thus that pillars crush. Pillar crushing takes place behind advancing stope roofs distant from active mining infrastructure, which circumstance is an advantage. Details regarding crushing of pillars and the stability of pillar crushing have not been studied, but they are investigated further.

Moreover, the investigations pointed out that pillar strength and pillar behavior are a central aspect for the successful implementation of the de-stressing strategy and hence for the successful application of raise caving in Kiruna mine. A comprehensive knowledge of pillar strength and behavior is important for an appropriate design of pillars. The investigations related to strength and behavior of hard rock pillars (section 6.1.2.2) showed that the current knowledge is relatively limited in particular for the considered pillar dimensions in raise caving. For this reason, further studies regarding the strength and behavior of hard rock pillars are necessary and subject of ongoing investigations.

9.2.4.3.5 Seismicity

In order to evaluate mining-induced seismicity in raise caving in Kiruna mine at greater depths, analysis with the concepts of energy release rate (ERR) and excess shear stress (ESS) are conducted. The de-stressing phase and production phase are considered separately. In the de-stressing phase pillars are left between slots to control the stress situation and seismicity. Stoping extracts these pillars resulting in considerable regional stress and energy changes. Accordingly, the production phase is of greater importance from a seismicity point of view. ERR and ESS determination is based on existing approaches outlined by Jager and Ryder (1999).

- ERR is a measure for the expected overall seismicity. Currently considered mine layouts result in ERR levels lower than 5 MJ/m³ in the de-stressing phase. According to COMRO (1977), who related ERR levels to rock burst occurrence in narrow reef gold mining in South Africa, these ERR levels would be negligible. However, as this relation comes from narrow reef gold mining, it must be treated with caution in the present situation comprising relatively massive slots and the rock burst risk should be re-evaluated. During the production phase ERR has not been calculated yet, because it is not straightforward and it was out of scope of the conducted study.
- ESS describes the slip potential of discrete large geological structures and it is calculated for ore body parallel faults, which are present on a regular basis, behind slots and stopes for the de-stressing and production phases. Generally, fault slip in the de-stressing phase is not as critical as during the production phase. Areas of

positive ESS, which indicate a possibility of fault slip, are localized around slot roofs and they are small in extent and magnitude. In the production phase ESS analysis yields that ore body parallel faults could be activated around stope abutments and stope roofs. However, in areas of potential fault slip there is not any active infrastructure except of slot and production raises, in which remote-controlled or automated machinery is operated. So far only a horizontal roof and simplified stoping sequences have been considered. As the shape of the slot and stope roof have a noticeable influence on the resultant stress situation near slot and stope roofs, their shape can be changed to further protect raises from seismicity and to improve the characteristics of the energy release situation. Additionally, the mining sequence can be modified to improve the energy release situation.

A major difference between the mining methods of sublevel caving and raise caving is the characteristic of the seismic energy release. In sublevel caving faults, which are ore body parallel, are weakened over large areas simultaneously. The regional mining front in sublevel caving is about 4 km long, no pillars are left behind and mining takes place at approximatively the same depth. Inside a single 400 m wide production block a sublevel (height of about 30 m) is mined more or less with a straight front running parallel to the strike of the deposit from the hangingwall towards the footwall. Hence, faults, which run parallel to the ore body, are approached parallel on a regional scale as well as parallel inside a production block on a more local scale. This situation is not ideal from a seismicity point of view, because faults can be activated over large areas in a single event. In raise caving the situation is different. On a regional scale mining direction is on strike and on a local scale up-dip. The result is that ore body parallel faults are weakened in small steps, namely the burden and the striking extension of a production blast ring. Thus, energy release from fault activation is expected to be considerably lower than in the current sublevel caving situation. Additionally, active infrastructure is not required near faults, which may be activated by stoping.

9.2.4.3.6 Suitability of raise caving from a rock mechanics perspective

The results of the analysis outline the suitability of the raise caving method for addressing the problems of high stresses and seismicity experienced with the present sublevel caving method. The majority of infrastructure can be positioned in de-stressed ground and de-stressing activities themselves require only a minimum amount of infrastructure. Seismic energy is released distant from active infrastructure and in small steps. Stress shadows and seismicity are controlled by the mine layout and mining sequence. As raise caving is a quite flexible system and as it does not require a lot of ahead developed infrastructure, it enables adaptions to rock mass conditions, to ore body geometry and to mining experience on a short to medium term basis.

Based on the investigation results (Ladinig et al., 2019) raise caving is applicable from a rock mechanics point of view in Kiruna mine. However, it has to be noted that the conducted investigations are preliminary and that they focused on the overall application potential of raise caving. Hence, further investigations are necessary to implement raise caving in Kiruna mine successfully. These investigations comprise studies of key issues in greater detail as well as incorporation of other points such as hangingwall caving and the associated surface subsidence and the transition from sublevel caving to raise caving.

9.2.4.4 Comparison of raise caving with sublevel caving

The comparison of the initial analysis of currently experienced rock mechanics issues in sublevel caving with the conducted investigations on raise caving highlights the potential of raise caving from a rock mechanics perspective. Raise caving provides a considerable improvement over sublevel caving at current mining depth and even at greater depths up to 2000 m and beyond. Besides rock mechanics aspects raise caving offers operational benefits compared to sublevel caving as well. Analysis of the required development effort yield that infrastructure can be reduced by 50 % or even more compared to the current sublevel caving layout. Moreover, most of the infrastructure in raise caving is situated in de-stressed ground. Hence, the support effort can be reduced. Additionally, infrastructure does not need to be developed years ahead freeing up a significant amount of capital. On top, the circular geometry of the raises is ideal for the utilization of remote-controlled or automated machinery inside raises. The required machinery has to be designed, developed and built. In contrast to sublevel caving the production drawpoints are in use long-term allowing for the installation of permanent loading infrastructure. The ore flow characteristic is also different. It transits from a ring by ring behavior in sublevel caving, which is associated with dilution problems, to a massive, interactive flow in raise caving. A better draw control is possible in raise caving, which enables delaying of hangingwall caving and its associated dilution. In the case of Kiruna mine caving characteristics and surface subsidence are critical because of the city being located on the hangingwall side near the mine. So far, no detailed surface subsidence analyses in raise caving have been conducted, but first considerations indicate that surface damage is most likely to be different to that of sublevel caving. Deformations may be delayed and whether the surface impact is of similar extent is yet unknown. A trend break in surface subsidence can eventually lead to delayed or less city transformation efforts.

Finally, the above-mentioned advantages result in cost, productivity and safety improvements. Personnel can operate the main production equipment remotely and the majority of infrastructure is situated in de-stressed ground distant from highly stressed areas and seismically active areas. Due to the automation potential, the increased productivity and the decreased development and support effort the mining costs are likely to be decreased significantly too.

9.2.4.5 Outlook on the application of raise caving in Kiruna mine

Mining progresses to greater depths in Kiruna mine and the control of rock pressure and mining-induced seismicity has become central for a safe and successful operation. The implementation of the proposed stress management concept in Kiruna mine was investigated. The analyses show that the raise caving mining method is implementable in Kiruna mine and that the active stress control approach of raise caving offers significant advantages from a rock mechanics perspective. The currently encountered rock pressure problems in sublevel caving are addressed effectively and the rock pressure situation can be improved considerably. However, the conducted analyses were preliminary and they did not focus on details, because their objective was to evaluate the application potential of raise caving in Kiruna mine. Hence, further studies are required to deepen the understanding of associated rock mechanics issues as well as operational aspects and machinery requirements.

Due to the positive results of the first investigations on raise caving in Kiruna mine (Ladinig et al., 2019), LKAB decided to investigate and develop the raise caving method and associated technology further towards its implementation. (LKAB, 2021) A comprehensive development project, which concentrates on rock mechanics, production and machinery key issues of raise caving, was launched. Part of this development project is a test site in high stress conditions, in which relevant rock mechanics aspects are tested and investigated. Furthermore, the test site aims on demonstrating the advantages of the active stress control approach in raise caving.

9.3 Concluding remarks regarding the application study

The application of the proposed stress management concept in steeply dipping deposits was outlined in this chapter. The shown implementation of the de-stressing strategy is based on raise mining, which offers significant opportunities. Namely raise mining allows to conduct the high stress mining activities in the de-stressing phase with a minimum amount of infrastructure. Furthermore, the infrastructure can be developed late and just before its utilization. Therefrom results a considerable degree of flexibility, which is considered important in high stress mining. Another advantage of raise mining is the possibility to remote-control or automate the work in the raises and hence to remove personnel from highly stressed zones. In the production phase raise mining is also advantageous because of the minimum amount of required infrastructure. Consequently, large-scale mineral extraction can be ramped-up relatively quickly, after the de-stressing phase was finished. High production rates are possible and high productivity can be achieved with the raise mining method. Furthermore, flexibility in the layout and sequence on short to medium notice is provided and the work in the raise and thus near areas of stress and energy changes can be remote-controlled or automated. In contrast to raise mining other widely applied stoping or caving methods either do not enable the efficient implementation of the de-stressing strategy or they do not enable a high production and high productivity, if they are combined with the de-stressing strategy. Reasons for this are a significant amount of infrastructure pre-development, such as required in open stoping and sublevel stoping methods, which exposes large amounts of infrastructure to high stresses and which reduces flexibility considerably, or small scale extraction methods, such as cut-and-fill methods, which do not enable a high productivity.

In summary, raise mining is considered an ideal mining method to extract steeply dipping or massive deposits in a deep mining environment in particular, if horizontal or near horizontal stresses must be blocked. Hence, raise mining in combination with the proposed de-stressing strategy can facilitate or even enable the extraction of deposits at great depths. The case study, which was conducted in Kiruna mine, highlights the application potential of the de-stressing strategy based on raise mining.

10 Discussion and conclusion

The objective of mining is the supply of the society with minerals and in order to fulfill the supply the safe, as complete as possible and economic extraction of mineral deposits. As mining progresses to greater depths, the safe, as complete as possible and economic extraction become more difficult amongst others because of the increasing primary rock stresses. High rock stresses can cause fracturing and failure of rock mass or trigger the release of seismic energy, which can cause rock burst damage. Specific measures and approaches are required to handle the high stress situation. The need for these measures and approaches to control rock pressure distinguishes mining at great depth from mining at shallow depth, where the control of rock pressure is not central and hence where specific measures and approaches are not required. If the increasing rock pressure is managed improperly, rock pressure problems, which endanger the objectives of mineral extraction, can be the consequence. Possible strategies addressing rock pressure problems can be divided into passive and active. The passive approach addresses the consequences of rock pressure problems mainly through support and reinforcement, whereas the active approach addresses the sources of rock pressure problems, in general high stress zones and the release of seismic energy, through specifically designed mine layouts and mining sequences. The active stress control approach is principally superior over the passive stress control approach, because potential sources of rock pressure problems are eliminated. Despite the significant advantages of the active approach a number of reasons was identified, why the active approach is not utilized routinely in deep mining. These reasons comprise considerations regarding production requirements and production scheduling, rock engineering aspects related to mine design, but also missing acknowledgement of the importance of rock pressure control in deep mining. Therefore, there is a shortage of active stress control approaches for many situations and environments. An exception are deep South African gold mines, where an active stress control approach has been applied successfully for several decades. The mining experience in deep South African gold mines demonstrates clearly the advantages of an active stress control approach.

In order to address the identified shortage of active stress control approaches, a stress management concept was proposed in the present work. The objective of the stress management concept is to control the stress situation and seismic energy release in a systematic and strategic manner. Potential sources of rock pressure problems are tackled actively to improve the extraction of mineral deposits in terms of the safety, completeness and economic of extraction. The stress management concept is comprised of elements. The most important elements are excavations, pillars, loading system and time. These elements provide in isolation or in combination certain functions, which are based on the physical effects of elements on the mining environment. The functions comprise besides rock mechanics aspects, such as providing of stress shadows or the transfer of high stresses, also production aspects, such as providing access or extracting of minerals. Considering both rock mechanics and production aspects in the stress management concept highlights that stress management is an integral part of mineral extraction. For the implementation of the stress management concept the individual elements and their functions are combined to specific mine layouts and mining sequences to achieve an appropriate control of the stress situation and released seismic energy. The actual layout and sequence must consider the peculiarities of the prevailing mining environment and the production requirements and thus they must be specifically designed. The implementation of the stress management concept was discussed further for the so-called de-stressing strategy. The de-stressing strategy comprises a de-stressing phase and a production phase. In the de-stressing phase an active stress control approach is implemented. Therefore, de-stressing excavations, which provide stress shadows for the infrastructure and mining activities in the production phase, are created in the de-stressing phase. Regional stress transfer pillars are left between de-stressing excavations to control the stress situation and energy release during the high stress mining activities in the de-stressing phase. Two different generic layouts and sequences, which distinguish themselves in the time and position of infrastructure development in the de-stressing phase, are outlined for the de-stressing strategy. The production phase follows the de-stressing phase and large-scale mineral extraction takes place in this phase. Besides enabling an efficient and productive mineral extraction the layout and sequence in the production phase must ensure that the established active stress control approach is maintained. Overall, the implementation of the active stress control approach in the de-stressing and production phase is an investment into improved mining conditions, which facilitates the objectives of mining. The application of the de-stressing strategy is further demonstrated for steeply dipping or massive deposits. The raise mining method is utilized therefore because of its offered advantages from a rock mechanics and production perspective. A possible layout and sequence are outlined and the individual steps of the implementation of the de-stressing strategy are discussed. A case study on the application of the de-stressing strategy in Kiruna mine points out the potential advantages and improvements compared to the currently applied sublevel caving method.

In summary, the considerations, investigations and analyses in the present work highlight the considerable advantages and chances of an active stress control approach and of the proposed stress management concept. However, there are some open points, which complicate or prevent the implementation of the stress management concept and which therefore need to be addressed in future research and development work as well as for the application of the concept in practice. These points comprise:

- The design of layouts and sequences, which make use of the proposed stress management concept, is demanding from a rock engineering as well as from a production perspective. A high level of skills and expertise are required. The training and education of personnel is central. However, there has been a constant decline of training and education centers and capabilities as well as of the number of properly educated and trained engineers. Consequently, the required high level of skills and expertise may not be available. A long-term strategy emphasizing on this central point is recommended. This strategy should include the establishment of education and training centers as well as the ongoing training of personnel on all levels in the operation.
- The knowledge regarding the mechanical properties and behavior of rock mass, geological structures and structural elements, such as pillars, is limited. Furthermore, the determination of the prevailing mining environment, such as the

primary stress state, the rock mass properties etc., is associated with technical and practical difficulties. Thus, the prevailing mining environment is not exactly known and often rather uncertain. These aspects can in general be addressed best with a long-term research and development approach, which is strongly based on in-situ observations and targeted in-situ test campaigns, because the complex behavior of rock mass, pillars etc. can be barely replicated under laboratory or numerical conditions without having appropriate in-situ data and experience for calibration available. It is therefore important that this research and development is conducted in close contact between the industry and research organizations. There is a lack of highly skilled personnel and expertise in research organizations present as well and this lack needs to be addressed too.

- The uncertainties regarding the mining environment and the limited knowledge regarding the mechanical properties and behavior are currently best addressed by means of in-situ observations, data collection and structured back analyses. These measures require on the one hand well trained and skilled personnel and on the other hand observation and monitoring measures, which enable to collect data over (large) areas of interest at reasonably low efforts. The availability of such observation and monitoring measures is limited and requires improvement. Moreover, the mine layout and mining sequence must provide a sufficient degree of flexibility on a short to medium term to implement learning and findings from back analyses. Providing flexible layouts and sequences adds additional demands on the mine design from a rock engineering and production perspective.
- The active stress control approach is not widely applied at the moment. The majority of (productive and efficient) mining methods and mining operations relies on the utilization of a passive stress control approach. Hence, only a limited number of examples for the advantages of the proposed stress management concept and its corresponding active stress control approach are available. This circumstance can potentially pose a resistance against the implementation of the stress management concept.
- The importance of rock mechanics aspects in deep mining may be underestimated and thus not considered appropriately in mine design. This lack of appreciation for the need of an active stress management can prevent its implementation. A critical aspect is that such a lack of appreciation is predominantly present at high-level management, which makes (final) decisions on the mining methods, mine plans etc. The decisions are normally based on costs, profits and risks. As the impact of a proper or improper rock engineering design is often difficult to quantify in terms of costs, profits and risks due to the prevailing uncertainties and limited knowledge, the impact of rock mechanics is often not considered appropriately in decisions on the mining method, the mine layout and the mining sequence. In order to overcome this issue, further work should be conducted on this point, namely outlining and quantifying the impact of a proper or improper rock engineering design, which should best be done based on case studies, as well as creating awareness of the importance of rock mechanics and the gained benefits from an appropriate rock engineering design at a (high-level) management level.
- The commitment for the stress management concept and its implementation must be present. The implementation of the stress management concept is a difficult and

challenging task and requires considerable engineering skills, an appropriate mine design and production scheduling, a (high-level) management decision for its implementation and a proper execution in the daily operation. Accordingly, all levels of a mining operation are involved in the stress management concept. Furthermore, several different disciplines, which comprise mine management, geology, rock mechanics, production planning etc., are involved and they must work closely together on a daily basis. Creating awareness of the importance of active stress control and its advantages and involving all disciplines is important to generate the required commitment.

The above outlined points have in common that most of them require skilled and trained personnel and a long-term approach. Furthermore, the points call for a multidisciplinary approach and the involvement of all required disciplines is important. In order to make progress on the outlined points and in order to implement the proposed stress management concept successfully, there must be a willingness to invest in active stress control measures as well as in the long-term education and training and the long-term research and development. Both, the education and training and the research and development need to address aspects, which are of relevance for the industry, and they need to be conducted in close collaboration between the industry, which provides mining experience, in-situ data and expertise on a practical, operational level, and specific organizations focusing on education and training and research and development so that they can provide experience and expertise in specific theoretic and applied disciplines to the industry.

In conclusion, the stress management concept of the present work can contribute to improving or in some instances even to enabling the mineral extraction at great depth. The implementation of the stress management concept is multidisciplinary and requires a high level of skills and expertise in a planning and execution stage. Furthermore, strategic long-term research and development, ongoing training and education, continuous improvement and optimization and finally a commitment to the stress management concept are decisive for its successful implementation.

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14 List of Abbreviations

AE	Acoustic emission
BC	Block caving
c	Cohesion
D	Disturbance factor in Hoek-Brown strength criterion
d	Depth below surface
d_{tunnel}	Tunnel diameter
DB	Draw bell
DP	Draw point
D_{beam}	Maximum deflection of a beam
D_{LS}	Deformation of loading system
E	Young's modulus
ERR	Energy release rate
ESS	Excess shear stress
e	Extraction ratio
e.g.	Example given
etc.	Et cetera
F	Degradation factor used in RCF criterion
$F_{p,equ}$	Equivalent force
F_{LS}	Force of loading system
F_{M}	Force applied to specimen
GN	Giganewton
GPa	Gigapascal
GSI	Geological strength index
H_{e}	Excavation height
H_{ell}	Ellipse height
H_{p}	Pillar height
IDL	Intermediate draw level
I_{beam}	Moment of inertia of a beam
k	Ratio between primary horizontal and primary vertical stresses
km	Kilometer
kN	Kilonewton

k_{LS}	Stiffness of loading system
k_M	Stiffness of loading machine
k_S	Stiffness of specimen
L_e	Excavation length
m	Meter
m_i	Rock constant in Hoek-Brown strength criterion
max.	Maximum
min.	Minimum
MJ	Megajoule
MPa	Megapascal
Mt	Million tons
n	Porosity
OP	Ore pass
p	Line load
PI	Pillar
PL	Production level
PR	Production raise
PS	Primary stress state
RL	Raise level
R_{StSt}	Ratio between the maximum tangential stress and the rock mass strength
RCF	Rockwall condition factor
RESS	Rock Engineering Support Service
SDL	Slot development level
SL	Slot level
SLC	Sublevel caving
SLS	Sublevel stoping
SR	Slot raise
ST	Stope
STSL	Start slot
S_{beam}	Span of a beam
S_{tunnel}	Spacing between two neighboring tunnels
UCS	Uniaxial compressive strength of rock
W_e	Excavation width
W_{ell}	Ellipse width

W_p	Pillar width
W_{ts}	Width of tabular stope
x	Times
°	Degree
°C	Degree celsius
%	Percent
γ	Unit weight
$\sigma_{A,ell}$	Tangential stress in point A of an ellipse
$\sigma_{B,ell}$	Tangential stress in point B of an ellipse
σ_{avpil}	Average vertical pillar stress
σ_h	Horizontal stress
σ_{hp}	Primary horizontal stress
$\sigma_{h,avg}$	Average horizontal stress
$\sigma_{h,p}$	Primary horizontal stress
σ_n'	Effective normal stress
σ_p	Peak stress
σ_{per}	Stress perpendicular to an excavation boundary
$\sigma_{per,p}$	Primary stress perpendicular to an excavation boundary
$\sigma_{p,avg}$	Average pillar stress
σ_{rad}	Radial stress
σ_{RM}	Rock mass strength
σ_{tan}	Stress tangential to an excavation boundary
$\sigma_{tan,p}$	Primary stress tangential to an excavation boundary
σ_{tmax}	Maximum tangential stress
σ_{UCS}	Uniaxial compressive strength of rock
σ_{vp}	Primary vertical stress
$\sigma_{v,avg}$	Average vertical stress
$\sigma_{v,p}$	Primary vertical stress
σ_1	Maximum principal stress
σ_3	Minimum principal stress
T_d	Dynamic shear strength
T_{max}	Maximum shear stress magnitude

$T_{max,p}$	Primary maximum shear stress magnitude
T_s	Static shear strength
τ_p	Peak shear strength
τ_{sh}	Shear strength of a discontinuity
φ	Friction angle
∞	Infinity