Chair of Mining Engineering and Mineral Economics

Master's Thesis

Evaluation and Risk Analysis of Open-Pit Mining Operations

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March 2019

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Datum 10.03.2019

Unterschrift Verfasser/in
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Acknowledgement

The implementation of the thesis was enabled thanks to the support of FLSmidth and the guidance of several employees of the university.

I would like to thank Univ.-Prof. Dipl.-Ing. Dr.mont. Nikolaus Sifferlinger for his time and effort to find solutions for various problems that occurred during this master thesis.

Additionally, I would like to thank Ing. Claus Butter from FLSmidth for the support and time. Important approaches were built through discussions and brainstorming.

I am thankful for the help provided by Dipl.-Ing. Angelika Haindl regarding the proper usage of mining software.

Finally, I would like to thank my whole family for their permanent support throughout my academic education.

Abstract

Mining of raw materials is a process that consists of several stages. It starts with an order of a company or a private taker. For Greenfield projects, prospection and exploration must be done at first to investigate the mineral occurrence. If the resources are economical mineable, application of machinery has to be decided. The decision is primarily based on rock mass properties.

In open-pit mining, material with high compressive strength is extracted by drilling and blasting and material with low compressive strength is extracted by e.g. a bucket wheel excavator. After drilling and blasting, material must be broken down into smaller pieces of rock using a crusher, so that it can be transported with conveyor belts. Most important influencing factors for crusher decision are compressive strength, clay content, moisture content, abrasiveness, amount of fines, and desired reduction ratio. Depending on sequence of mining, fixed, semi-fixed, semi-mobile, or mobile crusher stations can be applied. Compressive strength, tensile strength, cleavage, fracture behavior, and stickiness are the most significant influencing factors for bucket wheel excavator selection. Before manufacturing a bucket wheel excavator, investigation of material's cutting resistance with a suitable test method and comparison of mine condition with condition of other mines is recommended.

The waste removal and dumping associated with mining must be handled very well, so that the environmental impacts are as low as possible and to guarantee dump stability. Essential are dump foundation properties, design of dump, and construction of dump.

Open-pit mining operations harbor risks which can lead to project delays, operation standstill, injury to personnel, damage to equipment, or negative impacts on the environment. Therefore, risk identification and prevention of risks is essential.

Zusammenfassung

Der Abbau von Rohstoffen ist ein Prozess, der aus mehreren Schritten besteht. Es beginnt mit dem Auftrag einer Firma oder eines privaten Interessenten. Bei Greenfield-Projekten müssen zunächst Prospektionen und Explorationen durchgeführt werden, um das Mineralvorkommen zu untersuchen. Wenn die Ressourcen wirtschaftlich abbaubar sind, muss der Einsatz von Maschinen entschieden werden. Die Entscheidung basiert hauptsächlich auf den Eigenschaften der Gesteinsmassen.

Im Tagebau wird Material mit hoher Druckfestigkeit mittels Bohren und Sprengen und Material mit niedriger Druckfestigkeit z.B. mittels Schaufelradbagger gewonnen. Nach dem Bohren und Sprengen muss das Material mit einem Brecher in kleinere Gesteinsfragmente zerkleinert werden, sodass es mit Förderbändern transportiert werden kann. Die wichtigsten Einflussfaktoren für die Entscheidung des Brechers sind Druckfestigkeit, Tongehalt, Feuchtegehalt, Abrasivität, Feinanteil und gewünschtes Zerkleinerungsverhältnis. Abhängig von der Abbausequenz können fixe, halb-fixe, halb-mobile oder mobile Brecherstationen eingesetzt werden. Druckfestigkeit, Zugfestigkeit, Spaltbarkeit, Bruchverhalten und Klebrigkeit sind die wesentlichsten Einflussfaktoren für die Auswahl eines Schaufelradbaggers. Bevor ein Schaufelradbagger gebaut wird, ist eine Untersuchung des Schnittwiderstandes des Materials mit einer geeigneten Testmethode und ein Vergleich der Abbaubedingungen mit den anderer Tagebaue zu empfehlen.

Die mit dem Abbau verbundene Entsorgung und Verhaldung des Abraums müssen bestens gehandhabt werden, damit die Umweltauswirkungen so gering wie möglich sind und die Stabilität der Halde gewährleistet ist. Wesentlich sind die Eigenschaften der Haldenbasis, das Design der Halde und die Errichtung der Halde.

Der Tagebaubetrieb birgt Risiken, die zu Projektverzögerungen, Stillstand des Betriebes, Personenschäden, Geräteschäden oder negativen Auswirkungen auf die Umwelt führen können. Daher ist die Risikoerkennung und -vermeidung von wesentlicher Bedeutung.

Table of Contents

1 Task Formulation

First step of the self-contained cycle is a mine project order given by a company or a private taker. The objective of the thesis is to create a guideline that helps during the open-pit operation from the very beginning until the end of the self-contained cycle. It covers the whole procedure of a mining project starting with the analysis of the orebody. Each mineral deposit is different and must be investigated properly to ensure right decision making for further progress. In the next step, evaluation of the most qualified equipment for the existing mine condition must be done based on rock mass properties. Various influencing factors have to be considered to choose suitable machinery. The thesis focuses on determination of most efficient investigation methods prior to excavation start.

After the excavation, waste handling and waste management must be done. Main issues are stability problems of dumps and dump sequencing due to a high accident risk. Mining is a very dangerous activity and it is associated with a high injury rate. Therefore, risk analysis of the most important risks is made to create a checklist to go through during all stages of the mining operation. Each of the mentioned parts is discussed based on conceptions of FLSmidth. Operational expenditure (OPEX) and capital expenditure (CAPEX) calculations are not part of the thesis.

FLSmidth is a large mining concern that acts around the whole world and works on both Greenfield projects and existing projects in more than 50 countries. Working area of FLSmidth involves the supply of mineral and cement industry with everything from engineering, single machines and complete processing plants, to maintenance, support devices, and operation of processing facilities. The objective is to implement a system which optimizes technical specifications, output rates, and safety issues. FLSmidth focuses on cement, coal, copper, gold, iron ore and fertilizers, providing one source for the products, solutions and services they need. Nickel, Zinc, Lead, Tin, Silver, and Platinum Group Metals (PGMs) are also part of the assortment.

2 Analysis of the Orebody

2.1 Orebody Definition

The orebody is a natural given structure of an accumulation of valuable minerals and rocks [1]. Factors that influence the value of a deposit are geometrical parameters (thickness, strike, dip, depth, depth extension), shape and size of deposit (tabular, massive, irregular), and regularity of deposit. A general distinction is made between ore deposits, industrial minerals, and fossil energy resources [1].

To get an idea of location, regularity, and value of the deposit, prospection and exploration methods must be conducted. Different geological methods as geochemistry, geophysics, aerial photograph interpretation, and investigation of drill cores in shallow depth are part of the detailed follow-up exploration [1]. In evaluation phase, drill patterns are getting smaller, rock mechanics investigations are made, and processing tests are performed to know exactly how to handle the material. After that, accurate calculations of reserves are possible. Results are shown in a feasibility study [1].

Drilling in great depth is very expensive and therefore, drilling patterns must be chosen wisely. The following interpretation of investigated drill cores is the key of understanding the shape and regularity of the orebody. Drill cores must be stored and documented properly (photo, depth, number). Databases are used to collect the whole drilling data and to make sure that no data is lost.

Deposit models are created to improve and support understanding of the deposit. These models are permanently updated by adapting newest exploration data. Based on drill data and geostatistics (e.g. estimation approach based on weighted average of samples), a possible model of the deposit is generated. The key is not to trust these models without thinking. The model should serve as a decision support whereby knowledge of experts must be incorporated.

Most important industries for FLSmidth are cement, iron ore, copper, gold, coal and phosphates.

Iron-ore deposits

Most important type of iron ore deposits are marine-sedimentary deposits (banded iron formations). They represent about 75 % of world reserves [1]. Often weathered areas (laterites) are mined. Liquid-magmatic and contact-metasomatic deposits play also an important role [1].

Banded iron formations (BIFs) are fine-layered (0,5 – 3 cm) and micro-laminated (< 1 mm) rock formations. The easiest composition consists of magnetite and quartz layers with a vertical thickness of a few hundreds of meters and a lateral extent of up to thousands of kilometers [1].

BIFs are distinguished because of their country rocks. Formation of Algoma type BIF took place in volcanic surroundings, Superior type BIF whereby shelf sediments dominate, and Rapitan type BIF which is bound to glaciogene marine sediments [2].

Cu-ore deposits

Most important type of copper ore deposits are porphyry copper deposits. They represent about 60 % of world reserves. Stratabound deposits in sediments are also quite important [1].

Au-ore deposits

2/3 of world production of gold was provided by recent and fossil placer deposits. Most important example represents the Witwatersrand basin [1]. Plutonic gold deposits (Au-Qtz gangues, stockwork mineralization, breccia pipes, gold porphyry, polymetallic skarns) are bound to acidic and intermediate magmatic rocks. Metamorphic Au-Qtz gangues are mostly related to archaic/old-proterozoic greenstone belts and this type of deposit is often called orogenic gold deposit [1]. They represent the most important type of primary gold deposits.

2.2 Mineral Deposit Influence

The mineral deposit influences the way of mining through several aspects e.g. mine size, depth of mining, mining method. If a mineral deposit is mined in an open-pit mine, the goal is always to mine the deposit as economical and completely as possible with the highest safety standards. Therefore, the geometry of the pit has to follow the geometry of the deposit. The pit is extended vertically and horizontally during the process of material excavation. Regarding the mine plan, several parts of the pit extend faster than others.

The material (waste/ore) must be transported out of the mine. This can be done through truck haulage or with an in-pit crushing and conveying (IPCC) system. The most important objective is to choose the most economical solution. Important influencing factors are depth of pit, haulage distance to faces and mine facilities, pit geometry, emissions, fuel prices and so on.

FLSmidth is focusing on preparing haulage solutions with IPCC systems. It is always tricky from an engineering point of view to locate the crusher on a suitable place where relocation times are minimized. Relocation must be done frequently if the pushback rate is high and relocation costs are quite high.

Planning of conveyor belt and semi-mobile crusher location is performed on a gold mine called Vostochny. It is very important to mention that the best approach for cost calculation would be to compare the haulage costs generated through truck and conveyor haulage inclusive costs for crusher relocation. Therefore, the crusher must be located on several benches (in and outside the working area). The evaluation for following options is done by discussing and comparing advantages and disadvantages of these options. FLSmidth is focusing on crusher relocation because of great cost. Two options for crusher and belt location are selected to be the most effective.

Option 1

The crusher in option 1 is located on bench 558 m above sea level (see Figure 1). The conveyor belt is connected two times with bridges at position x_1 and x_2 to guarantee that truck haulage can be implemented beneath conveyor belt. Maximum inclination of conveyor belt is 7,93° and therefore, unproblematic for construction and haulage. In sum, about 2.473 m of conveyor belt must be installed and about 3,7 Mio. m^3 of material must be removed prior to operation start (Figure 2 and Figure 3) to ensure a proper slope angle.

- Advantages
    - The crusher is located outside zone of maximum pushback
    - Usage of predefined haulage route for conveyor belt haulage
    - Location of crusher beneficial for truck haulage distance
- Disadvantages
    - Removal of large amount of material prior to operation start
    - Installation of two conveyor bridges is associated with high CAPEX
    - Development of a ramp to crusher location is necessary

Option 2

The crusher in option 2 is located on bench 558 m above sea level (see Figure 4). The tunnel is developed from this bench upwards until it reaches the elevation 765 m above sea level. From this point the conveyor belt is developed straight to the dump. Maximum inclination of the conveyor belt is 12,52° and therefore, unproblematic for construction and haulage. About 1.529 m of conveyor belt are needed for this option and about 933.037 m^3 (7*5*943,91 ≈ 33.037 m^3 for tunnel) of material must be removed prior to operation start (see Figure 5 and Figure 6).

- Advantages
    - Crusher located outside zone of maximum pushback
    - Usage of a tunnel with an inclination < 14°
    - Location of crusher beneficial for truck haulage distance
    - Removal of moderate amount of material prior to operation start
- Disadvantages
    - Great cost for creation of tunnel
    - Development of a ramp to crusher location is necessary

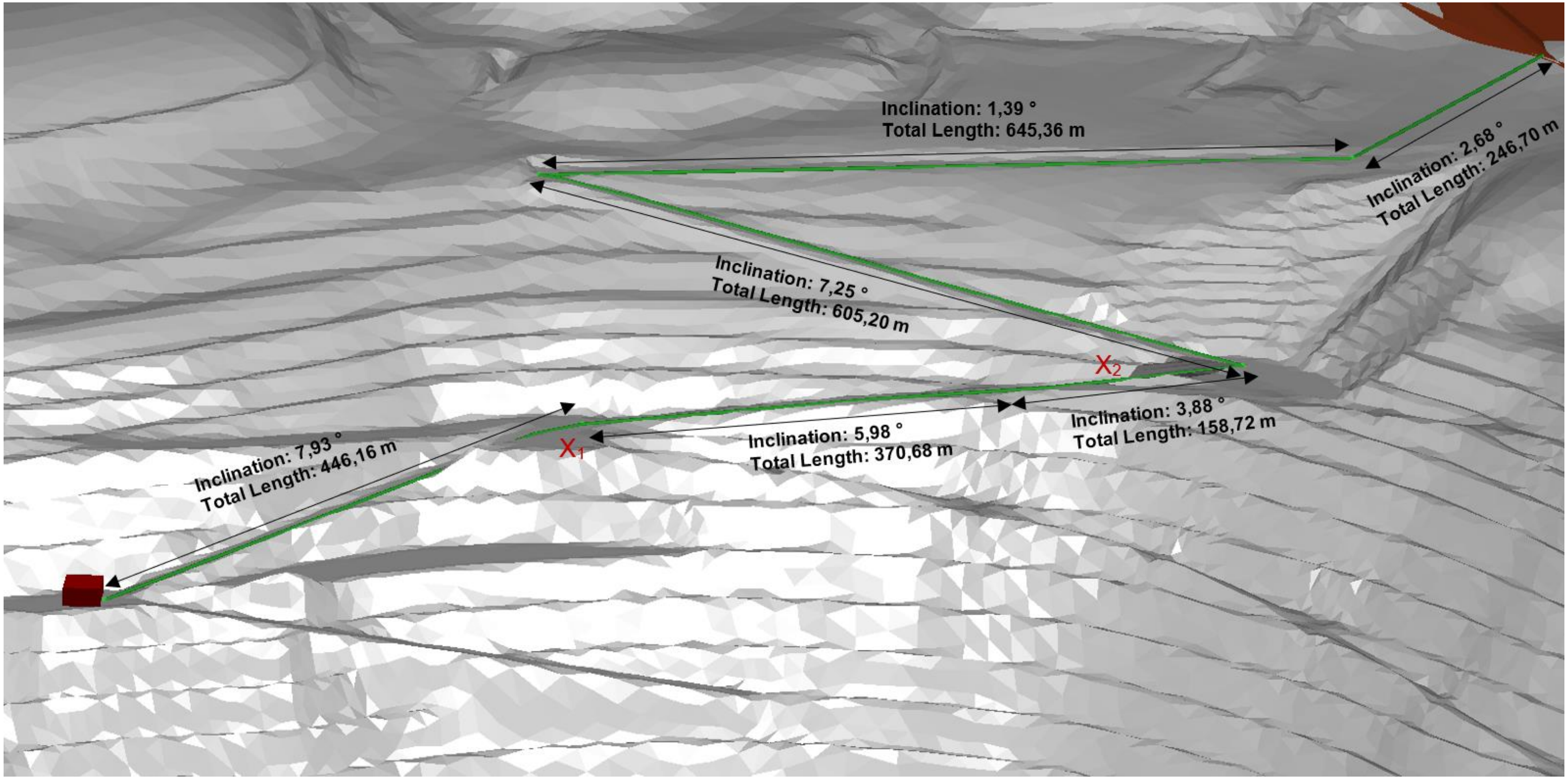


Figure 1: Option 1 for IPCC system in Vostochny Mine with mine dump (= colored brown)

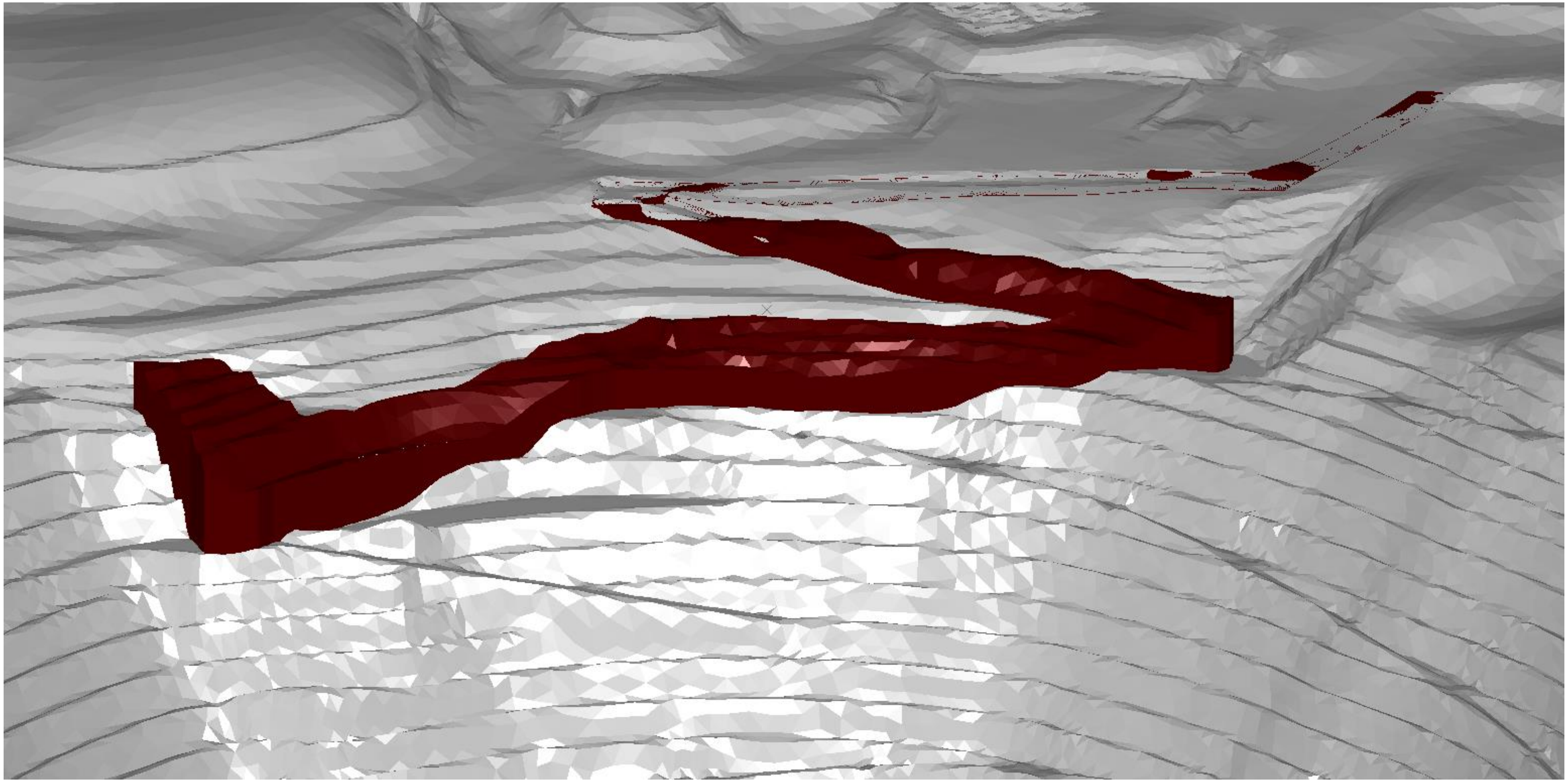


Figure 2: Material removal for Option 1 with pit

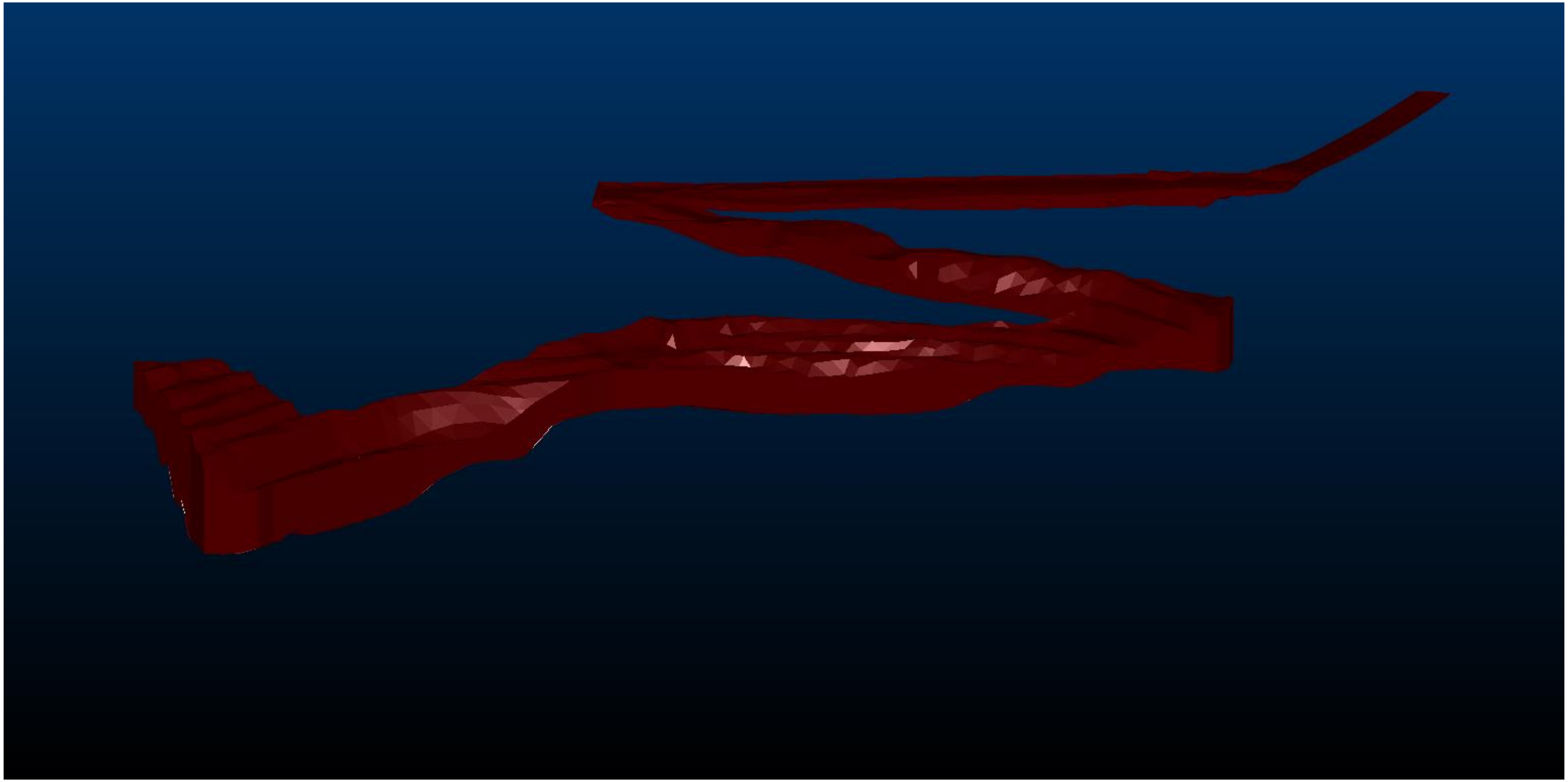


Figure 3: Material removal for Option 1 without pit

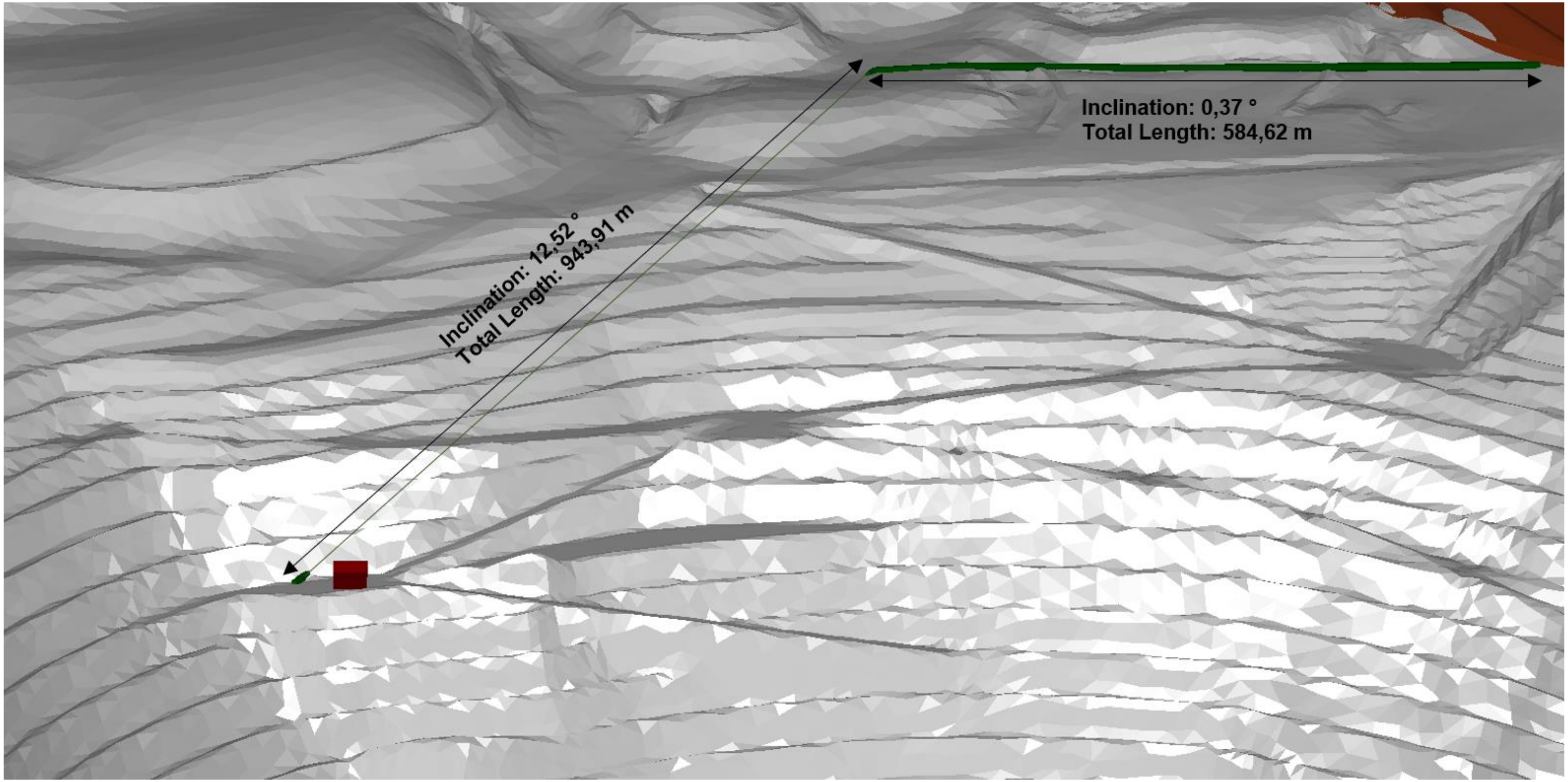


Figure 4: Option 2 for IPCC system in Vostochny Mine with mine dump (= colored brown)

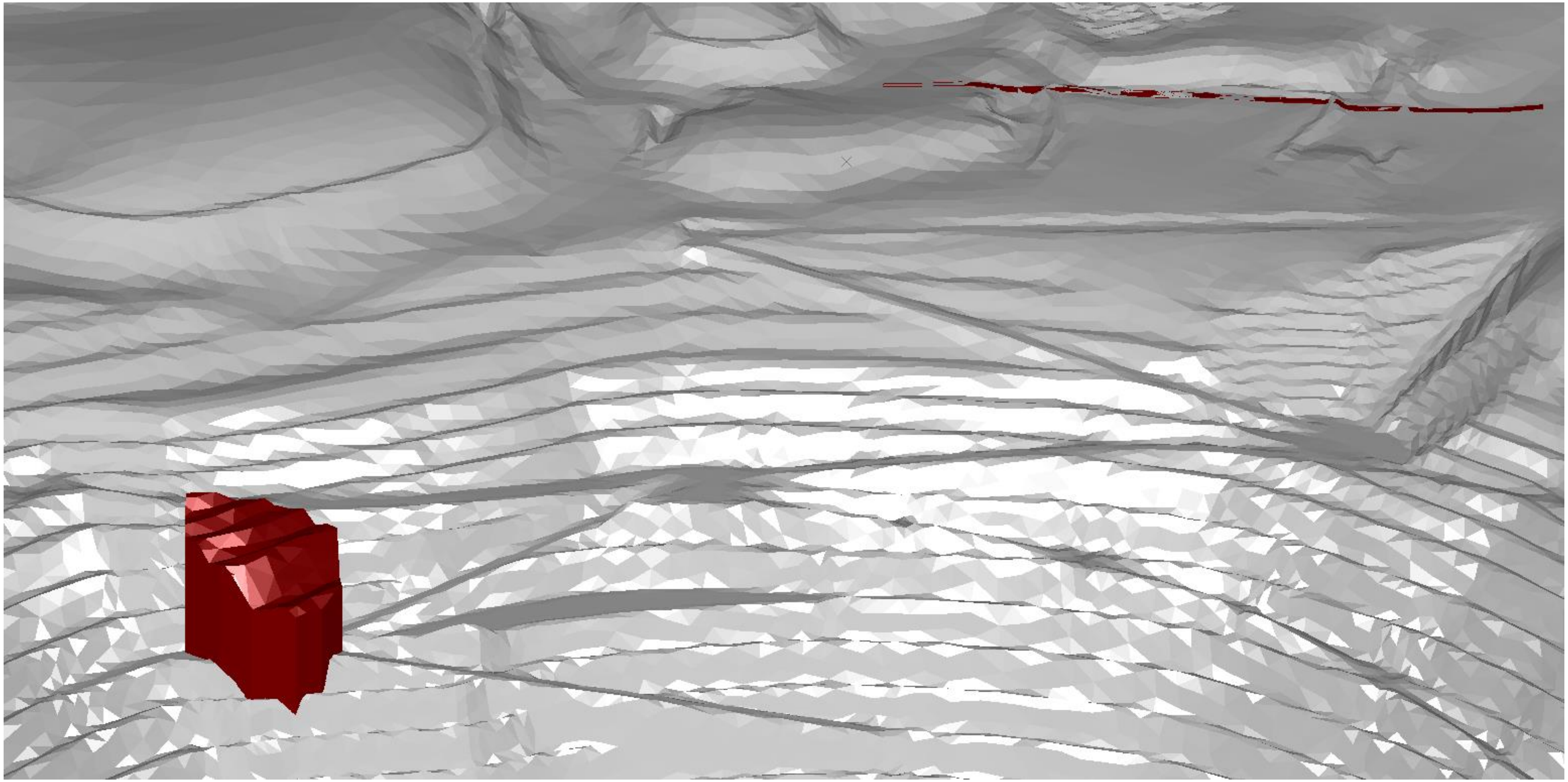


Figure 5: Material removal for Option 2 with pit (without material removal for tunnel)

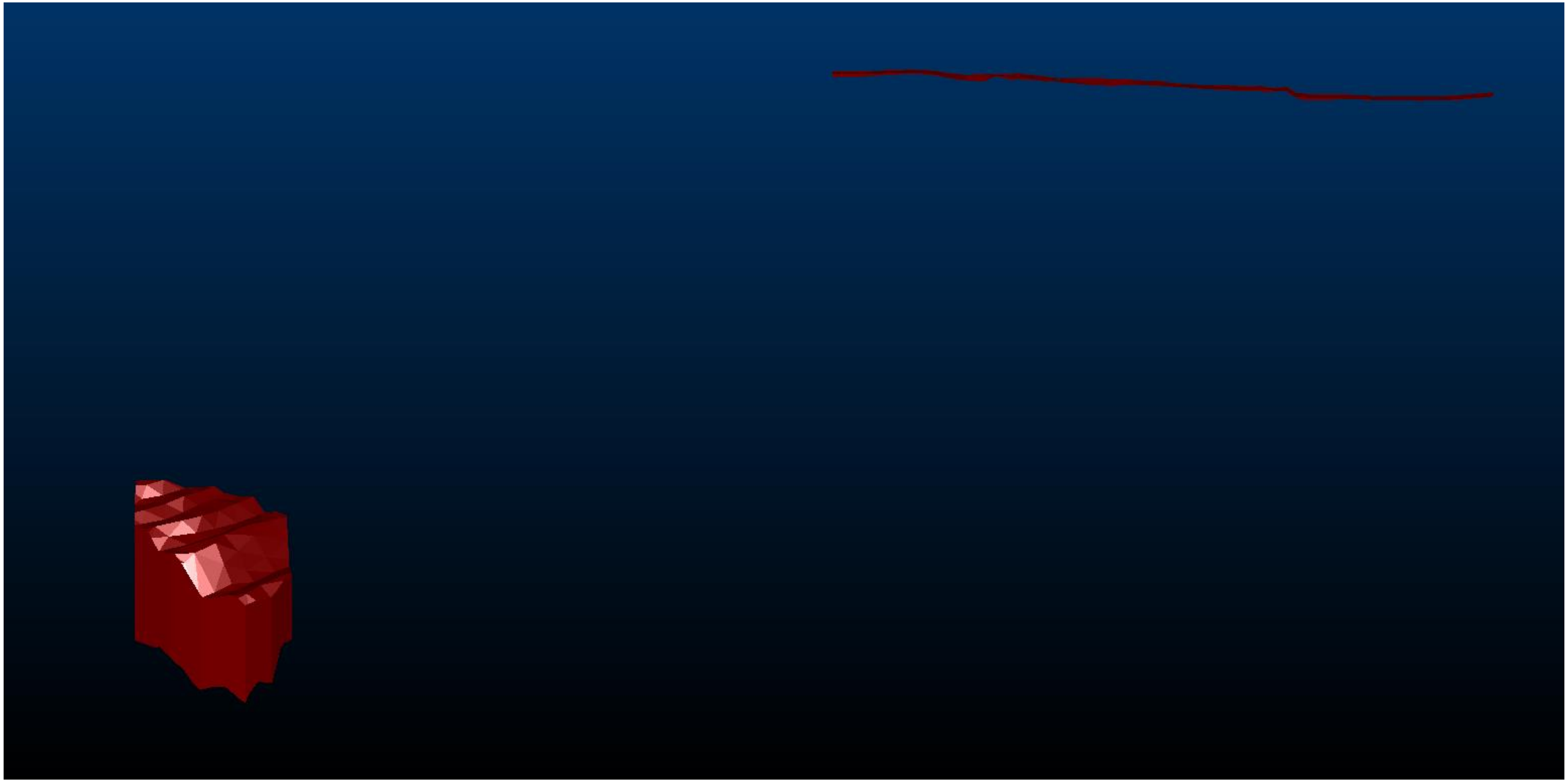


Figure 6: Material removal for Option 2 without pit (without material removal for tunnel)

3 In-Pit Crushing and Conveying

3.1 Definition and Evaluation Parameters

IPCC systems are continuous haulage systems for open-pit mines (see Figure 7). The sequence of IPCC consists usually of a feeding system which feeds the blasted/excavated material into a crusher system (fixed, semi-mobile, mobile). The crusher system is located within the pit and relates to a downstream conveying system for hauling the crushed material to a certain discharge point.

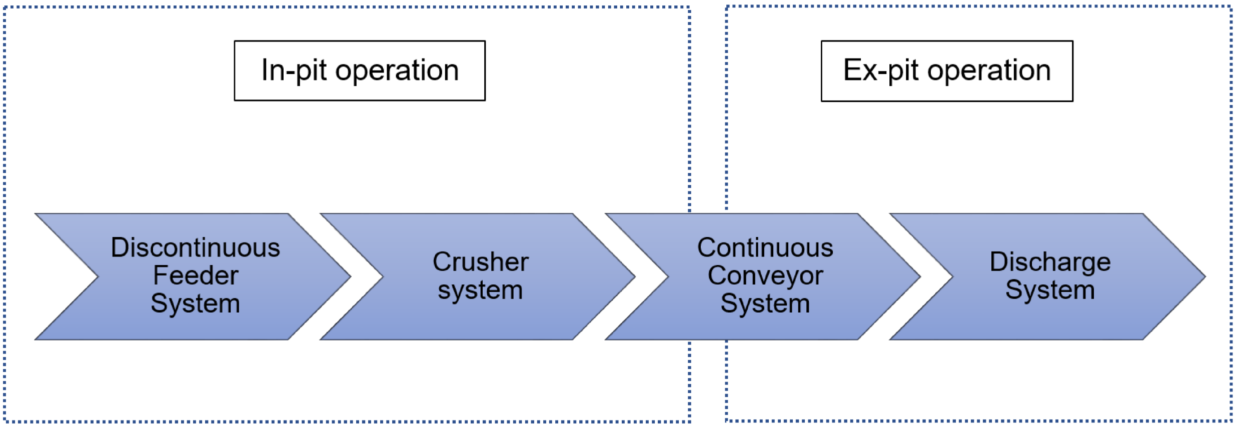


Figure 7: Sequence of IPCC operation (modified after [3])

Evaluation of continuous mining systems is based on the type and properties of ore and waste being mined. Bucket wheel excavator (BWE) in combination with a system of conveyors is used in case of light and loose earth. For mining in harder ore (minerals, hard coal), crushers are applied to reduce the run-of-mine ore to a conveyable size [4].

Important design factors are production requirements, truck sizes, CAPEX and OPEX, ore characteristics, orebody geometry, reserve life, estimating infrastructure and equipment, availability of power and diesel, country risks, safety and environment, project location, life-of-mine/expansion plans, operational consideration, and maintenance requirements [4]. Certain mining-based factors are described below.

Production Requirements

The design capacity of feed hopper is between two and three truckloads and the discharge chamber below the crusher must be designed to carry a minimum of 1,25 times the capacity of the receiving hopper to avoid damage to the crusher [4].

Ore characteristics

Ore characteristics influence crusher and conveyor selection. Larger measures for dust suppression and collection must be considered for dry ores. Blockage of chutes and crushers, reduction of surge capacity, and incorrect alignment of belts are caused by wet, sticky ores [4].

Project Location

Costs for construction are generally much higher for altitudes, in cold climates and at remote sites. In case of a flat quarry operation, it is suitable to install the conveyor in one position for a long time. On the other hand, the crushing station and receiving conveyor in a deep copper pit need to be moved from time to time. If exploitation is finished at a face, the conveyor could be installed at this face with a high-angle conveyor. The other possibility is a gap designed to install a conventional conveyor [4].

Plant Layout and Design

Cost driving factors of the crushing plant are structures and infrastructure. High investment costs regarding these factors can be saved by designing the plant layout accurately [4].

A close co-operation of crusher manufacturers and plant designer is required whereby high-priority elements are production, process, economic, safety, and operational design [4].

3.2 Feed System

The feed system functions as a connection element between the operation at the working face and the crusher system. Ritter [3] divided the system into cyclic excavation and cyclic intermittent haulage. Various combinations are shown in Figure 8 depending on applicable haulage range and crusher system. Typically, excavation in IPCC systems is done by front-end loaders, hydraulic excavators, or rope shovels. In some cases (e.g. gravel pit in Milford), direct feed of crusher is done using dragline or dozer [3].

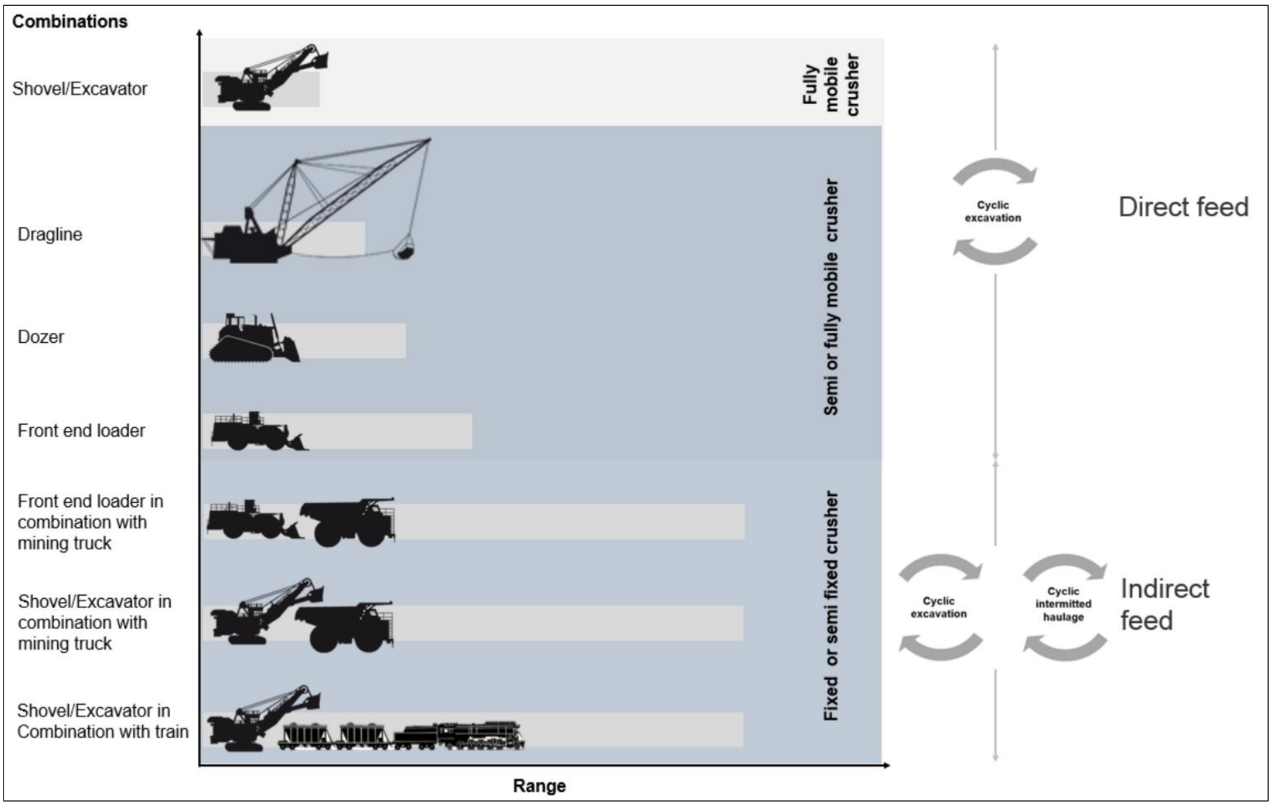


Figure 8: Possibilities of feed system [3]

3.3 Crusher System

The crusher system receives material from the feed system which is excavated at working face. Boulders must be crushed to a certain grain size to become conveyable with conveyor belt.

In-pit crusher stations can be divided into [3]:

- Fixed
- Semi-fixed
- Semi-mobile
- Fully-mobile

The classification is based on degree of mobility, structural design and location of operation [3].

Fixed In-Pit Crusher Station

Fixed in-pit crushers (Figure 9) are typically gyratory or jaw crushers which are designed to operate the whole lifetime of mine at the same place. The crushers are usually located near the pit rim or inside the pit to prevent exposures to mining activities. [3]. The two types of fixed crushers are named in-ground and rim-mounted crushing plants. Both are installed in a concrete structure. In-ground crushers are located ex-pit and rim-mounted crushers are fixed at or a part of the bench wing wall. Rim-mounted stations are installed for 15 years and more [4].

Figure 9: Fixed In-Pit Crusher Station of FLSmidth [5]

Semi-fixed In-Pit Crusher Station

Semi-fixed in-pit crushers are mostly located at junctions within the pit and they are fed by mining trucks from various working benches and loading points. Crushers can be divided into modular and non-modular crusher stations. The difference is that modular crusher stations must be relocatable very quickly without high costs for dismantling and erection. Depending on presence of integrated feed system, both types can be divided into direct dump and indirect dump stations. Relocation times for modular stations are about several days and for non-modular stations several weeks up to one month [3]. Relocation frequencies are between 5 and 10 years [4].

Semi-mobile In-Pit Crusher Station

Semi-mobile crusher stations (Figure 10) are normally located at the operating bench and they can be fed by multiple loading machines (e.g. front-end loaders). This system doesn't consist of integrated transport mechanisms. Transport crawlers or dozers are used for relocation of system which takes about several hours [3]. A subdivision into direct-dump and indirect feed crushing plant can be made. Both are located near the centroid of the working portion of the mine to minimize haulage distance for trucks. The indirect feed system consists of an apron feeder, the crushing plant with the crusher, and a separate tower that harbors the control room. In comparison, the direct-dump crushing plant is mounted on a steel structure which comprises the whole auxiliary equipment and subsystems for crusher operation. Relocation frequencies of semi-mobile stations are between 1 and 10 years for direct-dump and between 3 and 5 years for indirect feed systems [4].

Figure 10: Semi-mobile In-Pit Crusher Station of FLSmidth (provided by FLSmidth)

Fully-mobile In-pit Crusher Station

Fully-mobile crusher stations (Figure 11) aim for the total elimination of truck usage by feeding the run-of-mine ore directly to a continuous materials-handling system [4]. Direct feeding of crusher takes place using a single loading machine. The crusher system can be moved using integrated transport mechanisms as crawler tracks, hydraulic walking pads or tires. Due to their agility, a simultaneous movement along the working face is possible but only a few are actually able to follow the movements of the loading unit. However, design of most fully-mobile crusher systems requires discharge of hopper before movement of crusher can start. Therefore, operational delays of loading unit occur [3].

Figure 11: Fully-mobile In-Pit Crusher Station of FLSmidth (provided by FLSmidth)

Best applications for fixed IPCC systems are in deep, pre-existing pits with a low vertical advance rate. The crusher must be able to handle the operation without being relocated over a time greater than five years [6].

Semi-mobile in-pit crushers are relocated every two to five benches in a deep mine depending on vertical advance rate [6]. Transport crawlers or self-propelled modular transporter are used for relocation of semi-mobile and semi-fixed systems. Transport crawlers are able to bear loads up to 1.500 t on a maximum gradient of 10 %.

Fully-mobile in-pit crushing stations are best applied in greenfield operations [6]. Wherever low ground pressure and quick relocation of crusher without downtimes of crusher are required, crawler tracks are used as transportation system. Travel speeds between 8 – 12 m/min and 17 – 20 m/min can be reached for large and small crusher stations, respectively [3].

3.3.1 Evaluation of Crusher Type

Main purpose of crushers in IPCC systems is to reduce the grain size of the fed material to a specific grain size that is necessary for the conveying with downstream conveyor belt.

Crusher selection depends on following parameters [3]:

- Material properties (moisture content, density, hardness, stickiness, abrasiveness)
- Application requirements (product size, feed size, fines, product size distribution, capacity)

Figure 12 shows the in-pit crushers used for IPCC systems depending on maximum output and compressive strength of material.

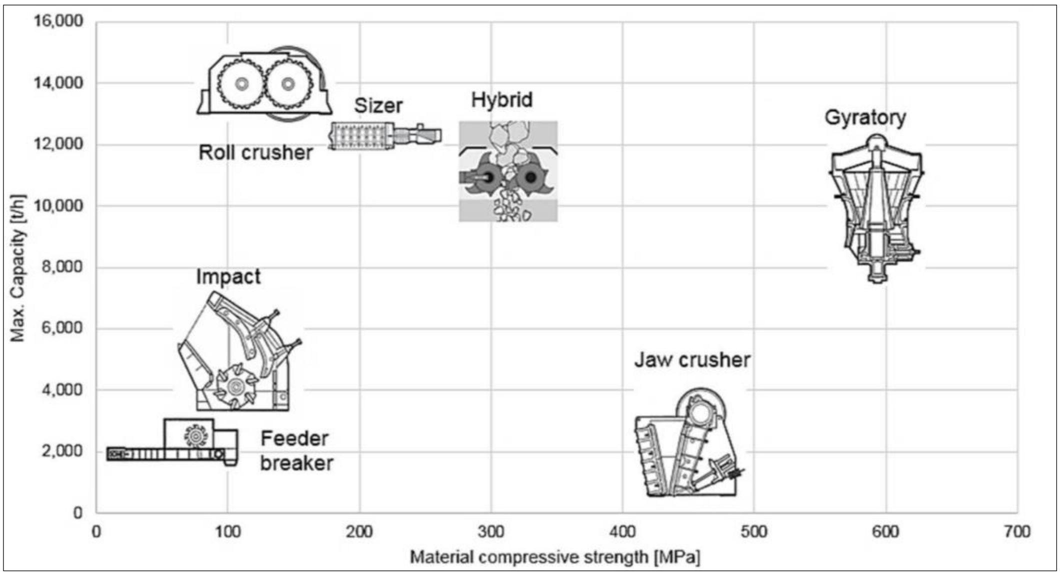


Figure 12: Crusher types related to maximum capacity and compressive strength [3]

Table 1 and Figure 12 show data of various primary crushers based on data from various references [7–16]. Main parameters for selection of crushers are achievable capacity, achievable reduction ratio, maximum feed size, and material compressive strength [3].

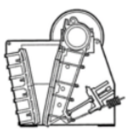
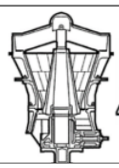
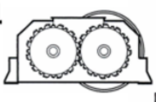
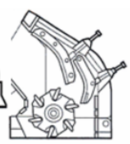
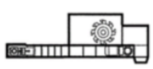
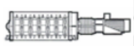
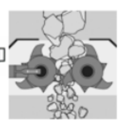
The impact crusher is most commonly used for diorite, dolomite, granite, limestone, marble and basalt deposits with an amount of 50 %. Reasons are the achievable reduction ratio that can go up to 1:50 and the ability of crushing materials with a moisture content up to 10 % [3].

The gyratory crusher represents the main crusher type for copper, gold deposits (86 %) and for iron ore deposits (39 %). Main reasons are probably high capacity rates and possibility of processing high resistance material [3].

Sizer and double roll crusher have the highest application rates for coal (54 %) and oil sand (26 %) deposits due to their ability of cutting wet materials at high capacity rates [3].

Hybrid crushers are often used in combination with fully-mobile crusher stations nowadays [3]. They produce a driblet of fines and they are able to handle material with a high moisture content.

Table 1: Data comparison of primary crusher used for IPCC systems [3]

Crusher		Jaw	Gyratory	Roll Crusher	Impact	Feeder Breaker	Sizer	Hybrid
Year introduced		1858	1883	1910	1920	1960	1979	2005
Mechanical reduction method		compression	compression	compression, impact & shear (for single roll)	impact, attrition, shear	compression, impact, shear	shear, compression	compression
Moisture content [%]		<5	<5	>20	<10	>20	<20	>20
Application for high clay materials		poor - fair	poor	good	poor	fair	excellent	very good
Abrasiveness		high	high	low	not applicable	low	low - medium	low - medium
Fine generation		low-medium	low-medium	low	high	low-medium	low	low
Max. capacity [t/h]		1250	10940	14000	4500	6000	12500	12000
Material compressive strength [MPa]		450	600	150	115	50	200	300
Max. feed size [mm]		1500	1830	1600	3000	1500	2000	2500
Reduction ratio		1:4 - 1:9	1:3 - 1:8	1:5 - 1:10	1:10 - 1:50	1:2 - 1:4	1:2 - 1:4	1:4 - 1:6
Design variations		single/double toggle	Gyratory, Jaw-type gyratory	Single/double roll	Horizontal/vertical and single/double shaft		single/double roll, side/centre	
Max. Dimensions [mm]	height	5400	10800	3500	8100	2000	1800	2000
	length	5200	6450	9700	5500	6500	10100	9300
	width	4200	6250	8200	5700	4500	4050	7000
Max. Weight [t]		115	530	230	190	50	190	102
Max. Installed power [kW]		400	1200	2000	2800	300	1200	2500
Schematic								

4 Bucket Wheel Excavator

One of the most important influencing factors for specific application of a BWE is the chosen design based on various parameters e.g. material characteristics. Material characteristics consist of compressive strength, cleavage, tensile strength, fracture behavior, and stickiness [17].

Additionally, significant parameters like specific cutting/digging force and specific energy are used to get an idea of the behavior of the material that must be excavated. The specific energy is defined as the amount of energy required to excavate a unit volume of rock [18]. Specific linear cutting force only is not a proper parameter for optimization of BWE design, especially for hard rock conditions. Therefore, BWE geometry and the chosen mining method must be taken into account with a method using a fracture surface-related energy requirement [17]. Specific cutting force related to the cross section of chip shows better results for BWE operations in harder materials [19].

An approach for hard rocks which is related to mining energy (LSE) is developed and modified by Machniak and Kozioł [20]. It describes the workability of rock and the necessary energy to excavate hard rock. Basis is the comparison of machines with same working characters e.g. BWEs and rippers. Andras et al. [21] examined lignite and overburden rock of Oltenia coal field and discovered that best results for cutting forces arise using the specific energy approach.

Figure 13 shows the evaluation steps of a Greenfield project to determine useful application of a BWE. First, prospection and exploration methods must be done on site e.g. bore holes are drilled and drill cores are taken. After prospection and exploration phase, test methods are conducted on drill cores to determine cutting resistance and mechanical properties of rock. BWE design is based on UCS and cutting strength parameters. After final BWE type is manufactured and already operating, monitoring and documentation of required driving power should be done permanently. This procedure leads to a better understanding of the connection between excavated material and operating BWE.

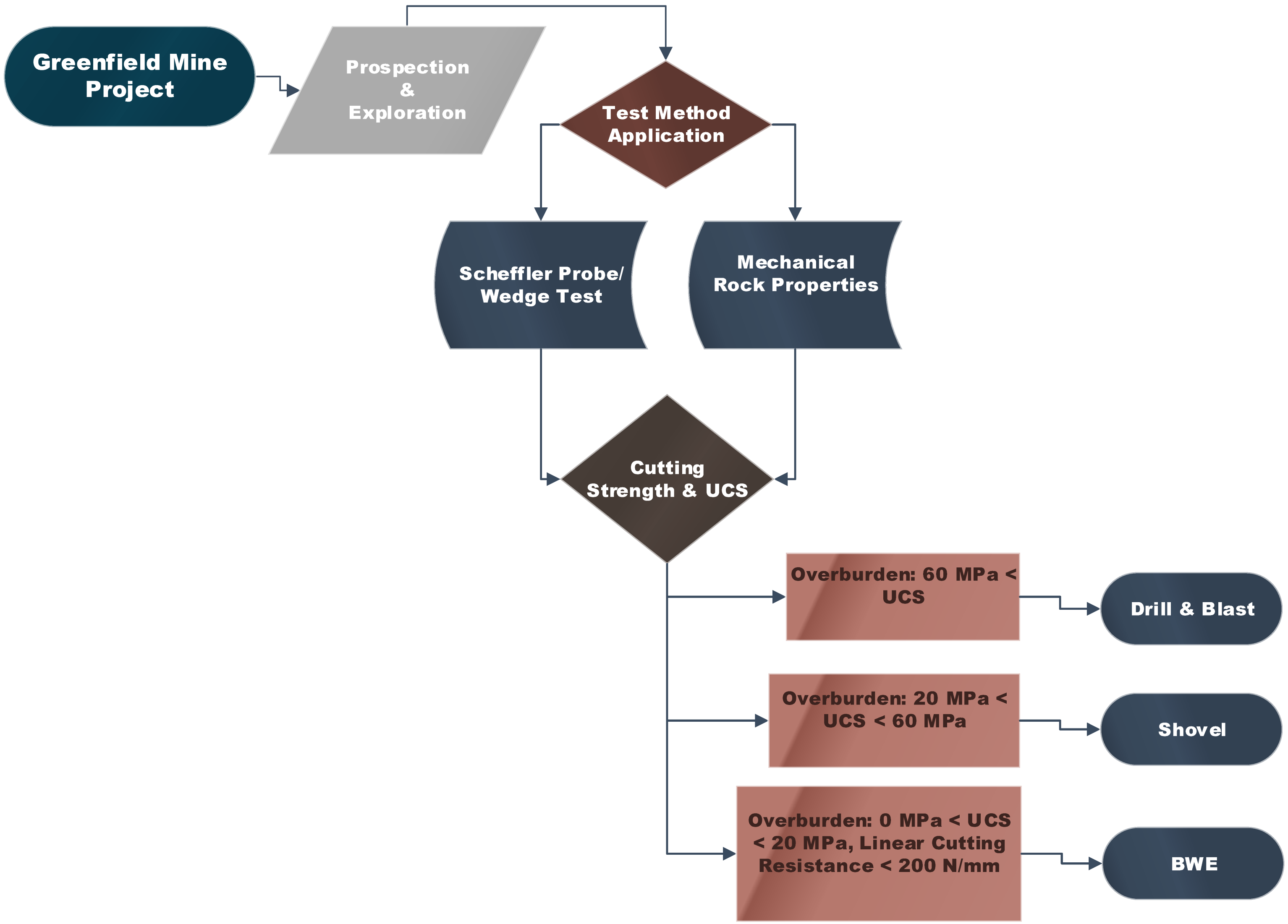


Figure 13: Evaluation of Bucket Wheel Excavator

Based on the equipment of FLSmidth it can be said that the limit for operability of BWEs (BWE100, BWE200) is reached at a uniaxial compressive strength (UCS) of the rock mass of about 20 MPa (see Figure 14). Durst and Vogt [19] described that BWEs can excavate soil classes in the range between class VI to X (see Table 4). Hard material layers (maximum UCS: 70 to 140 MPa) and boulders with thickness up to 600 mm can be excavated by heavy design BWEs. These BWEs don't cut the material, they break it into smaller pieces [22]. Very important is the relation between the UCS that is determined on an intact rock sample in laboratory and the UCS of rock mass. A proper investigation of the rock mass is indispensable to ensure a right derivation.

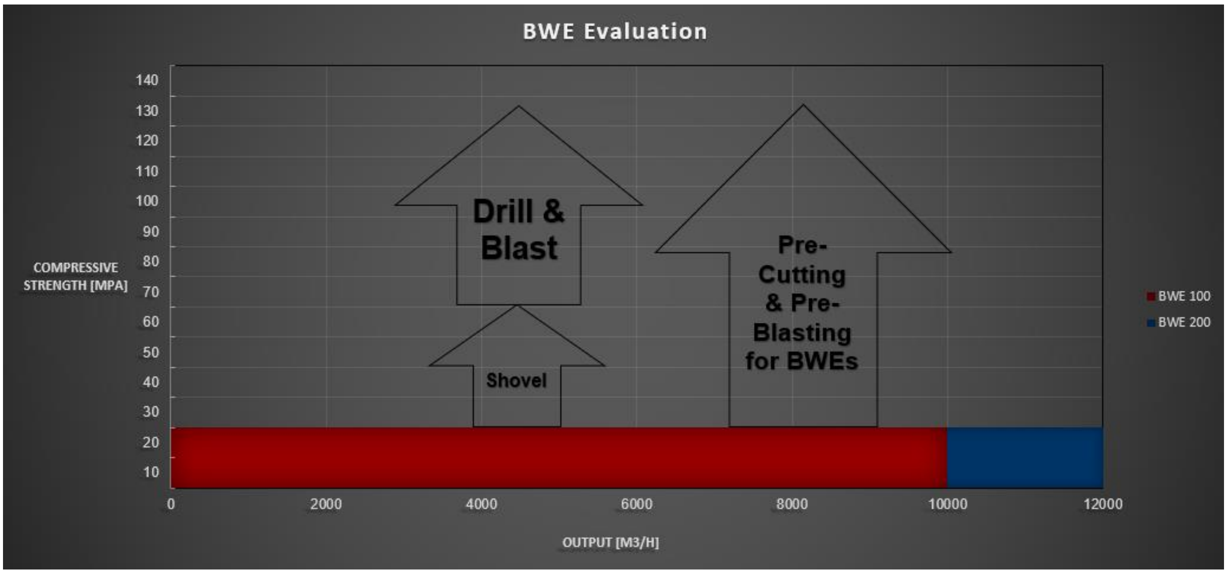


Figure 14: Comparison of applicable extraction method for Bucket Wheel Excavators based on FLSmidth equipment

4.1 Cutting/Digging Resistance

One of the most important characteristic values that describes a relation of cutting tools of the machinery and the properties of rock is called cutting resistance [23].

Influencing factors are geo-technological parameters (geology, water content, shear strength, compressive strength, discontinuities), technical parameters of the excavator (cutting tools, installed power), and technological parameters (chip and block parameters, cutting speed, slewing direction) [23,24].

The cutting resistance is described as the necessary force to penetrate the rock with a tool and loosen a defined chip and can be separated into normal and tangential components [23].

The tangential cutting force ($F_{s,t}$) is defined by an equation that consists of the ratio of the cutting power P_S in Nm/s and the cutting speed v_S in m/s [23]:

$$F_{s,t} = \frac{P_S}{v_S} \ [N] \qquad (1)$$

The tangential digging resistance ($F_{g,t}$) additionally includes the power demand for filling and circulating processes P_F in Nm/s, the power demand for friction between the extracted material and the bucket P_R in Nm/s, and the power demand for acceleration of the material P_B in Nm/s [23].

$$F_{g,t} = \frac{P_S + P_F + P_R + P_B}{v_S} \ [N] \qquad (2)$$

There are different parameters to which the tangential force can be referred [25]:

- 1 cm of the mean cutting knife length of the sickle cut
- 1 cm^2 of the mean slice cross-section of the sickle cut

Mean values are taken as granted due to sickle cut shape and changing parameters with cutting angle.

Dombrovskij [26] described k_A (specific digging force) values for various lithologies, half-blocked cuts and specific cutting parameters (slice thickness > 200 mm, slice width > 400 mm) (see Table 2). The connection between specific digging force and specific cutting force (k_S) is given by the factor ς whereby specific cutting force is about 75 % of specific digging force starting at about k_S = 1 N/mm² [26].

Table 2: Specific digging force for various lithologies [26]

k_s: *---*

k_A: •---• Löffelbagger

+---+ Schleppschaufelbagger

x---x Eimerkettenbagger

∇---∇ Schaufelradbagger

⊗---⊗ Grabenbagger

	Erdstoffklassen	k_s; k_A in N/mm² (10⁻² 1 2 3 4 6 8 10⁻¹ … 10⁰ … 10¹)	Konstanten C	Konstanten C_1
I	Sand; Feinsand; weicher, mittelfeuchter und aufgelockerter Lehm ohne Einschlüsse	*---* •---• +---+ x---x ∇---∇ ⊗---⊗	5	1,1
II	Lehm ohne Einschlüsse; feiner und mittlerer Kies; weicher feuchter oder aufgelockerter Ton	*---* •---• +-+ x-x ∇---∇ ⊗⊗	10	2,8
III	dichter Lehm; mittelharter bzw. harter feuchter oder aufgelockerter Ton; sehr weicher Tonstein; Schluffstein	*-* •---• +-+ x---x ∇∇ ⊗⊗	16	3,6
IV	harter Lehm mit Steinen oder Geröll; harter und sehr harter feuchter Ton; weiche Kohle; sehr schwach verkittetes Sedimentgestein	*-* •--• +---+ x-x ∇∇ ⊗⊗	26	4,5
V	mittelharter Schiefer; harter trockener dichter Ton; dichter verhärteter Löß; Kreide; Gips; sandiger sehr weicher Mergel; weiches Sedimentgestein; weiches Phosphor- und Manganerz; gut gesprengtes Felsgestein	*-* •--• + x---x ∇∇ ⊗	38	6
VI	Muschelkalk; weicher poröser Kalkstein; Kreide; Schiefer; mittelharter Mergel und Gips; harte Kohle	*-* •---• x ∇---∇ ⊗---⊗	50	8
VII	harter Schiefer; Mergel; harte Kreide; harter Gips; mittelharter Kalkstein; weicher sandiger Frostboden	*---* •---• x---x ∇---∇ ⊗---⊗	80	10
VIII	Felsgestein und Frostboden, gesprengt	•	26	-

Golosinski [27] examined diggability of pre-blasted and undisturbed oil sands at a mine located in Northern Alberta, Canada. The conditions for BWE operation were very difficult because lenses of hard materials and glacial boulders were present in form of interbeds. Pre-blasting was done about one year before investigations started. For measurements, BWE was erected on a limestone layer at the bottom of the pit [27]. Slew cutting/digging forces, total cutting/digging forces, and peripheral cutting/digging forces were tested during investigations (see Table 3).

Table 3: Cutting and digging forces of undisturbed and pre-blasted oil sands [27]

		PDFL kN/m	PDFA kPa	PCFL kN/m	PCFA kPa	SDFL kN/m	SDFA kPa	TCFL kN/m	TCFA kPa	TDFL kN/m	TDFA kPa
UNDISTURBED OIL SANDS 1112 Data Points	MEAN	126	2480	100	2300	4.15	47.6	101	9620	127	9795
	VAR.	25.3×10^3	103×10^6	20.9×10^3	103×10^6	58.7	114×10^3	22.2×10^3	46.5×10^9	26.7×10^3	46.5×10^9
	ST.DEV	159	10.2×10^3	144	10.1×10^3	7.66	338	149	216×10^3	164	216×10^3
PRE-BLASTED OIL SAND 1201 Data Points	MEAN	87.9	888	62.8	714	7.08	62.7	64.2	725	88.4	893
	VAR.	9.86×10^3	8.12×10^6	6.07×10^3	7.82×10^6	122	23.9×10^3	6.21×10^3	7.84×10^6	9.98×10^3	8.14×10^6
	ST.DEV	99.3	2.85×10^3	77.9	2.80×10^3	11.0	155	78.8	2.80×10^3	99.9	2.85×10^3

PDFL - Peripheral Digging Force (length)
PDFA - Peripheral Digging Force (area)
PCFL - Peripheral Cutting Force (length)
PCFA - Peripheral Cutting Force (area)
SDFL - Slew Digging Force (lenght)
SDFA - Slew Digging Force (area)
TCFL - Total Cutting Force (length)
TCFA - Total Cutting Force (area)
TDFL - Total Digging Force (length)
TDFA - Total Digging Force (area)

Results show that undisturbed sands require greater cutting forces which are 50 % (PCFL) to 300 % (PCFA) higher as for pre-blasted sand [27].

The excavator output can be increased up to 15 % by changing cutting parameters and cutting devices [28].

Optimum chip angle reduces necessary cutting forces and specific energy demand. In case of Gacko mine (Bosnia) specific power demand could be reduced by 10 % using optimal chip angle [29].

Cutting tool adaption is shown in literature [30,31] as an important factor to reduce necessary cutting force, to create a wear-independent cutting edge geometry, to increase output up to 15 %, to reduce over-sized grains in the haulage systems, and to damp the oscillation energy induced by the cutting process.

Table 13 in Annex shows a list of several mines with the current lithology and successful/unsuccessful working BWEs. Important things are described in comments. Linear cutting resistance with a value of/greater than 200 N/mm is colored red because of the application limit for BWEs. The list is based on literature from [19,24,25,32–41].

4.1.1 Test Methods

Following described test methods were conducted by Drebenstedt [23] on various clay samples of the surface lignite mine Nochten which is located in the Lusian mining district in the east of Germany. A BWE "Schaufelradbagger auf Raupenfahrwerken, schwenkbar" (SRs) 6300 is used to extract the clay.

Drebenstedt [23] outlined state of the art test methods for examination of digging and/or cutting resistances:

1. Laboratory tests
2. Technical scale tests
3. Field measurements
4. New Concepts

1.1 Micro Cutting Test

The test station involves a microscope and a mechanical device for analyzing the sample. During the procedure feed force and the feed path are measured. Large contact surfaces between sample and cutting tool must be ensured [23].

Results (Figure 15) show the propagation of a crack with increasing cutting depth of the cutting tool [23].

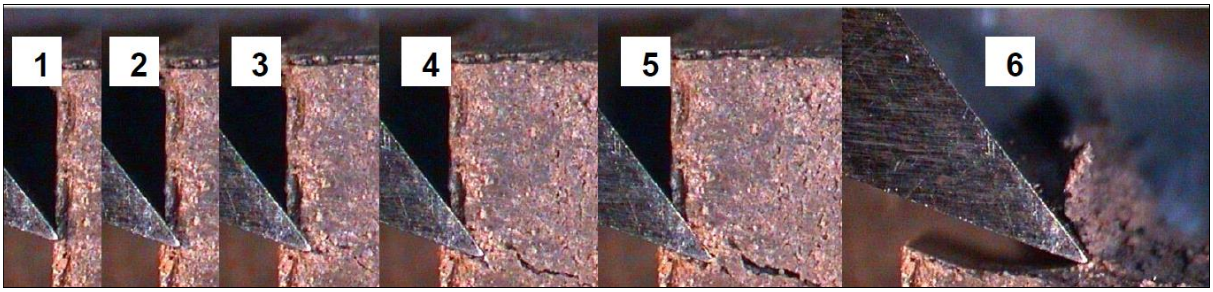


Figure 15: Crack propagation during cutting process [23]

1.2 Soil-mechanical Analysis

Approach of this analysis is an empirical equation whereby the linear digging resistance is direct proportional to the effective cohesion [42]:

$$F'_{Grl} = 14 + 10^3 * c'_{CD} \quad \left[\frac{\text{kN}}{m}\right] \tag{3}$$

where c'_{CD} in kN/m is the consolidated, drained cohesion, F'_{Grl} in kN/m is the linear digging resistance.

Equation (3) is an estimation of digging resistance and it is only valid for homogenous soils. Further prognosis must be added for significance [24].

Shear parameters can be determined using a box shear apparatus or a ring shear apparatus [23]. The angle of internal friction of the investigated clay at the surface lignite mine Nochten varies between 9,3° and 24,1° and the effective cohesion varies between 14,4 kN/m^2 and 78,4 kN/m^2. So, the examined clay is a heterogenous material though samples were taken in the immediate neighborhood [23].

Different empirical equations showed different results. A ranging between 28 kN/m^2 and 92 kN/m^2 could be observed [23].

2.1 Direct measurement of cutting resistance at Test Field

Using a technical scale test field, it is possible to determine the cutting forces (see Figure 16a). The cutting resistances will be investigated on especially for the test created blocks with defined particle size and geotechnical parameters (see Figure 16b) [23].

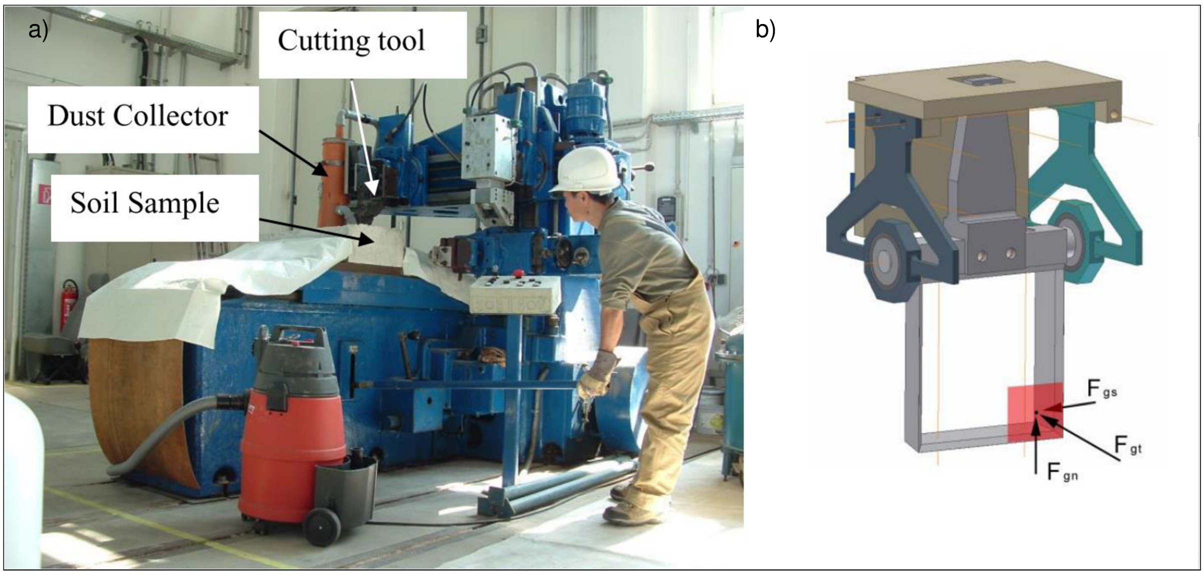


Figure 16: a) Test field for determination of cutting forces b) Determination of cutting resistance [23]

3.1 Impact Probe Test

This testing procedure involves a cutting tool, a guide bar, and a drop weight. The drop weight falls from a defined height onto the cutting tool and transmits a particular amount of energy [23].

Dynamic impact probe tests are conducted to gauge the magnitude of cutting or digging resistance. Approximation formulas are used to get a guessing of these parameters whereby the blow rate functioned as basis [23]. An advantage is that the tool tip can be freely designed, so influences of the tool parameters can be observed [23].

Test probes according to Dornij and Scheffler (Figure 17) were used to get an information about the digging resistance. For clay specific digging resistance values within 50 kN/m and 94 kN/m could be observed using Dornij test probe and values within 70 kN/m and 128 kN/m using Scheffler test probe [43].

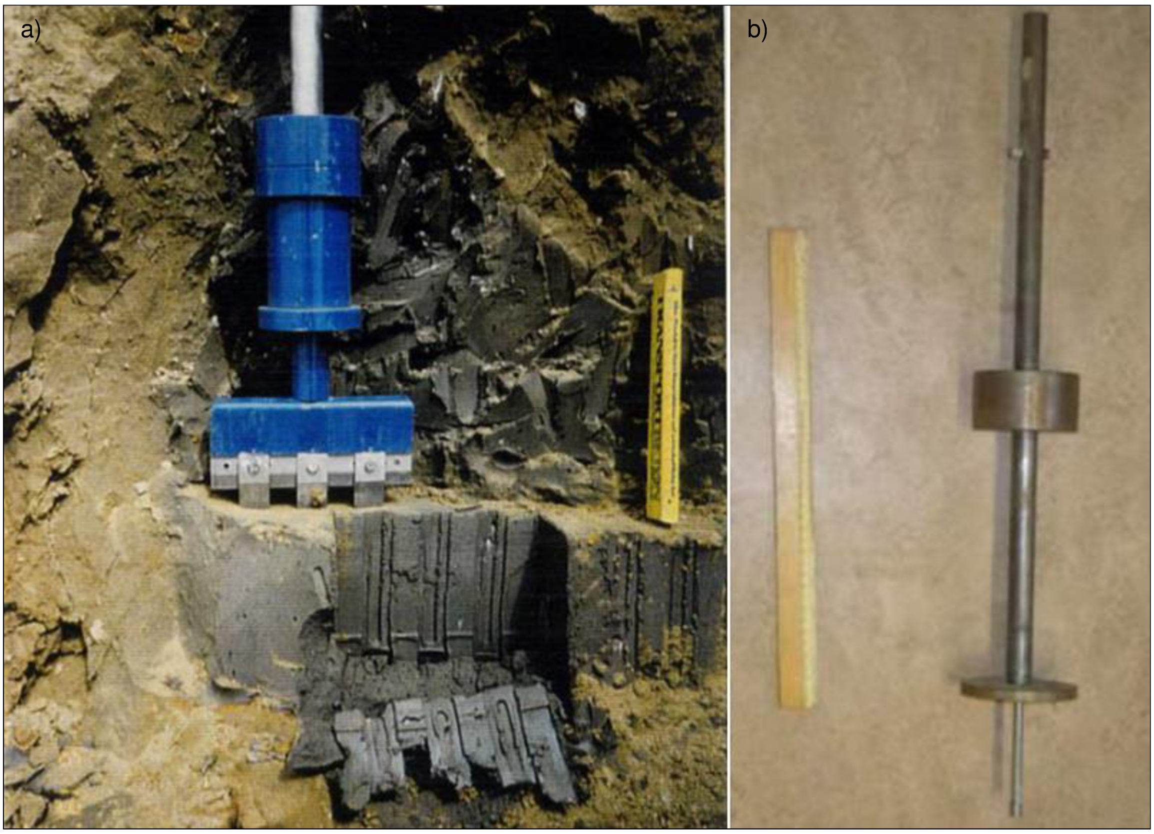


Figure 17: a) Scheffler and b) Dornij testing probe [23]

Scheffler and Jurisch [24] developed preliminary equations ((4) – (7)) using Scheffler probe to calculate specific cutting resistance and required cutting energy of bucket wheel:

$$F'_{Sl,SRs} = \alpha_{SRs/Sonde} \times \overline{n}_S \times 1{,}2 \quad \left[\frac{\text{kN}}{m}\right] \tag{4}$$

$$W'_{S,SRs} = \beta_{SRs/Sonde} \times \overline{n}_S \times 4{,}6 \times 10^{-3} \quad \left[\frac{\text{kWh}}{m^3}\right] \tag{5}$$

$$F'_{SA,SRs} = \beta_{SRs/Sonde} \times \overline{n}_S \times 16 \quad \left[\frac{\text{kN}}{m^2}\right] \tag{6}$$

$$\alpha_{SRs/Sonde}, \beta_{SRs/Sonde} = f(\overline{n}_S) \tag{7}$$

where $\overline{n}_S$ is the average blow count, $F'_{Sl,SRs}$, $F'_{SA,SRs}$ in kN/m^2 are the specific cutting resistances of bucket wheel, $W'_{S,SRs}$ in kWh/m^3 is the cutting energy effort of bucket wheel, and $\alpha_{SRs/Sonde}, \beta_{SRs/Sonde}$ in kN/m and kN/m^2, respectively are the quotients of specific cutting resistance and cutting energy of probe values and bucket wheel values.

3.2 Direct Measurement on Cutting Tool

Wire strain gauges (Figure 18) are mounted on one prepared bucket of the BWE SRs 6300 to directly measure the digging or cutting resistance and to record the data in a storage unit with a sampling rate of 100 Hz [23].

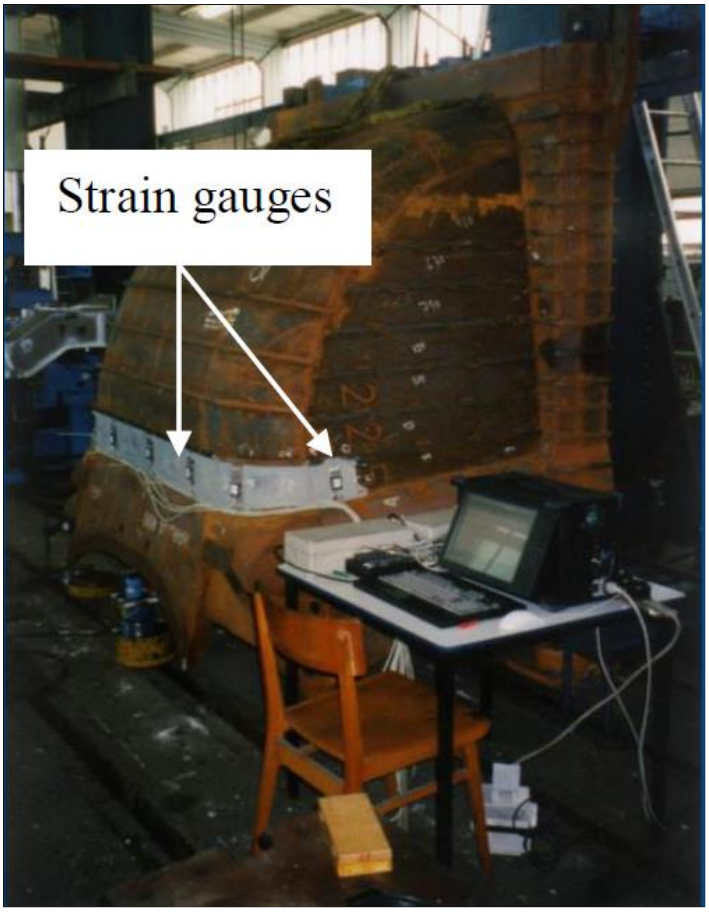


Figure 18: Wire strain gauges on SRs 6300 [23]

The recorded data shows that there is a difference in cutting Pleistocene sand and clay. For clay, cutting resistance instantly jumps to a certain mean value when the cutting process starts.

A variation of cutting resistance values occurred during the slewing process because of the so-called “secondary cut” phenomenon (see Figure 19). This effect can only be observed if the shape of the shovels is rectangular. Investigations show that secondary cutting consumes 10-32 % of the available digging force [44].

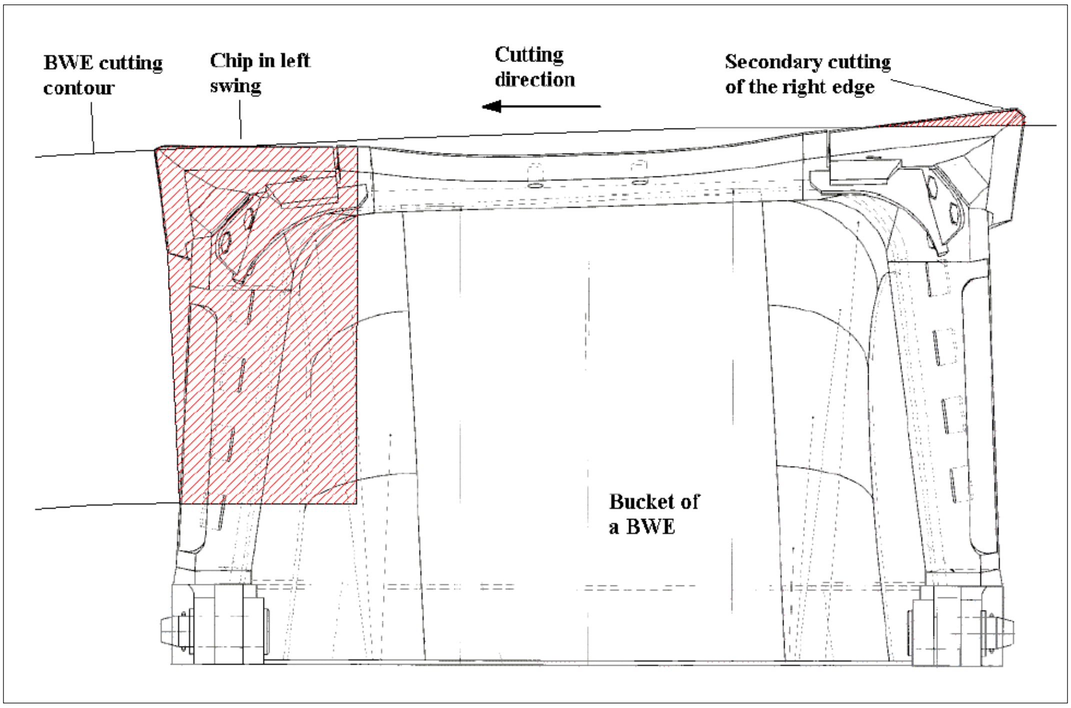


Figure 19: Scheme of secondary cutting process [44]

To conduct measurements on drill cores directly on site, a wedge test was developed by Orenstein & Koppel (O&K) (Figure 20a), where a 65 mm wedge is used. The wedge is connected to a tensiometer, so the cutting force can be determined reading the device [19].

For the study of Inal [45] a wedge test apparatus similar to O&K test was developed at the University of New South Wales (see Figure 20b). 250 mm cube specimens were prepared from the original block.

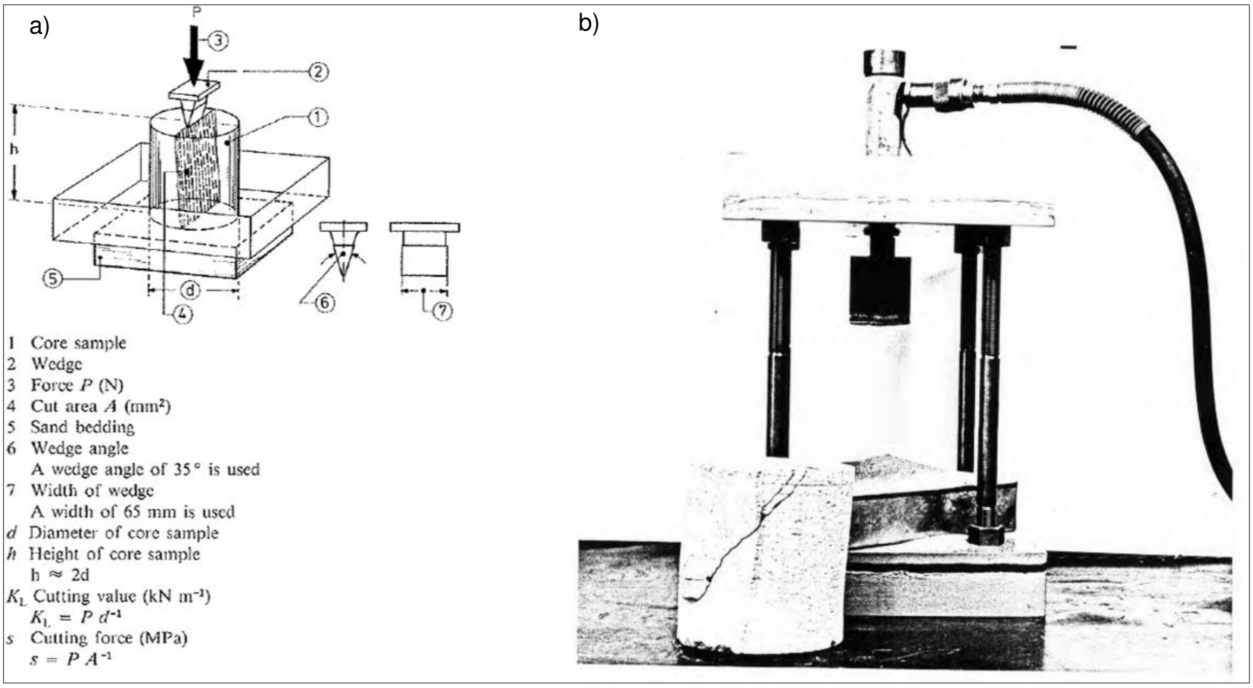


Figure 20: Wedge test apparatus of a) O&K [19] and b) University of New South Wales [45]

Schlecht et al. [46] examined cutting forces of a compact BWE S100 with piezoelectric sensors that are mounted on a prepared measurement tooth on the bucket of the excavator. Various problems occurred during measurement because of an increase in strain during digging, telemetry, reflections of the signals at the face and plugging with lignite between pipework and sensor head [46]. Figure 21 shows the measurement chain for determination of cutting forces.

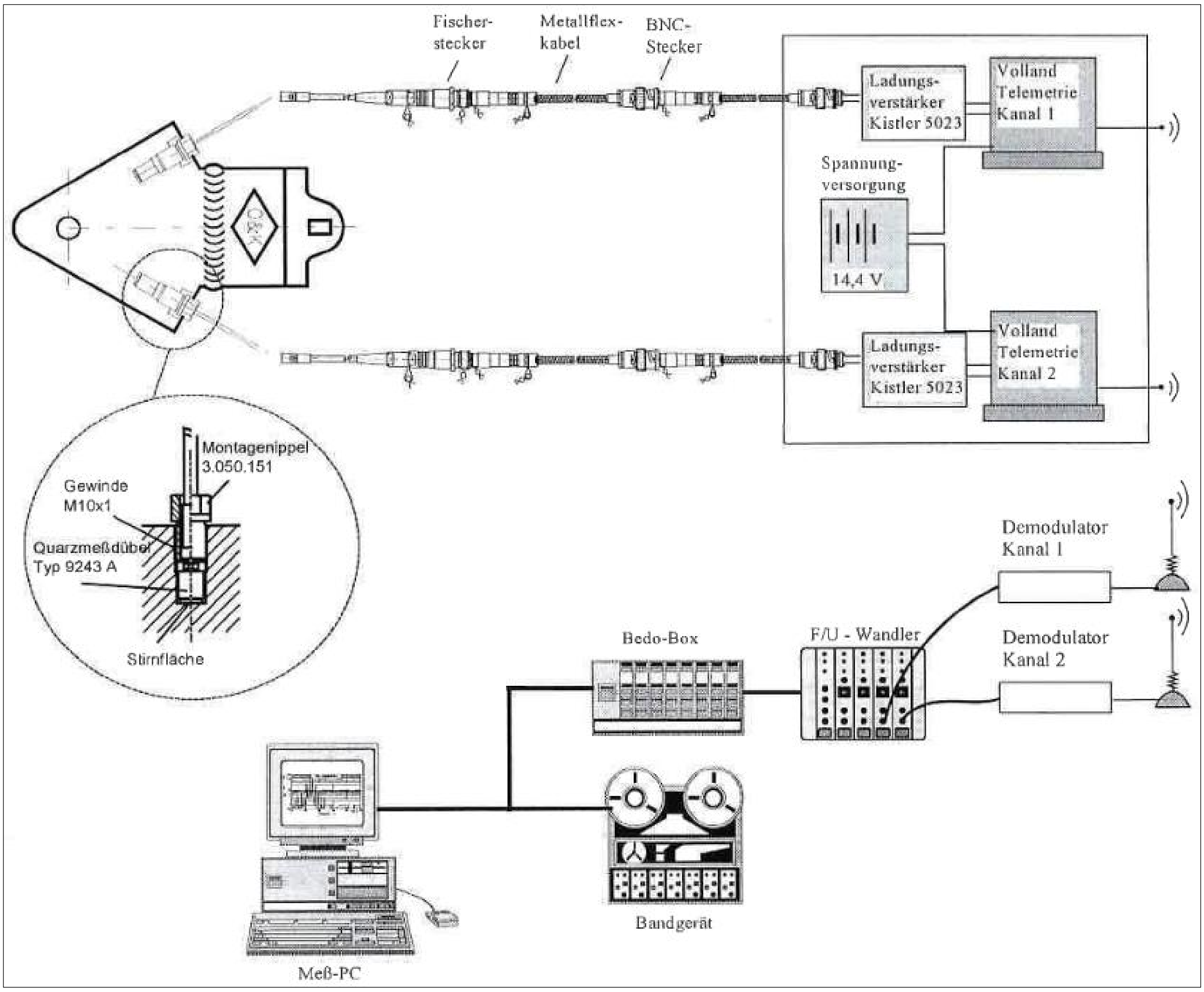


Figure 21: Measurement chain for determination of cutting forces [46]

3.3 Indirect Measurement using driving power

The cutting/digging resistance can be determined indirectly by measuring the bucket wheel's electric driving power or the mechanical driving torque [23]. Saving the data is no problem due to the low data processing effort. In Figure 22 can be seen that driving power has the greatest influence on the effective excavation output. Distinction of generations is made because of the various cutting tools. The capacity test was conducted using optimal chip and block parameters (face height = 7 m, chip depth = 0.8 m) [23].

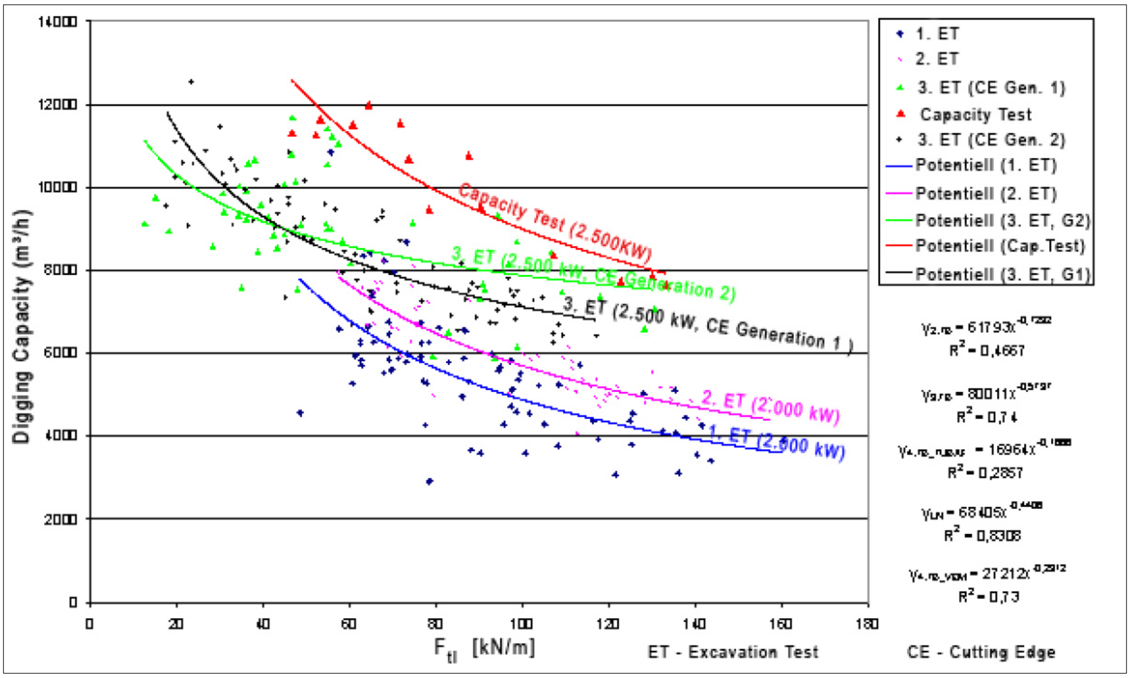


Figure 22: Digging capacity in dependence of linear cutting resistance [23]

4. New Concepts/Tests for Determination of Digging Resistance

A new concept developed at the University of Freiberg should collect geological data and process data in a common data base. The so-called Geo-Technical Data Base (GTDB) (Figure 23) connects the data and uses it for certain data analysis that should improve the information quality (e.g. necessary drive power in a specific geological environment) for a better planning and understanding of the production process [23].

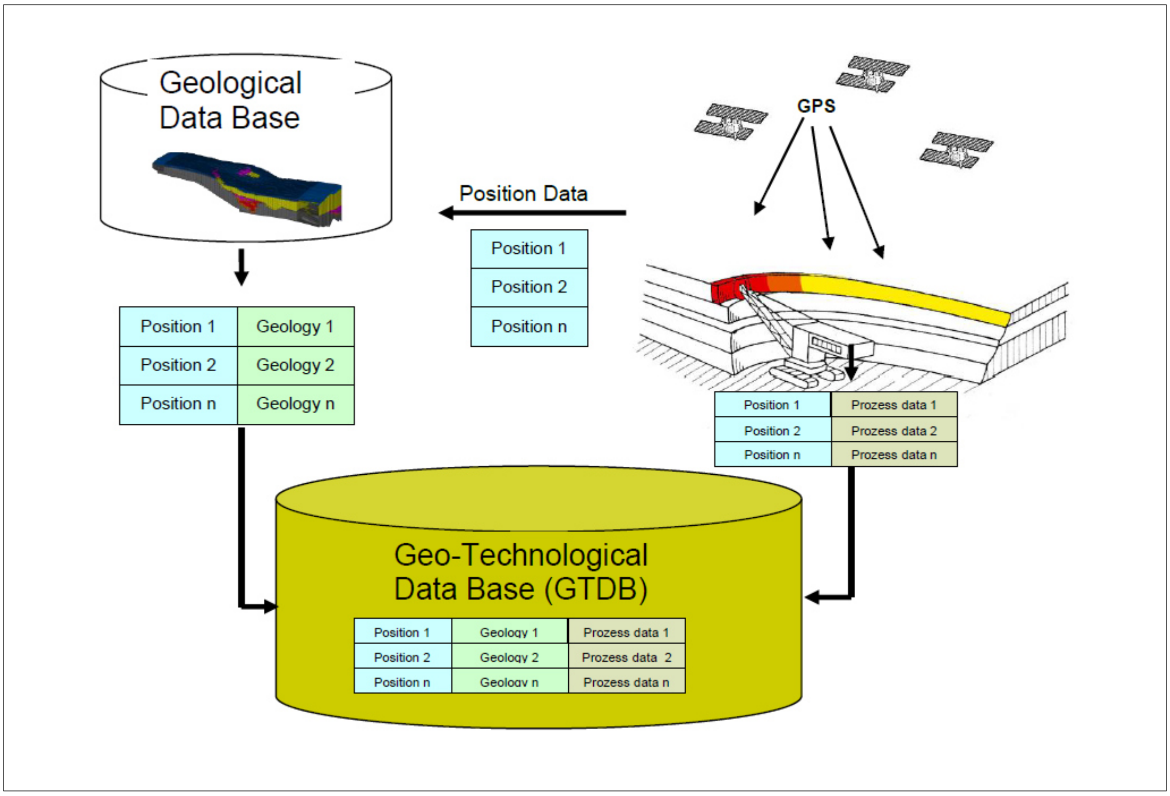


Figure 23: Geo-Technical Data Base process [23]

A "new" mobile and mountable/demountable testing equipment is presented by Yasar and Yilmaz [47] and is called Vertical Rock Cutting Rig (VRCR). It consists of a hydraulic system, a rigid press frame, and the VRCR (see Figure 24). A servo-electromechanical motor that is part of hydraulic system is receiving signals from the load cell. Signals are used to regulate amount of hydraulic oil for movement of the frame piston. During downward movement of the piston, load cell gauges the loads and sends them to the data acquisition system. The frame piston is directly connected with the piston of VRCR and both move simultaneously. Eight clamping screws are available to fix samples with any diameter and block size up to 10 cm x 23 cm x 20 cm. After cutting tool penetrates rock sample, cutting force data is sent to data acquisition system and then to PC [47].

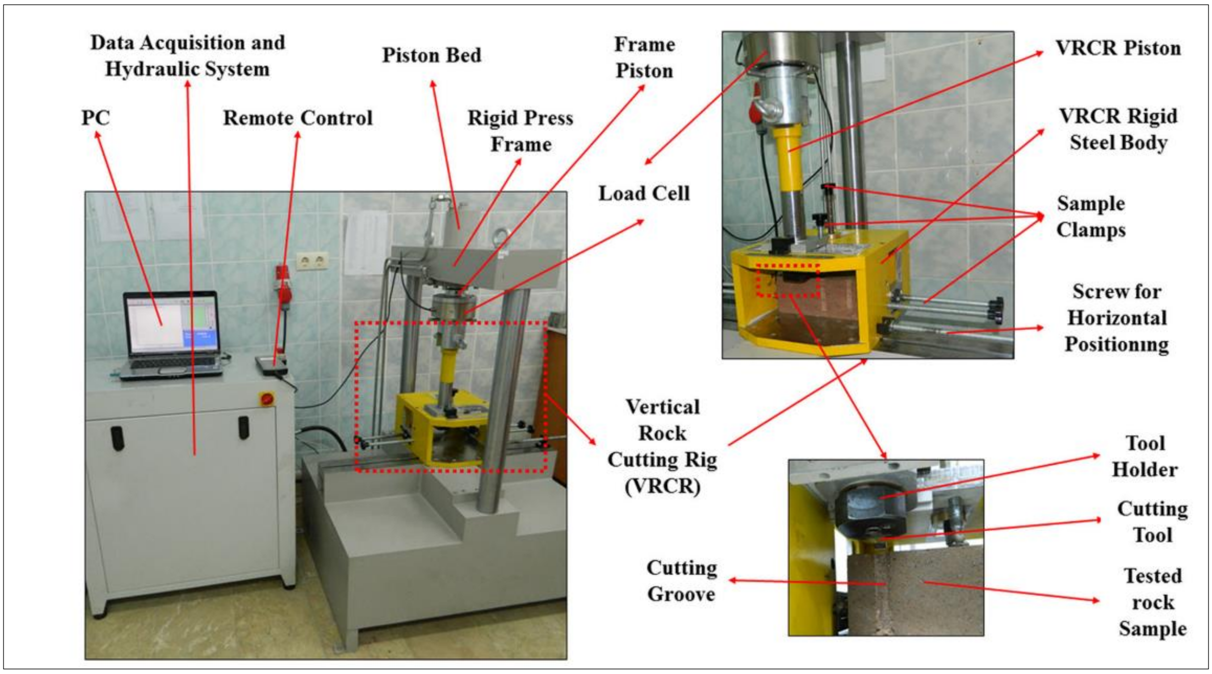


Figure 24: Main components of VRCR testing equipment [47]

Yasar and Yilmaz [47] conducted relieved (interaction between cutting grooves) and unrelieved (no interaction between cutting grooves) rock cutting tests on various lithologies like red andesite (RA), brown vitric tuff (BVT), green tuff (GT1), grey tuff (GT2), and yellow vitric tuff (YVT).

Block sample dimensions of 20 cm x 23 cm x 10 cm and a wedge-shaped cutting tool with a width of 10,8 mm, a rake angle of 12°, and a back-clearance angle of 0° were used. Additionally, UCS was determined. Unrelieved tests were conducted using a cutting depth range from 1 mm to 6 mm and relieved tests were carried out using a fixed cutting depth of 6 mm and various spacing to cutting depth ratios (s/d). Reason for fixed cutting depth was the fact that unrelieved tests showed best results for a cutting depth of 6 mm (see Figure 25) [47].

BVT has the highest compressive strength with a value of 88,15 MPa and as expected the highest resistance against cutting with a cutting tool. YVT (UCS = 62,48 MPa) and GT1 (UCS = 51,65 MPa) have a lower resistance against cutting [47].

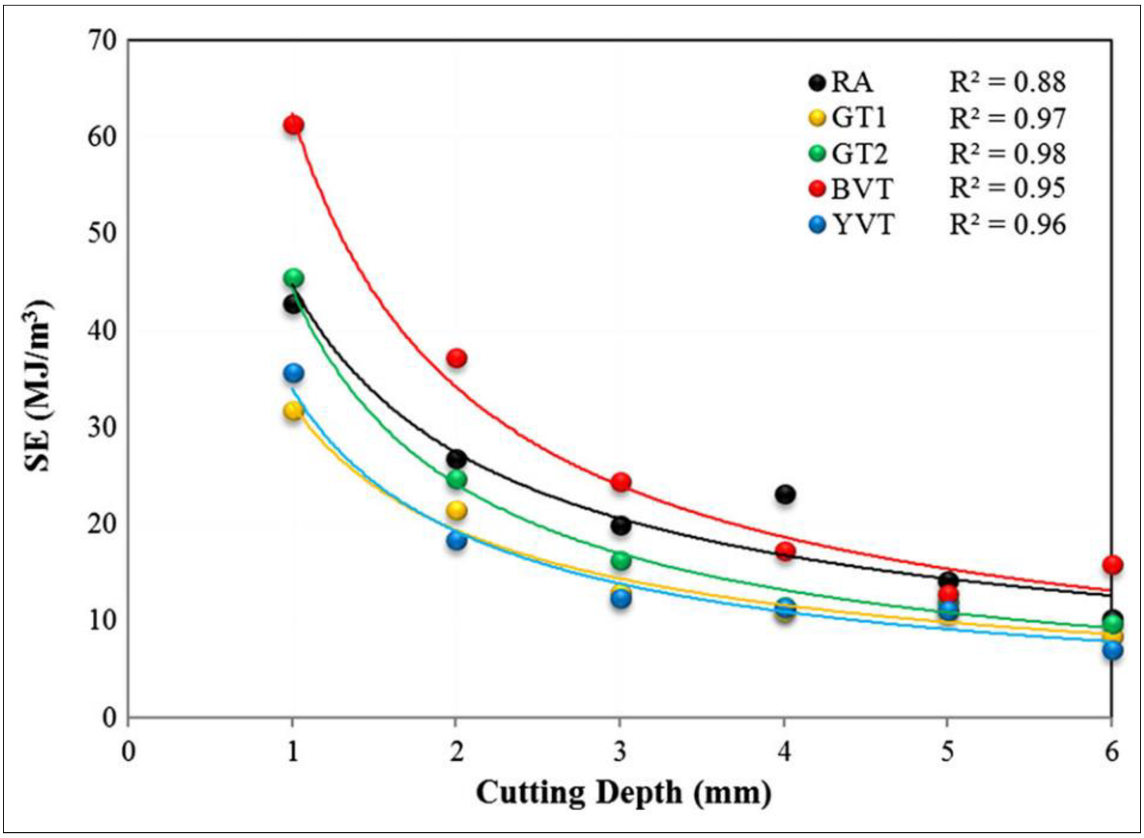


Figure 25: Relation between specific energy (SE) and cutting depth of rock samples for unrelieved rock tests [47]

To conclude, the most effective way is to get a first estimation of cutting strength by using a wedge test or a testing probe. The next step is to collect data of the measured driving power during operation and to connect it with data from geology, so that an overview is created where lithology and power consumption is linked. Additionally, bucket wheel diameter, rotational frequency (transmission), and bucket number must be documented.

4.2 Relation between Cutting Resistance and Rock Properties

The excavation process depends on properties of the rock mass. It would be very helpful to get an understanding of the relation between cutting resistance and mechanical properties of the excavated material. Many literatures only describe the cutting resistance in dependence of the cutting cross section or the mean cutting knife length [19,25].

Protodyakonov [48] presents a relation between strength (f_{pr}) value and UCS (p) of rock (Table 4) whereby UCS is divided by a factor of 10 to get f_{pr}.

Table 4: Relation between strength value and compressive strength [48]

Class	Strength of soil/rock	Type of soil/rock	Strength value f_{pr} (MPa)	Compressive strength p (MPa)
I	high-strength rocks	solid and tough quartz and basalt	20	200
II	very hard rocks	porphyritic quartz, granite	15	150
III	hard rocks	granite, hard sandstone, hard iron ore	10	100
IV	relatively hard rocks	normal sandstone, iron ore	6	60
V	medium hard stone	hard clay slate, soft sandstone and limestone	4	40
VI	relatively soft stone	soft slate, very soft sandstone, chalk, fine sand, anthracite, cemented pebble stones and sand	2	20
VIa	relatively soft stone	gravel soil, broken slate, hard fossil coal, hardened clay	1.5	15
VII	soft stone	hard clay, soft fossil coal, clayey soil, hard brown coal	1.0	10
VIIa	soft stone	gritty clay, coarse clay, loess	0.8	—
VIII	soils	top soil, peat, loam, sand	0.6	—
IX	loose soils	sand, dumped soils, soft brown coal	0.5	—
X	muddy soils	mud, muddy loess	0.3	—

A summary of diggability criteria published by Wade et al. [49] is shown in Table 9 in Annex. These criteria are used as a basis for MONENCO criteria which is represented in Table 10. MONENCO is a modification of Coleman's criteria including sonic travel time [49]. Cutting Resistance was determined using O&K wedge test.

Inal [45] described as a part of his thesis the relation of the compressive strength and peak cutting forces for three block samples (B2, B3, B4) of Goonyella Riverside mine (Figure 26) with a variable cutting depth range from 5 to 15 mm.

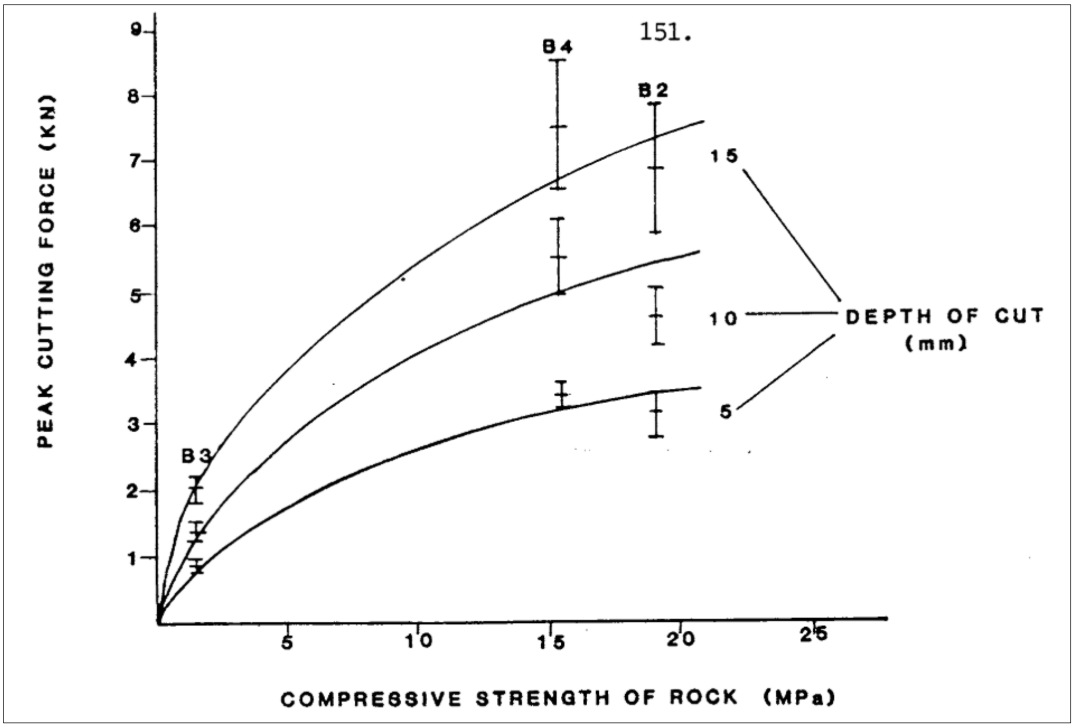


Figure 26: Relation of peak cutting force and UCS of three blocks of Goonyella Riverside Mine [45]

He also measured the compressive strength of Block 1-4 from Goonyella Riverside mine by varying sample dimensions (see Table 5). It can be observed that the compressive strength of the blocks varies between 1,35 and 19,3 MPa. A proper identification of the rock type was not possible for Block 1 and 2. Block 3 and 4 belong to the group of sedimentary rocks whereby Block 3 is called "Yellow Sandstone" and Block 4 is called "Pink Sandstone" [45].

Table 5: UCS for various blocks of Goonyella Riverside Mine [45]

Block No.	Specimen No.	Specimen Dimensions Length mm	Specimen Dimensions Diameter mm	Failure Load kN	Compressive Strength MPa
B1	B1/1	141	57.4	5.47	2.11
	B1/2	140	57.5	6.67	2.57
	B1/3	142	57.4	4.44	1.71
	Mean			5.53	2.13
B2	B2/1	145	57.5	53.8	20.7
	B2/2	143	57.5	46.5	17.9
	Mean			50.2	19.3
B3	B3/1	126	56.7	2.3	0.91
	B3/2	140	56.9	4.3	1.69
	B3/3	130	56.8	3.7	1.46
	Mean			3.4	1.35
B4	B4/1	145	57.5	44.5	17.1
	B4/2	145	57.5	43.5	16.8
	B4/3	146	57.5	35.4	13.6
	Mean			41.1	15.8

Strzodka and Scheffler [50] present a relation of specific cutting resistance and UCS which is shown in equations (8) and (9):

$$F'_{SA} = 100 + 21 * \sigma_D \quad \left[\frac{kN}{m^2}\right] \tag{8}$$

$$F'_{Sl} = 20 + 4{,}7 * \sigma_D \quad \left[\frac{kN}{m}\right] \tag{9}$$

where F'_{SA} in kN/m^2 is the specific cutting resistance related to cross section of slice, F'_{Sl} in kN/m is the linear specific cutting resistance and σ_D (≥ 5 MPa) is the UCS.

The equations (8) and (9) describe an estimation of specific cutting resistance and they are only valid for homogenous soils. Further prognosis must be added for significance [24].

Lazar et al. [51] identified most important physical, mechanical, and technological properties of rocks and their relation to the excavation process. A relevance scale from 0 to 10 (0 = non-relevant, 10 = very relevant) was used to get an overview of the importance of the properties. The evaluation is based on the experience of the research team obtained during studies in open cast mines from Oltenia lignite field. The relation of various properties and cutting resistance can be considered on Table 6-8 in Annex.

4.3 Pre-Cutting and Pre-Blasting

Pre-cutters are spaced between the buckets without pockets (see Figure 27). The influence of pre-cutting on the cutting process is used for hard materials to break smaller pieces out of the rock mass, so that filling of buckets can be achieved. After cutting the material is falling into the pocket and then transported to the discharge area [19].

Today, use of pre-cutters is reduced because additional buckets are mounted on the circumference of the bucket wheel instead [19].

Pre-blasting of material ensures a pre-fragmentation which is preferable for BWEs to extract hard material. Hard interbedded inclusions/boulders have a big influence on the workability of a material that must be excavated e.g. to get access to the coal seam. Blasting of overburden or usage of other machinery (impact rippers, classic excavator) is necessary if the amount of inclusions is large [21].

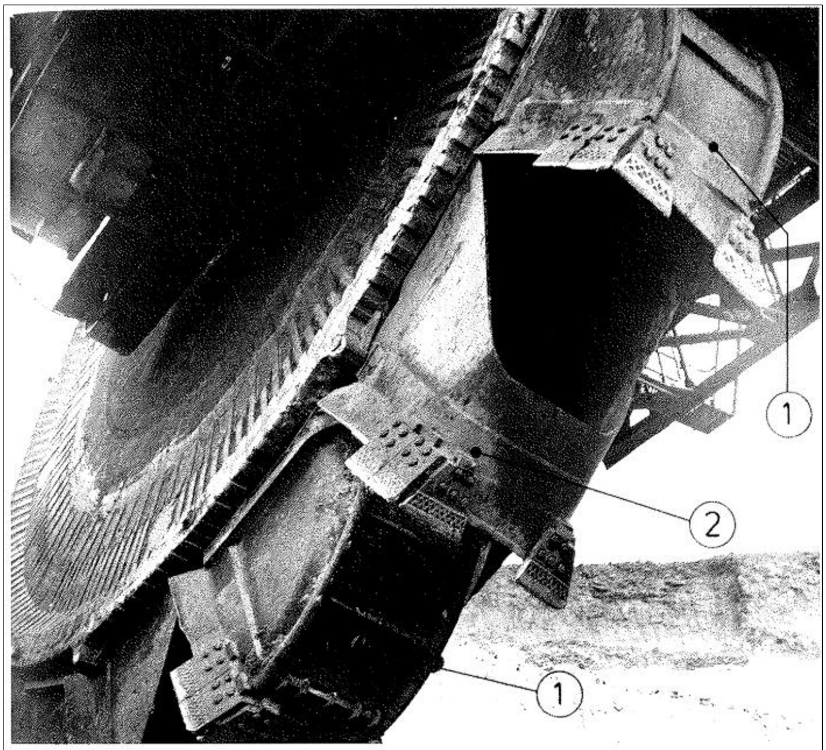


Figure 27: Pre-cutters positioned between buckets with pockets [19]

Andras et al. [22] ascertain that present BWEs can operate in conditions where boulders from 0,5 to 1 m in size with an UCS ranging between 10 and 143 MPa occur. Larger inclusions must be blasted or handled by using other machinery.

5 Waste Removal and Management

5.1 General

Removal of overburden can be done via drill & blast or mechanical excavation to get access to the deposit. The choice depends on the properties of the material that must be excavated. Drill & blast operations are not limited to a specific UCS value. Mechanical excavation of overburden via BWEs and shovels can be applied up to a UCS of 60 MPa (Figure 14) without pre-blasting or pre-cutting. If UCS is higher than 60 MPa, drill & blast operations should be conducted due to great hazards that could damage the equipment. Under certain circumstances, BWEs can also work in harder conditions if inclusions/boulders/layers are pre-blasted or pre-cut (already mentioned in Chapter 3.3).

While excavating overburden with BWEs, dumping is normally done by discharging the material onto a dump using conveyor systems and spreaders which run along the pit wall to the dumping area. Spreaders are mostly mounted on crawler travel gears and they are fed by trains or conveyor systems [19]. To overcome large distances, conveyor bridges can be used additionally.

Direct casting of material using an excavator-spreader system is restricted to certain operating conditions e.g. the limited coal reserves which can be uncovered, stability of the dump slope, and the depth and uniform cover of the overburden [19]. Draglines or shovels can also be used as a method of direct dumping. In this mentioned case, only small strips of ore are uncovered and mined using BWEs or shovels [19].

Mining activities and beneficiation processes are directly related to waste generation and their disposal on Earth's surface or in mine openings. Heaps, dumps or ponds represent the impacts of these actions. Pollution of water and removing of forest land constitute negative influences on the environment [52]. Priority concerning stability problems should be given to dumping of fine materials and deposition of slurries in accumulation areas. These phenomena are in relation with rising pore-water pressure and therefore, wrong estimation of available shear strength [53].

5.2 Stability of Waste Dumps

Waste dump stability is affected by various factors e.g. hydrogeological and rainwater condition of dumping area, geometry and strength of dump material, load bearing capacity of dumping ground, and external loading conditions [54–56]. Rise of pore-water pressure deteriorates shear strength of dump material. Trigger factors are e.g. heavy to moderate rainfall periods whereby infiltration of water into slope forming material occurs [57].

Zovodni et al. [58] recommended the implementation of grain size analyses and Atterberg limits, direct shear test for soil and critical rock discontinuities (undrained conditions), triaxial test for soil (consolidated and unconsolidated undrained conditions), hydraulic conductivity on undisturbed foundation samples, and determination of density and moisture content, consolidation, attenuation and water quality. Knowledge of regional tectonics is also very important due to stability of waste dumps.

A shallow, large radius surface extending from a tension crack to the toe of the slope is likely formed because of failure in dump materials [59].

5.3 Dump Foundation Properties

Foundation stability and bearing capacity is assessed using shear and compressive strength characteristics [60]. If foundation consists of competent soil strata (e.g. over consolidated, hard glacial till, dense colluvium, dense sand and gravel), conservative estimates of shear strength in relation with soil classifications, in situ strength index testing (e.g. pocket penetrometer, hand-held vane shear), and index properties can be applied. To determine effective strength parameters, natural slope or former foundation failures should be recalculated [60–62]. If conditions are more complex (e.g. soils in foundation are fine grained or vulnerable to consolidation, occurrence of pore pressure) additional field and laboratory testing must be conducted.

Presence of fine-grained soils in foundation must be handled with care. As a result, unconfined and triaxial compression tests, and direct shear tests need to be conducted on undisturbed samples e.g. shelby tube, piston samples, block samples [60]. Pore pressures, loading rates, strain rates, pre-consolidation pressures, and confining stresses must be controlled during erection of the dump subsequently [60].

Mixed grained or coarse-grained soils, softened glacial tills with a considerable amount of gravels, and cobbles/boulders are difficult to sample in an undisturbed state. In such a case, penetrometer or vane shear testing provides most reliable strength information [60].

The occurrence of discontinuities has an essential influence on stability of foundation bedrock. First estimations are done using empirical relations or simple hardness tests. Point Load Index testing of core samples would be conducted if more detailed rock strength information is required [60].

Shear strength characteristics and bearing capacity of bedrock foundation can deteriorate with time because of degradation. Early investigations of weathered outcrops, swelling or degradation of exploration drill cores give an indication [60].

Further examination and testing methods, properties of rock and influencing factors are described in [60] and important Tables (Table 11 and Table 12) introduce these factors and describe testing procedure. Table 11 and Table 12 should work as evaluation basis for given conditions.

Poulsen et al. [63] found out that residual friction angle of the basis material plays an important role for dump stability. The occurrence of clay rich soils in the basis of dumps can lead to mobilization of both the dump and the foundation. Driving factor is a change in shear strength due to operational induced strains and/or presence of water [63].

There are different ways to sort out problems that occur if foundation consists of softer materials such as normally consolidated clays [53]:

- Reduction of dump slope inclination to coordinate with the initial undrained strength of foundation material
- Disposal of low strength material prior to dumping

Example – Polish Copper Industry

Kudelko [52] presented and evaluated four effectiveness models of waste management of copper industry. The amount of waste that is generated during refinement can be calculated by using the formula [52]:

$$\gamma_o = \frac{\beta - \alpha}{\beta - \vartheta} \times 100\ \% \quad [\%] \tag{10}$$

where γ_o is the waste yield in %, β is the content of useful component in the concentrate in %, α is the content of useful component in the feed in %, and ϑ is the content of useful component in the waste in %.

Mineral waste can be often managed by [52]:

- Reprocessing to recover valuable components
- Using as hydraulic fill in mine openings or manufacturing of new products
- Utilization of other processes

If the waste is used to recover valuable components, the waste volume is not reduced significantly. The use of other processes is influenced by the fact that no damage to the environment should occur during these processes. Different damage estimation methods like restitution, substitution, and index methods can be distinguished [52].

5.4 Design and Construction of Dump

Basis for rational design of waste dumps and stockpiles is a proper examination of intertwined factors that may change during lifetime of mine.

First, selection of site for the facility must be done whereby key selection factors as regulatory and social factors, fill material quality, terrain and geology, mining, environmental factors, geotechnical components, and closure must be taken into account [64].

Hawley and Cunning [64] described procedure of dump construction as follows:

1. Initial site identification
2. Conceptual design
3. Pre-feasibility design
4. Feasibility design
5. Detailed design and construction
6. Operation
7. Closure

1. Initial site identification

After elaborating key selection factors, potential sites must be identified in an early project phase. This stage consists of study of available remote imagery (air photos, satellite images), regional geology plans and reports, topographic plans, regional environmental and socioeconomic studies, and other available reports and supporting data. It is very important to get a knowledge of the existence of nearby and historical operations. Above mentioned information should be discussed within the project development team to cover all partial aspects. Occurrence of multiple potential sites leads to a weighting-based ranking.

2. Conceptual design

After identification of conceivable sites, conceptual designs are developed for each site. Part of this stage are site preparation requirements, access routes, equipment options, construction alternatives, and initiation of baseline environmental studies.

3. Pre-feasibility design

Pre-feasibility design stage involves comprehensive field investigations and laboratory testing programs. Depending on strategies of mine proponent, an accuracy of ± 25 - 35 % of OPEX and CAPEX estimates can be reached in pre-feasibility study.

To identify foundation conditions and to get samples for laboratory testing, surface mapping, trenching, test pitting, and drilling is conducted. Physical and chemical properties of fill materials for waste dumps and stockpiles should be determined conducting preliminary laboratory characterization. This information is then used to improve the conceptual constituent models.

Based on updated models and input from mine planer's conceptual designs and the ARD management, water management and closure plans should be elaborated.

Cycle has to be repeated until consistent design is the result.

4. Feasibility design

Feasibility design stage should start with a detailed gap analysis to identify lacks in supporting data. Based on gap analysis results, further field and laboratory investigations, materials testing and characterization, site-specific and value-specific environmental and permitting studies, and supplemental condemnation drilling may be required.

CAPEX and OPEX estimates conducted at this stage provide usually an accuracy of ± 15 – 20 % in dependence on the policies of the mine proponent.

Outlines should consider sequence of waste dump development as provided in life-of-mine mine plans.

Various constituent models and site selection rankings should be updated on basis of newest understandings. It is also important to update preliminary stability classifications and rankings and to conduct preliminary risk assessments. Results of these analyses should serve in connection with updated CAPEX and OPEX estimates to approve feasibility, support final site selection, and develop feasibility-level design parameters.

Cycle may be repeated if parameters are incompatible with the mine plan.

5. Detailed design and construction

Supplemental site investigations, bulk sampling and materials testing to specify constituent models, water management and closure plans, enhance and update ARD management, and support detailed analyses are demanded for detailed design.

Detailed stability analysis could consist of numerical runout modelling, supplemental parametric/sensitivity analyses, detailed stability analyses by year or phase, deformation and dynamic response modelling, and quantitative risk assessment. Outcomes of these analyses in connection with input from mine planers are used to optimize the design. Short-term and medium-term (up to 5 years) detailed mine plans and key long-range waste dump and stockpile configuration should be the target of analyses.

Preliminary operational guidelines, monitoring procedures, and response plans development are part of development during this stage.

Another part of this stage consists of site preparation activities e.g. stripping and contouring of foundation, installation of foundation instrumentation, construction of diversions and underdrainage systems (if required), and development of access routes.

6. Operation

Operation stage is composed of ongoing monitoring of foundation preparation and material placement to be in accordance with design criteria. Additionally, site investigations, field trials and material testing to verify design assumptions, and deformation and performance monitoring should be conducted.

Water management, closure plans, and regular updating of ARD management is necessary. Operating and monitoring guidelines may need adaption due to performance documentation.

7. Closure

Closure plan for the facility must be finished and implemented if section of waste dumps is completed. Further monitoring of performance and deformation is necessary.

Various parameters that influence the process of dump design and construction need to be considered to ensure stability and safety of the operation.

The following described parameters influence the dumping process. They are part of British Columbia Mine Dump Committee guidelines [60]:

- **Preparation**

Poor foundations must be prepared (e.g. clearing, stripping or removal of poor or weak soils, installation of specific underdrainage measures and preloading of site) to ensure that in-situ conditions meet analysis and design assumptions.

- **Clearing**

Clearing of vegetation and organic overburden is required if dump foundation will be used to convey water.

- **Surface Water**

Surface water can lead to surface erosion or development of flow failures on dump surfaces. One solution is conducted through diversions which are feasible for sidehill and heaped dumps. Sidehill diversions need maintenance on regular basis during and after dump completion.

- **Material distribution and crest advancement**

Objectives are to identify the number of dumping sectors that can be activated and to maximize the length of dump crest in each area. Division into various dumping sectors prevents the spreading of a failure.

- **Topography**

Maximum advantage of topography should be taken during construction of dump. Figure 28 shows the optimum dumping sequence for steeply inclined terrain.

Dumping over steeply inclined slopes should be initiated using a gully as filling area. Advance of dumping must follow the axis of gully to prevent steep gully slopes. This results in a three-dimensional confinement of dumped material.

The dumping advance should be perpendicular to the contour until flatter topography is reached. Further extending of the dump follows the contour.

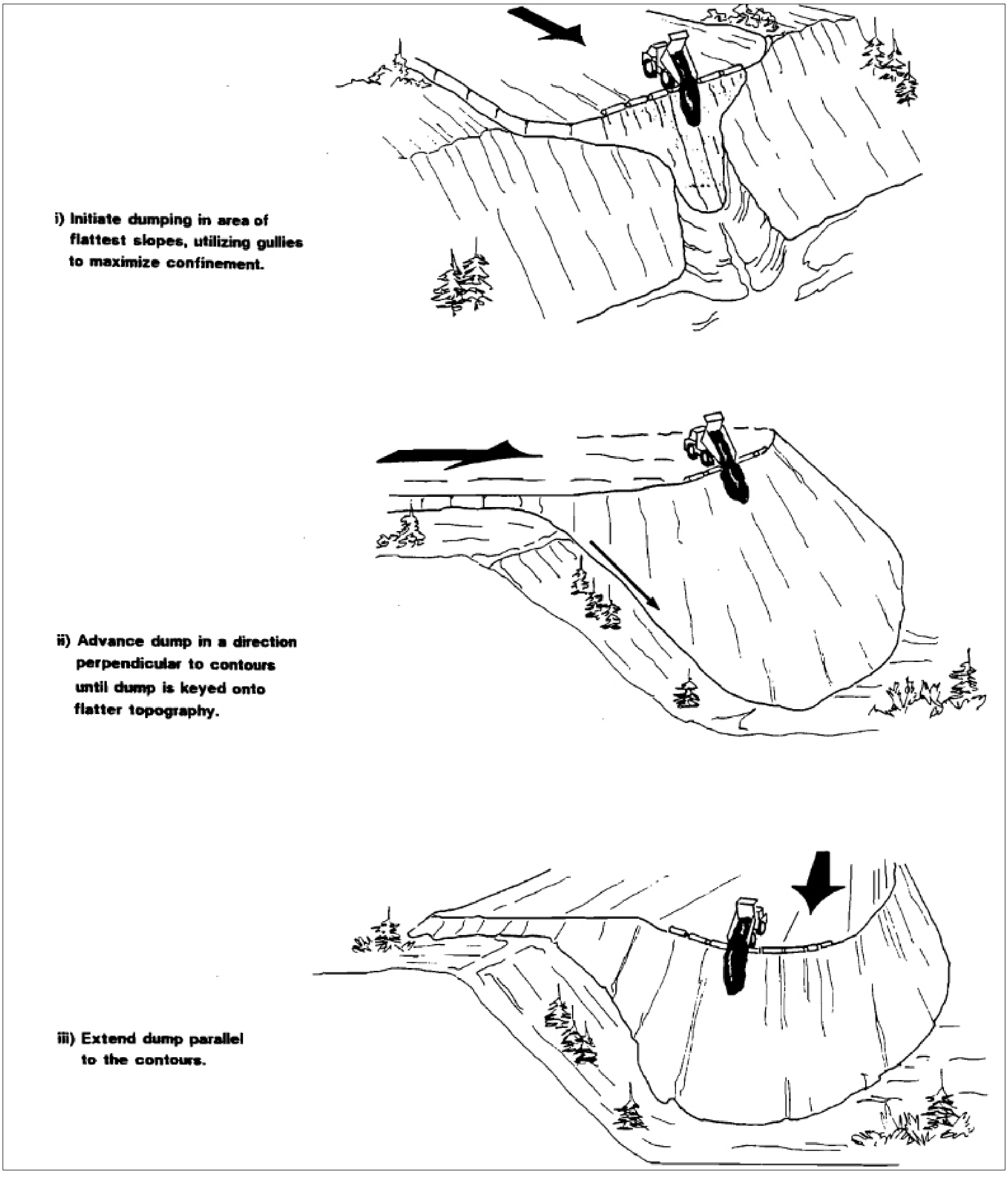


Figure 28: Steep terrain dumping sequence suggestion [60]

- **Snow**

During late spring and summer, failures occur due to residual snow and ice concentrations from winter in combination with fine dump materials. The combination of rapid melting and occurrence of a continuous layer could form a zone of weakness. Furthermore, pore pressure can exceed critical values and can’t be relieved in fine materials.

- **Buttress or Impact Berms**

Buttresses or Impact Berms are erected where dump construction is prohibited or restricted or where runout problems are associated with small slides and flows. To resist boulders and slides, impact berms should be constructed downslope of the final toe on flatter topography (see Figure 29). Leonardos [53] described that the only effective method for stabilization of waste dump in PPC south field lignite mine was construction of stabilizing berms (40 m high) with high friction angle material (mainly conglomerates) at the foot of the slope.

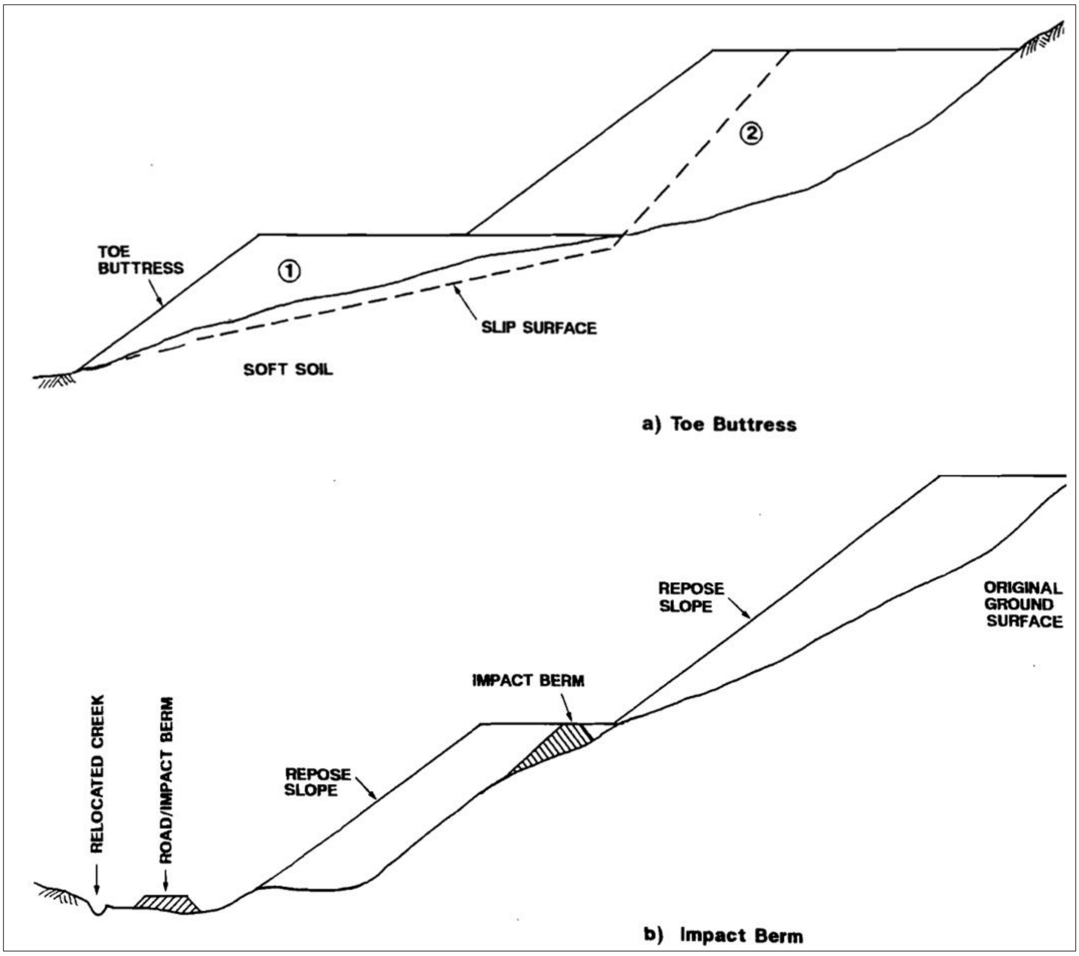


Figure 29: a) Toe buttress design and b) Impact berm design for improvement of dump stability [60]

- **Material quality**

Critical parts must be covered with high quality material e.g. for steeply sloping terrain only coarse, durable rockfill. Fine grained material can be used for upper parts of dump where no runoff flows occur. Creation of only thin lifts and compaction of material with haul trucks are necessary steps to improve stability and strength of fines. If dumping of degradable fill can't be prevented, material should be mixed with as much high quality (coarse) material as possible.

Handling of poor-quality dump material could also be ensured by creating cells within the dump. Erection should be chosen, so that no potential failure zones are generated.

Though base of the dump in PPC south field mine consisted of high strength conglomerates, poor quality material which was directly dumped above the base supported generation of slip surface [53].

- **Trial Dumping**

Trial dumping is useful if dump stability cannot be predicted properly e.g. if a probability of rising pore pressure occurs in soft foundations, pore pressure sensors should be installed so that a pore pressure model can be generated. Construction of trial dump must be done stepwise to ensure development of pore pressure trends for model development.

- **Reclamation design**

Seepage water quality is directly connected with metal contamination or acid rock drainage. Measures are encapsulation of potential contaminants within other neutralizing materials or creation of low permeable covers. The best way is to start treating the source (seepage). Land use and reclamation planning should be done at project start.

5.5 Stability Problems during Spreader Operations

Problems occur during dumping of fine materials or mixtures with a significant portion of fines because everyone tries to dump as high as possible in the mining industry. In Figure 30 is shown the critical height (H2) for dump construction. Material begins to flow at the toe (tongues) while top settles after exceeding H2 height. To work against this level drop, material is permanently dumped at the same point. A stable curved slope will be formed in contrast to the rectilinear slope (up to height H2) if moving dump toe shows a reaction (see Figure 30). Causes are higher pore water pressure at dump base and shear induced pore water pressure [53].

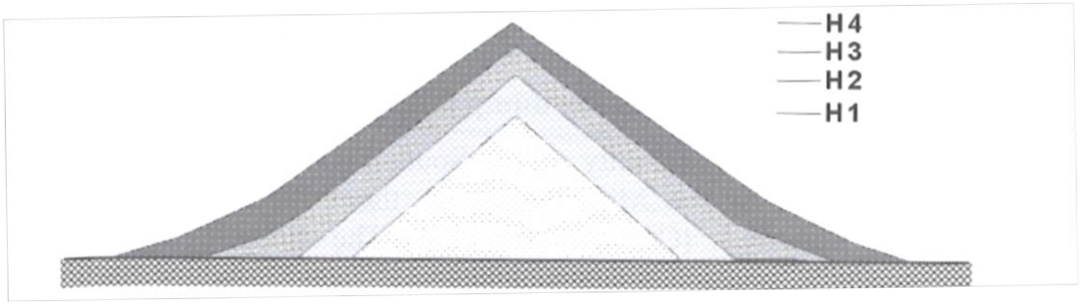


Figure 30: Critical height H2 of dumping [53]

This dumping operation (with tongues) causes further stability problems due to dumping additional material on fluidized material at the base [53].

To prevent this operation process, different solutions can be applied [53]:

- Dump height reduction to critical height (figured out by on-site testing)
- Building of dikes parallel to the dumping face at intervals to reduce the dump height to the critical height
- Regular moving of dumping point for decrease of water over pressure if dumping face is long enough. After relief of water over pressure, dumping of additional material is possible
- Utilization of geogrids for reinforcement of slope [65]

6 Risk Analysis

Open-pit mining operations harbor risks which can lead to project disturbances, operation standstill, injury to personnel, damage to equipment, or negative impacts on the environment.

Table 14 represented in Annex gives an overview of the most important risks in open-pit mining, their cause, preventative controls, impacts and mitigation controls.

The risk analysis should help to implement a sufficient mine design and a sufficient operating machinery, adherence of safety standards, and minimization of environmental impacts.

Risks were identified through a workshop together with Dr. Sifferlinger, literature research [66,67], and brainstorming.

7 Conclusion

Selection of crusher system depends on mine plan (sequence, design, system) and material properties of rock mass (density, moisture content, hardness, stickiness, abrasiveness). Relocation of systems is related to high effort and loss of money because of production standstill. Therefore, location of crusher in an open-pit mine must be chosen in such a way that relocation times are minimized and distance to working faces during pushback is optimized. The amount of material that must be removed prior to mining is also an important factor in respect of costs and development time. Creation of a tunnel for conveyor belt haulage reduces the amount of material that must be removed prior to mining but is associated with great cost.

Evaluation of BWE is usually based on cutting resistance and UCS of rock mass. Cutting resistance is very hard to determine sufficiently with field measurements. Wedge tests and Scheffler probe can be used as a first indication for the cutting resistance but should not be seen as an irrevocable value. It is very important to look at mines with similar geological conditions to get an idea of the applied machinery. This understanding should be implemented together with data collection of measured driving power during operation and with data from geology, so that an overview is created where lithology and power consumption is linked. Additionally, bucket wheel diameter, rotational frequency (transmission), and bucket number must be documented. The result is an overview of lithologies and associated machinery parameters for certain exploitation positions.

Accurate exploration in difficult areas is not only important for determination of the size and the shape of the deposit. It can show the occurrence of hard/competent layers/boulders/formations early, so that pre-splitting or pre-blasting can be implemented prior to getting in contact with the BWE.

Due to increasing amount of waste in open-pit mining, large areas on the surface must be used for dumping. Underground mines quite often use mine waste as backfill for underground openings. Such mines could be potential customers in terms of waste disposal. This solution could help to reduce needed area for waste dumping, to reduce the environmental impact, and to reduce the visibility of mining operations.

Before dumping of waste piles has started, construction of a proper dump foundation is crucial. Occurrence of fine-grained material and geological disturbances in the foundation must be handled with care. If the amount of fine material exceeds a certain value, it will get more difficult to dump properly. The objective is to dump only until reaching a maximum height of the pile and to move parallel to dumping face during dumping due to water over pressure decrease.

Dump construction consists of certain steps which become more and more detailed. Involved are financial calculations, site testing methods, monitoring measures, modelling, site selection rankings, emergency response plans, and field trials. Monitoring of waste dumps is necessary to observe slope conditions e.g. movement of dump parts. Additionally, investigation of weathered outcrops and indicators in drill cores can help to get early information due to condition of dump stability.

Mining is a sector of the industry which harbors several risks that can cause severe damage to both machinery and work force. Main reason is the huge amount of energy that is present within the system. The objective is to recognize risks in terms of operation, safety, geology, environment, finance, maintenance, repair, reliability, offer, and availability and to use preventative and mitigative controls to eliminate/reduce risks.

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11 List of Abbreviations

ASchG	ArbeitnehmerInnenschutzgesetz
BauV	Bauarbeiterschutzverordnung
BIF	Banded Iron Formation
BWE	Bucket Wheel Excavator
CAPEX	Capital Expenditure
CO	Carbon Monoxide
co	Coal
CO_2	Carbon Dioxide
COMEX	New York Commodities Exchange
FOPS	Falling Object Protection Structure
FSG	Führerscheingesetz
GGBG	Gefahrengutbeförderungsgesetz
GGBV	Gefahrengutbeförderungsverordnung
IPCC	In-Pit Crushing and Conveying
KFG	Kraftfahrgesetz
LME	London Metal Exchange
MSV	Maschinen-Sicherheitsverordnung
NO_x	Nitrogen Oxide
NYMEX	New York Mercantile Exchange
O&K	Orenstein & Koppel
OPEX	Operational Expenditure
ov	Overburden
PGM	Platinum Group Metals
Qtz	Quartz

RCD	Residual Current Operated Device
ROPS	Roll Over Protective Structure
SPSM	Site Power Supply Manifold
StVO	Straßenverkehrsordnung
TAV	Tagbauarbeitenverordnung
UCS	Uniaxial Compressive Strength
VRCR	Vertical Rock Cutting Rig

Annex

Table 6: Physical properties of rocks [51]

No.	Property	Symbol	MU	Relevance for cutting resistance
1	Mineralogical composition	-	-	5
2	Structure	-	-	5
3	Texture	-	-	5
4	Color	-	-	0
5	Reflectance	-	-	0
6	Grain size distribution	-	-	3
7	Specific gravity	G	kN/m^3	4
8	Unit weight	γ	kN/m^3	4
9	Density	ρ	kg/m^3	4
10	Porosity	n	%	4
11	Void ratio (pore index)	e		4
12	Moisture content	W	%	3
13	Consistency	-	-	3
14	Plasticity	-	-	6
15	Degree of saturation	S	%	2
16	Permeability	k	cm/s; m/d	2
17	Anisotropy	-	-	8
18	Fracturing degree	IQ	%	7

Table 7: Mechanical properties of rocks [51]

No.	Property	Symbol	MU	Relevance for cutting resistance
1	Compressive strength	σ_{rc}	kPa	7
2	Tensile strength	σ_{rt}	kPa	7
3	Shear strength	τ	kPa	7
4	Angle of internal friction	φ	degrees	6
5	Cohesion	c	kPa	6
6	Compressibility (Compression Index)	C_c	1/kPa	5
7	Compaction	-	-	5
8	Consolidation	c_v	cm^2/s	6
9	Cutting resistance	Kl; Kf; A	$kN/m;kN/m^2;kN/m$	10

Table 8: Elastic properties of rocks [51]

No.	Property	Symbol	MU	Relevance for cutting resistance
1	Young's modulus	E	MPa	6
2	Poisson's ratio	ν	-	3

Table 9: Overview of diggability criteria and remarks for Highvale Mine, Alberta [49]

Source	Parameters Required	Criteria Summery	Remarks
CANMET [68]	Specific Cutting Resistance, F_a	$F_a < 1$ MPa – diggable 1 MPa $< F_a <$ 2.4 MPa – difficult to dig $F_a >$ 2.4 MPa – not able to dig	Developed for various geological formations; Applicable to Highvale conditions
Coleman [69]	Fracture spacing, Point Load Index	Graphs of rock fracture classification vs. rock strength classification showing zones of easy to difficult diggability	Developed primarily for coal mining operations; Applicable to Highvale conditions
Gorylewicz [70]	Uniaxial Compressive Strength, Q_u	$Q_u <$ 45 MPa – diggable $Q_u >$ 45 MPa – not able to dig	Developed primarily for sulphur mining operations; Considered applicable to Highvale conditions
Kozlowski [71]	Nominal Digging Resistance [R_a]; Clay fraction; Moisture content	$R_a <$ 360 kPa – diggable 360 kPa $< R_a <$ 900 kPa – difficult to dig $R_a >$ 900 kPa – diggable only with special equipment	Developed for BWE operation in coal; No applicable Highvale data since R_a is obtained from field test with BWE
Krzanowski [72]	Specific Cutting Resistance [F_a]; Point Load Index [$I_s(50)$]	$F_a <$ 900 kPa & $I_s(50) < 0.7$ – diggable $F_a >$ 900 kPa & $I_s(50) > 0.7$ – difficult to dig	Criteria developed by relating geotechnical parameters to diggability; Applicable to Highvale conditions
Strzodka [73,74]	$f_p = \frac{Uniaxial\ Compressive\ Strength\ [Mpa]}{10}$	$f_p < 1.5$ – diggable $1.5 < f_p < 2.0$ – difficult to dig	Applicable to Highvale conditions

Table 10: Overview of diggability criteria and remarks for Highvale Mine, Alberta (continuation) [49]

MONENCO diggability criteria [49]						
MONENCO Class	**Diggability Rating**	**Range of Sonic Travel Time [µs/m]**	**Range of Q_u [MPa]**	**Maximum Thickness without Blasting [m]**	**Range of Cutting Resistance F_a* [MPa]**	**Range of Cutting Resistance Encountered by BWE** [MPa]**
1	Easy diggable	> 500	< 2	No limit	< 0,15	< 0,17
2	Diggable	420 – 500	2 – 10	2	0,15 – 0,4	0,17 – 0,36
3	Difficult to dig without blasting	340 – 420	10 – 20	0,5	0,4 – 1,25	0,36 – 0,54
4	Diggable only with light/medium blasting	260 – 340	20 – 30	< 0,5	1,25 – 5,25	0,54 – 0,8
5	Fragmentation blasting required to be diggable	< 260	>30	0	> 5,25	> 0,8
* Data from O&K wedge tests ** Data from field measurements by Kozlowski [71]						

Table 11: Material properties and testing for foundation soils [60]

MATERIAL PROPERTIES	APPLICATION	IN SITU / FIELD TESTING	LABORATORY TESTING	REFERENCES
DESCRIPTION -Colour -Odour -Texture -Fabric, structure	-Soils mapping, classification, interpretation -Identification of problem soils -Weathering characteristics -Important structures, fabric -Various empirical correlations -Grouping samples for testing	-Field description (1)	-Microscopic examination (20)	-Martin (1991): 6,11,18 -BCAMD Task Force (1990): 32-34 -OSM (1989): 4,6,10,12,16,18, 19,21-30,32-35 -CGS (1985): 1-6,10,12,16,17 -Craig (1985): 1-6,8,12,14,16, 17,21-30,35 -USBM (1982): 6,10,12,26,27,29, 30,35 -Zavodni et al (1981): 7 -Freeze & Cherry (1979): 6-8, 26,33,34 -Hurlbut & Klein (1977): 20,31 -Kerr (1977): 20 -MESA (1975): 2,3,6,21-24, 26-29,35 -Peck et al (1974): 1-5,10,12, 16,18, 21-30,35 -Dept. of the Navy (1971): 1-3,5, 9,10,12,18,21-27 -Terzaghi & Peck (1967): 1,2,5,8, 9,10,12,14,16,18,21-30,35 -Lambe (1951): 21-30,35
INDEX PROPERTIES -Gradation -Plasticity -Moisture content -Unit weight -Specific gravity	-Classification -Empirical correlations with permeability, strength, consolidation -Volume/weight relationships	-Visual estimation of gradation (2) -Estimation of plasticity via dilatancy, toughness, dry strength (3) -In situ density/moisture testing (4) -Preliminary classification (5)	-Sieve (21) -Hydrometer (22) -Atterberg Limits (23) -Various direct and indirect methods of measuring volume/ weight parameters (24) -Lab classification (25)	
HYDRAULIC CONDUCTIVITY	-Estimation of seepage, drainage quantities -Prediction of piezometric conditions -Assessment of effectiveness of soils as natural liner	-Piezometer and borehole testing (6) -Infiltration testing (7) -Pumping tests (8)	-Permeameter (26)	
CONSOLIDATION	-Pore pressure dissipation -Settlement	-Survey monuments, settlement plates and piezometers in conjunction with test fill (9)	-Consolidation (27)	
STRENGTH	-Foundation stability -Bearing capacity -Strain to failure	-Empirical correlations with penetration tests (10) -Field hardness (11) -Vane shear (12) -Pocket penetrometer (13) -Back analysis of natural failures (14)	-Unconfined compression (28) -Direct shear (29) -Triaxial (30)	
MINERALOGY / SOIL CHEMISTRY	-Presence of swelling or low friction clay minerals -Neutralization, adsorption potential -Documentation of existing contaminant levels	-Acid test for carbonates (15)	-X-ray diffraction, scanning electron microscope (31) -Acid-base accounting (32) -Adsorption (33) -Other physical/chemical tests to to detect specific contaminants (34)	
IN SITU DENSITY	-Empirical correlation with strength, settlement, liquefaction potential	-Penetration testing (16) -Pressuremeter (17) -Geophysics (seismic, density logging) (18)	-Consolidation (27)	
COMPACTION	-Design of liners -Design of mitigative or remedial measures	-Volumeter, sand cone , nuclear densometer on test fills (19)	-Consolidation (27) -Standard, Modified Proctor (35)	

NOTE: Numbers in parentheses refer to the selected references listed on the far right which contain detailed descriptions and/or specifications for the various field and laboratory tests.

Table 12: Material properties and testing for foundation bedrock [60]

MATERIAL PROPERTIES	APPLICATION	IN SITU / FIELD TESTING	LABORATORY TESTING	REFERENCES
DESCRIPTION –Lithology –Origin, name –Fabric, micro–structure	–Classification –Durability, weathering characteristics –Empirical correlations with intact strength –Strength anisotropy, weakness planes	–Field description (1) –Preliminary classification (2)	–Microscopic examination, thin sections (12) –Detailed classification (13)	–Martin (1991): 3,4,8,9,13–16, 19–21 –OSM (1989): 1,2,8,14–16,19,20 –CGS (1985): 1,2,3 –Barton & Kjaernsli (1981): 5 –Zavodni et al (1981): 10 –Freeze & Cherry (1979): 9–11,18 –Hurlbut & Klein (1977): 12,17 –Kerr (1977): 12 –Peck et al (1974): 1,2,8,9,11, 14–16,19
INTACT STRENGTH	–Foundation stability –Bearing capacity	–Field hardness (3) –Point load testing (4)	–Unconfined compression (14) –Triaxial (15)	
SHEAR STRENGTH OF DISCONTINUITIES	–Foundation stability	–Tilt tests (5) –Back analysis of natural failures (6)	–Direct shear (16)	
MINERALOGY AND PETROGRAPHY	–Presence of swelling or low friction clay minerals –Durability –Rock fabric, micro–structure –Rock classification	–Acid test for carbonates (7)	–X–Ray diffraction, scanning electron microscope (17) –Thin sections (12) –Geochemical analyses (18) –Atterberg limits on disaggregated rock (19)	
DURABILITY	–Potential for loss of strength, bearing capacity over the long–term –Trafficability –Potential for reduced hydraulic conductivity over the long–term	–Weathering of outcrops (8)	–Slake Durability (20) –Sulphate Soundness (21)	
HYDRAULIC CONDUCTIVITY	–Estimation of seepage, potential loss of leachate –Prediction of piezometric conditions for assessment of foundation stability	–Piezometer and borehole testing (9) –Infiltration testing (10) –Pump tests on aquifers (11)	–	

NOTE: Numbers in parentheses refer to the selected references listed on the far right which contain detailed descriptions and/or specifications for the various field and laboratory tests.

Table 13: Bucket Wheel Excavator application for various mines

Mine	Location	Group	Lithology	Laboratory results [kg/cm] (kg/cm^2)	Specific digging force [kg/cm] to Himmel	UCS [MPa]	Applied Machinery	Comments
Arjuzanx Mine	France	Sedimentary rock	Compacted hard clay	85,6	/	/	6300/9 - 50	/
Athabasca River - Great Canadian Oilsands Ltd.	Canada	Non-Cohesive Soil	Oilsand	60 120	/	/	2 SchRs 1000/1.5 - 26	/
/	Australia	Non-Cohesive Soil	Indurated Sands	142	/	/	/	/
/	Australia	Cohesive soil	Grey slatey clay	74	/	/	/	/
Bad Kösen (lime plant)	Germany	Carbonate	Foam lime	/	/	70	SRs 130 H	Trial operation with BWE SRs 130 H under consideration of structural factor was possible
BBI Mine	/	Cohesive soil	Cohesive & sandy soil (ov)	/	/	/	SchRs 200/0.5 - 12 SchRs 300/3.8 -24 - 6	/
Bedok	Singapore	Soil	Hard overburden; Yellow Bedoksoil	/	/	/	250/1 - 12 SchRs 150 S (Bedoksoil)	/
Belgium	Belgium	Cohesive soil	Hard clay	3,4 6,2	56	/	/	/
Belgium	Belgium	Carbonate	White chalk	47	/	/	/	/

Mine	Location	Group	Lithology	Laboratory results [kg/cm] (kg/cm^2)	Specific digging force [kg/cm] to Himmel	UCS [MPa]	Applied Machinery	Comments
Berzdorf Mine	Germany	Non-Cohesive Soil	Sand; Gravel	18	/	/	/	Sand/gravel = 18 N/mm
Big Brown Lignite Mine (Texas)	USA	/	/	/	/	/	2 HD 710	/
BKB Mining Company - Au Mine (California)	USA	/	Compacted sand; Mineral sand; Clay	(6.8)	/	/	/	/
Braidwood	New South Wales	Sedimentary Rock	Grey slatey clay	145 /	/	/	SchRs 1200/1.5 - 26	/
Bukit Asam Mine	Indonesia	Non-Cohesive Soil Sedimentary Rock	Gravel; Sand; Claystone (above A1); Claystone & Sandstone (between A1 and A2)	7,5 15,5	/	/	5 SchRs 800/1.2*15	7,5 N/mm - 15,5 N/mm for overburden between A1 and A2 coal seam
Cable Sands	Australia	Non-Cohesive Soil	Compacted sand; Mineral sand; Clay	(6.7)	/	/	/	/

Mine	Location	Group	Lithology	Laboratory results [kg/cm] (kg/cm^2)	Specific digging force [kg/cm] to Himmel	UCS [MPa]	Applied Machinery	Comments
Central North Dakota	USA	/	Unconsolidated Clay; Poorly consolidated sandy shale; Topsoil	/	/	/	SchRs 560/1.0 - 12.5	/
Central North Dakota	USA	/	/	60 120	/	/	2 SchRs 350/5 - 10.8 Ars 1200/80 - 33 2 BRs 1200/20*20 - 10	/
Chasma-Jhelum-Link-Canal	Pakistan	Non-Cohesive Soil	Abrasive Sand	/	/	/	SchRs 2000/1*12	/
Compagnie Senegalaise des Phosphates de Taiba	Senegal	Cemented Soil	Phosphate	/	/	/	SchRs 200/2 - 19 SchRs 300/2 - 19 SchRs 600/2 - 20 SchRs 150/0.5 - 10.5 (not cleary in one of the mines)	/

Mine	Location	Group	Lithology	Laboratory results [kg/cm] (kg/cm^2)	Specific digging force [kg/cm] to Himmel	UCS [MPa]	Applied Machinery	Comments
Demba Bauxite Mines - Arrowcane Mine, Yararibo Mine, Kara-Kara Mine - Demerara Bauxite Co.	South America	Sedimentary Rock	Bauxite	/	/	10	SchRs 200/2 - 19 & SchRs 150/0.5 - 10.5 (Arrowcane) SchRs 300/2 - 19 & SchRs 70/0.7 - 6.5 (Yararibo) SchRs 600/2 - 20 (Kara-Kara)	/
Demba Mines (Guyana) - Demerara Mining Co.	South America	Cohesive Soil Non-Cohesive Soil	Clay & loose sand (ov)	/	/	/	/	Overburden with hard scattered pockets of iron ore
Elbistan Mine	Turkey	Cohesive soil Carbonate	Non-compacted muds (Gyttja); Loam; Sandy lacustrine limestone	/	/	/	6 SchRs 2300/5*32	Consolidated rock layers cannot be excavated by BWE
Fort McMurray	Canada	Non-Cohesive Soil	Oil sand	/	/	1	/	/

Mine	Location	Group	Lithology	Laboratory results [kg/cm] (kg/cm^2)	Specific digging force [kg/cm] to Himmel	UCS [MPa]	Applied Machinery	Comments
Fortuna - Garsdorf Mine	Germany	/	Overburden	/	/	/	SchRs 3600/5 - 50	/
Fortuna Mine	Germany	Sedimentary Rock	Sandstone	/	/	0,26	/	/
Fortuna Mine	Germany	Cohesive Soil	Red Clay	/	/	3,9	/	/
Fortuna Mine	Germany	Cohesive Soil	Blue-gray clay	/	/	1,25	/	/
Fortuna Mine	Germany	Sedimentary Rock	Lignite	/ 200	/	/	/	/
Frechen	Germany	Cohesive Soil	Clay	/	/	/	2 SchRs 1000/1.5 - 26	/
Gacko Mine	Bosnia	Sedimentary Rock Non-Cohesive Soil	Marl batches; Sand	128 140	/	16	2 ER-1250 17/1.5	128-140 N/mm for marl; 16 MPa in averge for overburden (vary from soft, poorly cemented material to hard cemented sediments)
Glenharold Mine (North Dakota)	USA	/	/	/	/	/	SchRs 1000/3*28	/
Goitsche Mine	Germany	Non-Cohesive Soil Cohesive Soil	Sand; Gravel; Fattier clay	/	/	/	/	Sand/Gravel = 19 N/mm Fattier clay = 52 N/mm
Goonyella Mine	Australia	Non-Cohesive Soil Cohesive Soil Sedimentary Rock	Clay and fine sand banks; Sandstone	(6.0)	/	/	SchRs 1800/2.5*25	/

Mine	Location	Group	Lithology	Laboratory results [kg/cm] (kg/cm^2)	Specific digging force [kg/cm] to Himmel	UCS [MPa]	Applied Machinery	Comments
Goonyella Mine 2	Australia	Sedimentary Rock	Sandstone	(6.0 - 20.0)	/	/	SchRs 1800/2.5*26	Brown-grey Sst = 100 N/cm^2 Brown part cemented Sst = 60 - 80 N/cm^2 Highly weathered Sst = 40 - 60 N/cm^2 Green-green brown Sst = 75 - 85 N/cm^2 Pink to pink-green Sst = 100 - 150 N/cm^2 Grey Sst = 100 - 200 N/cm^2 Bucket wheel: 10 buckets & 10 pre-cutters (each with 8 teeth)
Greifenhain Mine	Germany	Sediment	Till	97	/	/	SRs 6300	Tested block width: 80 m, slice height: 6 and 8 m; Bucket wheel was mounted with rectangular buckets and cutting edges; Excavation output was between 7.000 and 11.000 m^3
Grusovsk Mine (Nikopol Mn ore district)	Ukraine	/	Overburden	/	/	/	ERG 1600 - 40/10 - 31	/
Hahotoe Mine - Compagnie Togolaise des Mines du Benin	West Africa	Cemented Soil	Phosphate	(max. 23)	/	/	SchRs 1000/1.5 - 2 SchRs 350/5 - 10.8	/

Mine	Location	Group	Lithology	Laboratory results [kg/cm] (kg/cm^2)	Specific digging force [kg/cm] to Himmel	UCS [MPa]	Applied Machinery	Comments
Hahotoe Mine (Togo)	West Africa	Cemented Soil	Phosphate with calcite layers	40 75	/	/	Standard type 150 (O&K) - SchRs 150 S	/
Hahotoe Mine (Togo)	West Africa	Cemented Soil	Phosphate (partly calcitic sea deposit)	91 140	40	/	SchRs 350/5*12.8	/
Hambach Mine	Germany	Non-Cohesive Soil Cohesive Soil	Sand and gravel; Cohesive clayey silt layers	/	/	/	Krupp,O&K, M.A.N (1113 - 1134 kN cutting force)	/
Itzehoe	Germany	Carbonate	Chalk (ov)	40 75	/	/	Standard type 150 (O&K)	/
Japan	Japan	Sedimentary Rock	Chalk-quartz breccia	35 85	/	/	/	/
Jugoslawia	Jugoslawia	Sedimentary Rock	Hard, stratified lignite	/	/	/	2 SchRs 150/0.5 - 10.6	/

Mine	Location	Group	Lithology	Laboratory results [kg/cm] (kg/cm^2)	Specific digging force [kg/cm] to Himmel	UCS [MPa]	Applied Machinery	Comments
Kardia Mine	Greece	Cohesive soil Sedimentary Rock	Clay; Loam; Marl; Interbedding sandstone banks and conglomerate	/	/	/	6 SchRs 600/3.3*21	Hard rock must be removed after exposure by BWE
Klettwitz Mine	Germany	Non-Cohesive Soil Cohesive Soil	Sand; Gravel; Loam; Sandy loam	/	/	/	/	Sand/gravel = 20 N/mm Loam = 33 N/mm Sandy loam = 33 N/mm
Komorany (CSR)	Czech	Sedimentary Rock	North Bohemian Lignite	380	/	/	/	/
Loy Yang Mine	Australia	Cohesive Soil	Clay with Silt and Sand	/	/	/	2 SchRs 2200/3*32 SchRs 2950/3*32	/
Lyxhe	Belgium	Carbonate	White highly compacted chalk	280	/	/		/

Mine	Location	Group	Lithology	Laboratory results [kg/cm] (kg/cm²)	Specific digging force [kg/cm] to Himmel	UCS [MPa]	Applied Machinery	Comments
Mae Moh	Thailand	Sedimentary Rock	Shale; Claystone; Limestone	/	/	/	SchRs 200/2 - 15 2 SchRs 400/2 - 15 SchRs 400/3 - 20 (ov)	/
Mons	Belgium	Carbonate	Light grey compacted chalk	/	/	/		/
Morwell Mine, Yalourn Mine - SEC Victoria	Australia	Sedimentary Rock	Lignite; Overburden	246	75	/	SchRs 350/5 - 12.8 4 SchRs 1000/1.5 - 22.9 SchRs 600/7.6 - 23.5 2 SchRs 1300/2.5 - 24.5 (ov)	Lignite = 246 N/mm
Muldenstein Mine	Germany	Non-Cohesive Soil Cohesive Soil	Sand; Gravel; Loam; Sandy loam; Fattier clay	/	/	/	/	Sand/gravel = 21 N/mm Loam = 29 N/mm Sandy loam = 38 N/mm Fattier clay = 54 N/mm
Nchanga Tagebau (Sambia)	Afrika	Cohesive soil	Grey clay	160 270	/	/	/	/

Mine	Location	Group	Lithology	Laboratory results [kg/cm] (kg/cm²)	Specific digging force [kg/cm] to Himmel	UCS [MPa]	Applied Machinery	Comments
New South Wales	New South Wales	Sedimentary Rock	Hard coal	(3.8)	/	/	/	/
New Vaal	South Africa	/	Chalk; Mineral sand; Soft overburden	270	/	/	3 SchRs 700/3 - 20 2 SchRs 500/0.6 - 10	/
New Zealand mine	New Zealand	Carbonate Non-Cohesive Soil	Chalk; Mineral sand; Soft overburden	35 40	/	/	/	/
Neyveli Mine	South India	Sedimentary Rock	Quarzitic sandstone (Cudalore sandstone)	max. 450 (7.2)	/	/	2 SchRs 350/5*12 & 4 SchRs 700/3*20 (Neyveli I) 2 SchRs 1400/2*26 & 2 SchRs 700/3*19 (Neyveli II)	/
Neyveli, Braidwood, Suriname	India, New South Wales, South America	Sedimentary Rock	Hard, sandy white clay	/	150 (max)	/	/	/

Mine	Location	Group	Lithology	Laboratory results [kg/cm] (kg/cm^2)	Specific digging force [kg/cm] to Himmel	UCS [MPa]	Applied Machinery	Comments
NLC India Ltd.	India	/	Compacted sand; Mineral sand; Clay	/	170	/	/	/
Nochten mine	Germany	Cohesive Soil Non-Cohesive Soil	Clay; Sand; Gravel	90 100	/	/	1510 SRs 6300	Heavily consolidated and solidified layers of clay with boulders at the Pleistocene basis because of domestic glaciations; Bottle CLAY: specific digging resistance of about 90-100 N/mm
North Bohemian lignite district	Czech	Sedimentary Rock	Grey clay, consolidated by hard intermediate layers	150 200	/	/	/	/
North Bohemian lignite district	Czech	Non-Cohesive Soil	Sandy gravel (frozen)	50 200	/	/	/	/
North Bohemian Mines	Czech	Sedimentary Rock	Dark grey clay and slate	33	/	/	/	/
North Bohemian Mines	Czech	Sedimentary Rock	Frozen Sand; Gravel	156	/	/	SchRs 1500/5 - 30.5	/

Mine	Location	Group	Lithology	Laboratory results [kg/cm] (kg/cm^2)	Specific digging force [kg/cm] to Himmel	UCS [MPa]	Applied Machinery	Comments
North Central Illinois #5 (Springfield) coal	USA	Non-Cohesive Soil	Glacial till and clay Topsoil (reclamation) Grey shales	/	/	0,53 - 1,06	/	/
North Central Illinois #5 (Springfield) coal	USA	Non-Cohesive Soil	Glacial till; Soft brown sandstone; Sandy clay	/	/	/	3 SchRs 400/5 - 128 (co&ov) SchRs 400/5 - 12.8 (co) SchRs 1400/7 - 30 (co&ov) 2 SchRs 1400/7 - 30	/
North Central Illinois #6 (Herrin) coal	USA	Non-Cohesive Soil	Loam and clay; Grey shales	/	/	/	SchRs 1500/6 - 31	/
Northeastern Wyoming	USA	Sedimentary Rock	Compacted sandy shale; Thin topsoil	/	/	/	SchRs 1950/5 - 30.5	/
Northern Bohemian Mines	Czech	/	Overburden	62	/	/	/	/

Mine	Location	Group	Lithology	Laboratory results [kg/cm] (kg/cm^2)	Specific digging force [kg/cm] to Himmel	UCS [MPa]	Applied Machinery	Comments
Northern Illinois Mine	USA	Sedimentary Rock	Hard Slatey Clay	/	/	/	3 SchRs 1260/5 - 21 (ov) SchRs 1800/1 - 21	/
Northern Illinois Mine	USA	Sedimentary Rock	Slatey Clay	/	/	/	SchRs 1500/5*30.5	/
Northern Illinois Mine - Peabody Coal Co.	USA	Sedimentary Rock	Bitum. Coal	/	/	/	SchRs 350/5 - 12.8 4 SchRs 1000/1.5 - 22.9 SchRs 600/7.6 - 23.5 2 SchRs 1300/2.5 - 24.5	/
North-Western Bohemia	Czech	Cohesive soil	Clay filling	30	/	/	400/5 - 12.8 (ov)	/

Mine	Location	Group	Lithology	Laboratory results [kg/cm] (kg/cm^2)	Specific digging force [kg/cm] to Himmel	UCS [MPa]	Applied Machinery	Comments
Oil Sands (Athabasca)	Canada	Non-Cohesive Soil	Oil Sand; Sands & clays with lenses of broken rock up to 500 mm (ov)	160	/	/	2 SchRs 1000/1.5 - 26 SchRs 1950/1 - 19.2 SchRs 2450/1.5 - 18 (1976) for ov & oil sands	High specific digging resistance for breaking out oil sand, sticking of oil sand to digging parts and conveyor belts; 160 N/mm (oil sand)
Oltenia, Cicani, Beterega Girla, Tismania	Romania	Sedimentary Rock	Lignite; Overburden	38,5	33	/	3 SchRs 400/5 - 128 (co&ov) SchRs 400/5 - 12.8 (co) 3 SchRs 1400/7 - 30 (co&ov)	85 N/mm for lignite
Onverdacht Mine - N.V. Billiton	South America	Sedimentary Rock	Bauxite; Clay (ov)	(3.5)	/	/	/	/

Mine	Location	Group	Lithology	Laboratory results [kg/cm] (kg/cm^2)	Specific digging force [kg/cm] to Himmel	UCS [MPa]	Applied Machinery	Comments
Onverdacht Mine - N.V. Billiton	South America	Cohesive Soil Non-Cohesive Soil	Clay, coarse sands & hard clays (cemented) - Coropina clay; Kaolin clay & coarse sands (cemented) - Coesewijne clay	/	/	/	SchRs 200/2 - 15 SchRs 400/3 - 20	Coropina clay & Coesewijne layers (very hard) require large cutting forces
Oranjemund Mine (Namibia)	South Africa	Non-Cohesive Soil	Sand	/	/	/	SchRs 400/0.8*11	/
Ordshonikidze Mine	USSR	Cohesive Soil	Loose loam (ov); Clay	49 118	/	/	SchRs 1500/6 - 24 (upper ov)	Problem during excavation because of stickiness of soils; Swell factor 1.50-1.65. 49 - 118 for loam
Pistone Works Norton - Tunnel Portland Cement Corp. Ltd.	USA	Carbonate	Chalk	98	/	/	SRs 470 2 SchRs 150/0.5 - 10.6	/
Pitstone UK	United Kingdom	Carbonate	White chalk	/	/	/	2 SchRs 500/3 - 13	/

Mine	Location	Group	Lithology	Laboratory results [kg/cm] (kg/cm^2)	Specific digging force [kg/cm] to Himmel	UCS [MPa]	Applied Machinery	Comments
Ptolemais Kardia & Main Field	Greece	Sedimentary Rock	Lignite; Overburden	88	/	/	3 SchRs 1260/5 - 21 SchRs 1800/1 - 21 (ov)	88 N/mm for lignite
River King Mine (Illinois)	USA	/	/	/	/	/	1054 WX (Kolbe-type)	/
Roerdal/Aalborg - L.A Smith Copenhagen	Netherlands, Denmark	Carbonate	Chalk	(9.8)	/	/	2 SchRs 150/0.5 - 10.6	/
Rovinari	Romania	Cohesive soil	Green clay	2400	/	/	/	/
Rovinari, Siam	Romania, Asia	Carbonate	Marly chalk	88	/	/	SchRs 150s	/
Schleenhain Mine	Germany	Cohesive Soil	Loam; Sandy loam; Fattier clay	/	/	/	/	Loam = 26 N/mm Sandy loam = 32 N/mm Fattier clay = 60 N/mm

Mine	Location	Group	Lithology	Laboratory results [kg/cm] (kg/cm^2)	Specific digging force [kg/cm] to Himmel	UCS [MPa]	Applied Machinery	Comments
Shelesnogorsk Mine (USSR)	USSR	Non-Cohesive Soil	Sand and Loam (ov)	/	/	/	SRs 2000/32 + Vr (ov) SchRs 1600 (ov) SchRs 630 (co) SchRs 630 (co) ERS 1000 (co) 2 SchRs 500/3 - 13 (end of 1964)	/
Singapore	Asia	Sedimentary Rock	Sandstone (weathered granite)	/	/	/	SchRs 630 (ov)	/
Singapore	Asia	Sedimentary Rock	Quarzitic sandstone	(11.8)	/	/	/	/
Singapore	Asia	Non-Cohesive Soil	Eroded Granite Bedoksoil	/	/	/	2 SchRs 150/0.5 - 10.6	/

Mine	Location	Group	Lithology	Laboratory results [kg/cm] (kg/cm²)	Specific digging force [kg/cm] to Himmel	UCS [MPa]	Applied Machinery	Comments
Skolo	USSR	Sedimentary Rock	Silica-Marl	/	/	/	SchRs 300 SchRs 300/4.5 - 14 (ov) SchRs 250/7 - 13 (ov)	/
South Illinois Coal Region #6 (Herrin) coal	USA	Non-Cohesive Soil	Brown friable clay-like soil and glacial till; Grey shale	/	/	1,43	/	/
Southwestern Illinois	USA	Non-Cohesive Soil	Glacial drift; Clay-like soil (soft and sandy)	/	20	/	/	/
Southwestern Illinois #6 (Herrin) coal	USA	Non-Cohesive Soil	Brown well lithified clay-like soil; Interbedded shales and limestone	/	29	/	/	/
Southwestern Washington	USA	Non-Cohesive Soil Cohesive Soil	Clay-Gravel; Sandy material	/	33	/	/	/
Sta Barbara	Italy	Sedimentary Rock	Hard, stratified lignite	/	56	/	/	/
Taiba Phosphate Mine (Senegal)	West Africa	/	Overburden	/	/	/	SchRs 560/1 - 12	/

Mine	Location	Group	Lithology	Laboratory results [kg/cm] (kg/cm^2)	Specific digging force [kg/cm] to Himmel	UCS [MPa]	Applied Machinery	Comments
Tamnava Mine East	Serbia	Non-Cohesive Soil Cohesive Soil	Gravel & various clays (ov)	/	19	/	/	/
Tamnava Mine West	Serbia	Sedimentary Rock, Soil	Aluvium Sediments (ov); Sandstone (inerburden)	/	20	/	/	/
Teutonia	South America	Sedimentary Rock	Shale; Claystone; Limestone	/	45-95	/	/	/
Teutonia Mine (Hannover)	Germany	Sedimentary Rock	Marl	/	/	max. 20	S 400/250	Marl has an average UCS of 10 to 20 MPa; After 2 years replacement of cutting bucket and teeth by using a system where lips and teeth casted in one piece.
Thoknia and Khoremi Mine - Megalopolis Lignite District	Greece	Sedimentary Rock Cohesive Soil	Coal and thin partings of clay and marl	/	/	/	5 SchRs 650/4*24	/

Mine	Location	Group	Lithology	Laboratory results [kg/cm] (kg/cm^2)	Specific digging force [kg/cm] to Himmel	UCS [MPa]	Applied Machinery	Comments
Thorez Mine	Hungary	Cohesive Soil Sedimentary Rock	Clay & Sandstone layers (ov)	150	/	/	SRs 2000	Cutting force before using new tooth design (5,5 cm shorter, rake angle reduced from 20° to 12°) was between 462,35 N/mm and 643,5 N/mm; High rates of excavator damage; Bucket lip deformation and breakage; Teeth and tooth socket breakage
								150 N/mm in average for Sandstone layers
Wölfersheim III Mine	Germany	Sedimentary Rock	Lignite; Hard clay & loess (ov)	84	/	/	SRs 470, SchRs 300/4.5 - 14 SchRs 250/7 - 13 (ov) SchRs 250/7 - 14 (lig)	0.265 kW/m^3 for clay 84 N/mm for clay
Zukunft Mine	Germany	Non-Cohesive Soil	Sand; Clay	/	/	/	/	/
/	/	Cohesive soil	Sand; Gravel	/	/	/	SchRs 1000/3 - 25	/
/	/	Cohesive soil	Clay	/	/	/	United Electric Kolbe W-5	/

Mine	Location	Group	Lithology	Laboratory results [kg/cm] (kg/cm^2)	Specific digging force [kg/cm] to Himmel	UCS [MPa]	Applied Machinery	Comments
/	/	Non-Cohesive Soil	Sandy loam	/	/	/	United Electric Kolbe W-5	/
/	/	Sedimentary Rock	Hard and saturated clay	/	/	/	Bucyrus-Erie 954-WX	Insufficient amount of material to be removed in certain areas
/	/	Non-Cohesive Soil	Sand (Sand Dunes)	/	/	/	Bucyrus-Erie 1054-WX	The machine is physically limited to excavating a maximum 100 feet of overburden. This was seldom a problem since the glacial material rarely exceeded 30 feet
/	/	Non-Cohesive Soil	Gravel (alluvial river deposit)	/	/	/	United Electric Kolbe W-4	/
/	/	Sedimentary Rock	Sandstone (with Fe-inclusions)	/	/	/	MX 3000 (modified)	Many of the problems encountered were due to the fact that the BWE was diverted from its original design function as a reclaimer
/	/	Sedimentary Rock	Sand/Rock layers	/	/	/	SchRs 1940/0.5 - 14	/
/	/	Sedimentary Rock	Coal	/	/	/	SchRs 1000/3 - 25	Unsuccessfully operating

Table 14: Risk analysis of most important risks in open-pit mining

Number	Stage	Risk Issue	Risk Event/Issue	Causes	Preventative Controls	Impact	Mitigating Controls
1	**Operation**	**Operability conditions**	Insufficient mining method	Lack of exploration; Lack of investigation; Lack of communication between teams within company	Investigation of mining conditions e.g. mechanical rock properties; Comparing mine conditions with other mines; Sufficient exploration work e.g. core drilling; Internal meetings/brainstorming	Operating costs too high; Problems with recultivation/reclamation; Pollution of environment; Operating without being profitable	Twice-checking of mine plan/mining method/mining sequence; Consulting through experts; Internal meetings/brainstorming; Monitoring/documentation of project progress
2	**Operation**	**Operability conditions**	Insufficient machinery/equipment	Wrong chosen equipment; Lack of exploration; Lack of communication between teams within company	Evaluation of mining equipment; Sufficient exploration work e.g. core drilling; Internal meetings/brainstorming; Application of testing methods e.g. cuttability tests; Comparing mine conditions with other mines; Comparison of equipment regarding the overall process e.g. What is the impact on the following process?	Damaging of equipment; Failing of mine project; Excessive maintenance/reparations; Discontinuous operation; Capital costs too high	Permanent monitoring of operation; Investigation of problems for further prevention; Check list to assess workability; Communication within company; Adaption/modification of machinery within valid frame;
3	**Operation**	**Operability conditions**	Safety of working unit	Refrain from safety instruction	Respond to safety of working units; Safety instruction of personnel	Damage to equipment; Injury to personnel	Ongoing inspection of working unit handling
4	**Operation**	**Operability conditions**	National safety regulations of machinery	Different safety regulations for various nations	Previous checking of national safety regulations	Standstill of mining operation; Problems with mines inspectorates	Adapting of machinery to national safety regulations at lowest costs
5	**Operation**	**Operability conditions**	Respond to machinery unit	Unknown risks for machinery (BWE, Spreader)	CE marking of machinery	Penal consequences	Checking book regarding machinery risks

Number	Stage	Risk Issue	Risk Event/Issue	Causes	Preventative Controls	Impact	Mitigating Controls
6	**Operation**	**Operability conditions**	Coal fire	Self-ignition of pyrite due to oxygen reaction; Poor heat emission due to unfavorable fill	Early detection of pyrite bearing layers/formations; Alternative extraction/ventilation method; Fully extraction of coal seam	Damage to environment; Standstill of mining operation; Injury to personnel	Measurements of temperature, gas content; Geophysical measurements (e.g. magnetic properties of country rock); Prevention of oxygen supply (e.g. usage of covers, barriers); Monitoring of fire area
7	**Operation**	**Operability conditions**	Ground stability problems	Wrong dumping sequence; Wrong dumping material (grain size distribution); Occurrence of water overpressure	Dumping in a manner to gain stress distribution; Usage of well-defined material for dumping; Localization of water bearing formations	Slope failure during spreader operation; Impermeable layers might lead to slope failures; Shear failure along weakening zone	Changing dumping sequence to reduce ground stability problems; Water drainage and further use of higher amount of coarse grains; Sufficient dumping sequence
8	**Operation**	**Operability conditions**	Slope stability problems	Slope angle too steep	Selection of slope angle in dependence of mechanical properties, rock mass conditions, geology, shear parameters	Destruction of/damage to spreader system	Adjusting slope angle to geological/geomechanical/weather conditions
9	**Operation**	**Operability conditions**	Material workability	Increasing strength of embedded layers; Occurrence of unknown geological structures	Increasing exploration; Collecting and documentation of drill cores (depth, photo)	Standstill of operation; Severe damage to BWE	Pre-splitting/Pre-blasting of more competent layers/zones
10	**Operation**	**Operability conditions**	Unfavorable stripping ratio	Insufficient pit design	Thinking about how to get wanted end situation with available equipment	Loss of revenues; Unfavorable mining conditions regarding operability of equipment; Additional area for dumping needed	Application of optimum adjustment that is possible
11	**Operation**	**Operability conditions**	BWE shutdown	Inefficient implementation of pre-splitting/pre-blasting	Geological investigations (e.g. exploration) for detection of more competent rock masses; Control of bucket distances; Pre-blasting of larger areas	Shut down of machinery and production standstill	Using another option for mineral extraction; Building up strategic stockpiles

Number	Stage	Risk Issue	Risk Event/Issue	Causes	Preventative Controls	Impact	Mitigating Controls
12	**Operation**	**Operability conditions**	Tailing pond dam failure	Inaccurate dumping sequence of dam	Dumping sequence control	Environmental pollution (river, groundwater, soil)	Erection of barriers; Use of chemicals to get a mitigated reaction of toxic components
13	**Operation**	**Equipment change**	Lack of knowledge	Lack of operator training; Limited experiences of operability	Dealing with theoretical equipment knowledge; Looking at already operating companies	Inaccurate usage of equipment up to destroying of equipment	Training of personnel
14	**Safety**	**Open pit design**	Instability of benches	Bench width too small; Bench height too high	Adjusting bench geometry to rock mass conditions	Instability of benches; Maneuverability problems of machinery	Barriers against rock falls; Keeping constant distances to bench edges
15	**Safety**	**Open pit design**	Slope failure	General slope angle too steep; Excessive rainfall and accumulation of water above impermeable layer	Drainage of water bearing formations; Sufficient design for benches (height, width); Increase of general slope angle if geological conditions allow	Slope failure; Damage to benches that leads to standstill of operation; Damage to equipment; Injury to personnel	Drainage of water bearing formations; Increasing of bench width and reducing of bench height is necessary
16	**Safety**	**Open pit design**	Rockfall accident	Rock fall hazards due to hang-ups and inaccurate scaling	Scaling of benches; Observation of benches; Erection of rock barrier to mitigate distance of movement of rock blocks	Damage to equipment; Injury to personnel; Standstill of operation	Instant scaling after blasting; Changing drill/blast pattern; Accurate observation of weak rock areas
17	**Safety**	**Open pit design**	Abandoned underground openings	Past underground mining activities	Investigation of old mine maps	Severe damage to machinery/equipment; Loss of human lives	Declaration of certain area as dangerous area and placement of warnings around that area; Prohibition of working in too narrow distances to this area
18	**Safety**	**General**	Extreme weather conditions	Freeze, hurricane	Early warning systems; Information checking on TV; Protective equipment for personnel; Erection of protective places	Disturbance of operation; Damage to equipment; Injury to personnel;	Emergency response plan; Assembly points for personnel; Usage of protective places until end of extreme conditions

Number	Stage	Risk Issue	Risk Event/Issue	Causes	Preventative Controls	Impact	Mitigating Controls
19	**Safety**	**General**	Methane fire	Methane concentration between 5 - 15 %; Sparking; Frictional ignition; Coal fire	Measurement equipment for gas concentrations; Method/plan for deletion of fires; De-gassing of coal	Coal fire; Injury to personnel; Damage to machinery/equipment; Disturbance of operation; Standstill of production	Emergency response plan; Removing minimum one element of fire causing elements (fuel, heat, oxygen - fire triangle)

Number	Stage	Risk Issue	Risk Event/Issue	Causes	Preventative Controls	Impact	Mitigating Controls
20	**Safety**	**Organization**	Entries and ways	General: Travelways within danger area; lack of secure of falling edges e.g. presence of stones, rock blocks; lack of preventative controls; seasonal hazards e.g. ice, snow; Minimum width and passing loops: Lack of regulatory compliance e.g. minimum width of ways, lack of passing loop; Inclination: Inclination of travelways not in compliance with manufacturer information; Scheduling: Lack of speed limits; ground stability of travelways; Wayside: Lack of wayside identification e.g. reflective materials; barricades; Lighting: Lack of lighting of travelways; Barrier: Lack of barrier of dangerous travelways; Entries and ways: Lack of accessibility of working place, office, facilities; falling objects; lack of way clearance; slippery areas on ways	Marking areas accurately at planning stage; Separation of driving and walking ways; Usage of driving regulations (including turning areas, dangerous places, speed limits, loading stations); Observation of safety distances; Prevention of reversing; Be aware of field of view problems; Safety instruction for external personnel; Formation of "safety culture" within company; Previous checking of regulatory framework e.g. TAV, BauV, ASchG	Damage to machinery; Operational accidents; Injury to personnel; Problems with mines inspectorates	Emergency response plan; First aid equipment; Monitoring of ways and entries; Communication within company; Ongoing preparation of ways

Number	Stage	Risk Issue	Risk Event/Issue	Causes	Preventative Controls	Impact	Mitigating Controls
21	**Safety**	**Organization**	Fire prevention	Fire caused by simultaneous occurrence of fire, heat and oxygen; Blasting; Frictional ignitions; Gases	Installation of extinguishers in suggested rooms; Instruction of personnel; Deposition of plans with access routes at local task force; Blockage of danger area during working with heat e.g. welding, drying; Usage of one type and manufacturer of extinguishers; Fire safety regulations; Placement of extinguishing agent in immediate distances; Placement of extinguisher on clearly visible places; Signs for fire extinguishing unit; Separation of inflammable substances of gas/pressure containers; Contact of local fire department for large mining operations and implementation of exercises	Damage to equipment; Standstill of production; Injury to personnel	Behavior during fire: Alerting of fire prevention officer/fire warden/fire department; emergency response plan; usage of means of first extinguishing help; keep calm and warn fellows; rescuing without self-endangerment; extinguishing without self-endangerment; within EU - call 112

Number	Stage	Risk Issue	Risk Event/Issue	Causes	Preventative Controls	Impact	Mitigating Controls
22	**Safety**	**Organization**	Lone working place	Observation of working processes; Working on technical facilities; Maintenance; Cleaning work e.g. scaling; Repair	Monitoring of remote working areas; Guarantee of help; Instruction of alone working personnel; Regulations regarding safeguard measures; Presence of additional work force during dangerous work e.g. explosive atmosphere, work in silos/pits, shafts; Evaluation of alone working in terms of presence of fellows, maximum time until first aid, comparison of various safeguards; Previous checking of regulatory framework e.g. ASchG, TAV	Injury to personnel; Loss of human lives	Usage of safeguards; Monitoring of working places; Checking of work force presence in intervals
23	**Safety**	**Organization**	Electric current in open pit (1)	General: Lack of checking electrotechnical regulations for machinery/facilities; electrical facility/machinery not installed through electrically qualified person; ignorance of user guide; lack of ground fault interrupter on socket; Site power supply manifold (SPSM): Locking of SPSM during work; placement of SPSM on unsafe places; lack of CE marking; lack of	Mechanical rating: Mechanical rating for electrical utilities; mechanical rating label; Control and Maintenance: Sufficient planning of systematic testing and maintenance; control and maintenance implemented by electrically qualified person; Safety distances and overhead lines: Observation of overhead lines during usage of vehicles; keeping of safety distances to overhead lines; Rescue of accident victim: Checking of current flow	Disturbance/standstill of operation; Damage to equipment; Injury to personnel	General: Monitoring of workings with electrical current; communication within company; documentation; early reaction of fellows; keep calm; Shock treatment: shock positioning; permanent support; First aid for burns: Cooling of burned skin with clear water; prevent usage of oil/balm/powder for wounds; High voltage accidents: Keeping of safety distances; execution of emergency call; implementation of rescue by professionals; First Aid: Self-protection; doctoral control;

				residual current operated device (RCD); lack of cold-resistant marking on RCD protection (-25°C); Mobile generator: Usage of insufficient measured generator; unstable installation and insufficient ventilation; non setting up of mobile generator with RCD by electrically qualified person; installation not implemented by electrically qualified person; removal of disturbances and start of generator not implemented by electrically qualified person; lack of user guide on site; Mobile generators with combustion engines: Insufficient ventilation; lack of deflection of exhaust gases; lack of safety crank for crank starter device; lack of rope catching device for rope starter	disturbance; prevent entry in voltage hopper		First measures: Implementation of first measures e.g. checking due to respiratory standstill and circulatory arrest, calling of accident ambulance; Position of accident victim: Checking of pulse rate and breathing

Number	Stage	Risk Issue	Risk Event/Issue	Causes	Preventative Controls	Impact	Mitigating Controls
24	**Safety**	**Organization**	Electric current in open pit (2)	Wires: Damage to isolation of wires; wires under tensile stress; reparation not implemented by electrically qualified person; lack of rubber tube wires or similar ones; lack of cold resistance (- 25°C) of wires/cables; lack of protection of wires under load (cover, protective tube); usage of damaged wires; lack of thermoswitch on wire roller; lack of CE marking on wire roller; Plug and socket device: Wrong connection of wires; lack of splash water protection; lack of resistant design; Hand machines: Lack of accurate design e.g. protective insulation; lack of protective extra-low voltage in confined and conductive places; lack of "protective insulation utilities" marking; Shiners: Lack of accurate design e.g. splash water protection or protective insulation; lack of protection glass and protection basket; usage of damaged	Mechanical rating: Mechanical rating for electrical utilities; mechanical rating label; Control and Maintenance: Sufficient planning of systematic testing and maintenance; control and maintenance implemented by electrically qualified person; Safety distances and overhead lines: Observation of overhead lines during usage of vehicles; keeping of safety distances to overhead lines; Rescue of accident victim: Checking of current flow disturbance; prevent entry in voltage hopper	Disturbance/standstill of operation; Damage to equipment; Injury to personnel	General: Monitoring of workings with electrical current; communication within company; documentation; early reaction of fellows; keep calm; Shock treatment: shock positioning; permanent support; First aid for burns: Cooling of burned skin with clear water; prevent usage of oil/balm/powder for wounds; High voltage accidents: Keeping of safety distances; execution of emergency call; implementation of rescue by professionals; First Aid: Self-protection; doctoral control; First measures: Implementation of first measures e.g. checking due to respiratory standstill and circulatory arrest, calling of accident ambulance; Position of accident victim: Checking of pulse rate and breathing

				protection glasses or protection baskets; heat emission of halogenous lamps; ignorance of precautionary measures during installation of portable shiners; splashing on hot lamps; <u>Feed points:</u> Lack of RCD			

Number	Stage	Risk Issue	Risk Event/Issue	Causes	Preventative Controls	Impact	Mitigating Controls
25	**Safety**	**Organization**	Outdoor working (1)	**Working in winter** Working places and travelways: Lack of protection; slippery working places; ice/snow on travelways and working places; lack of cover for stored materials; occurrence of overhangs; Lounges and sanitary fittings: Lack of heating; lack of air trap; Stationary working places: Lack of protection against cold/wind/rain; lack of heating possibility; Protective clothes: Lack of sufficient protective clothes; lack of drying facilities; Devices and machinery: Ignorance of operating instructions; working on frozen ground; Break: Lack of warming possibilities; lack of protected rooms; lack of warm drinks	**Working in winter** Usage of protection for machinery, ways and working places; Usage of deicing devices; Usage of heating devices/facilities; Wearing of sufficient protective clothes; Control of dangerous places	**Working in winter** Damage to machinery/equipment; Frostbite; Cold	**Working in winter** Supplying of warm drinks; Warming up in intervals

Number	Stage	Risk Issue	Risk Event/Issue	Causes	Preventative Controls	Impact	Mitigating Controls
26	**Safety**	**Organization**	Outdoor working (2)	**Working under direct sunlight** General: UV-light irradiation Time and assessment of load: Reflecting surfaces; working time between 11 a.m. and 3 p.m.	**Working under direct sunlight** Usage of shading, roofing or sunshades; Usage of sunscreen agent; Wearing of sufficient protective clothes; Drinking enough water	**Working under direct sunlight** Heat stroke; Heat thickness; Increase of body temperature; Sunstroke; Loss of concentration/performance	**Working under direct sunlight** Looking for shadows; Implementation of internal workings between 11 a.m. and 3 p.m.; Rotation between work force; Supply of cold drinks; Repeated usage of sunscreen agent
27	**Safety**	**Organization**	Occurrence of electromagnetic fields	Exposure to electric, magnetic and electromagnetic fields in a range between 0 and 300 GHz; Ignorance of regulations; Charging of body in electric field; Large amperage -> strong magnetic fields; Large electric voltage -> strong electric fields; Occurrence of electric voltage or electric currents e.g. magnetic separator, electronic welding, transmitting aerial, current supply facility	Adherence of thresholds; Checking for regulations e.g. VEMF (regulation for electromagnetic fields); Evaluation of hazards with e.g. norms, manuals of European commission, measurements/calculations, operations manual, homepage of work inspectorates; Prevent staying in mentioned areas or near mentioned machinery	Nerve irritation or stimulation of muscles in a range between 0 and 10 MHz; Warming of human histoid up to burns in a range between 100 kHz and 300 Ghz; Disturbance of medical implants e.g. pacemaker; Sparking	Choosing of an alternative working method; Usage of working tools with less emissions; Technical measurements e.g. ground, shielding; Increasing distance to source; Marking of areas or blockage of areas if measures don't work

Number	Stage	Risk Issue	Risk Event/Issue	Causes	Preventative Controls	Impact	Mitigating Controls
28	**Safety**	**Organization**	Chemicals/dangerous working material (1)	**Chemicals/dangerous working material** Air pollution caused by work, emissions or entry of polluted air; Gases during welding, cutting or combustion engine; Fumes during degreasing or cleaning; Fog during atomization of gear oil; Smoke during thermal and chemical processes	**Chemicals/dangerous working material** Checking of markings and safety data sheets; Safety instruction of personnel; Checking of GHS (Globally Harmonized System) markings; Accurate usage of GHS markings (name, ingredients, symbols, hazard warnings, security advice, address and telephone number of supplier); Prohibition/constraints for asbestos and quartziferous blasting media; Installation of extraction units; Usage of protective clothes e.g. breathing protection, eye protection, gloves; Prevention of skin contact; TLV (threshold limit values); REACH (registration, evaluation, authorization of chemicals): Checking of supplier's safety data sheet through e.g. Federal Environment Agency; alerting of supplier regarding lacks; implementation of risk management measures e.g. protective equipment, ventilation; checking of usage registration; storage of information (minimum 10 years)	**Chemicals/dangerous working material** Irritation/cauterization of skin, eyes, mouth, airway, and gullet; Long-term damage e.g. allergic reaction, cancer; Damage to internal organs e.g. liver, kidney, nerve system through poisoning; Daze and choking hazard through oxygen deficit or high concentration of solvent fumes	**Chemicals/dangerous working material** Replacement of dangerous substances; No replacement possible: Reduction of amount of dangerous substances; reduction of persons at work; reduction of duration and intensity of exposure; usage of closed working methods; exhausting of formation area; ventilation measures

Number	Stage	Risk Issue	Risk Event/Issue	Causes	Preventative Controls	Impact	Mitigating Controls
29	**Safety**	**Organization**	Chemicals/dangerous working material (2)	**Mineral dust** Dust during extraction of raw materials, processing or maintenance; Accumulation of pollutants in pits, shafts; Fire hazard or explosion hazard due to inflammable dissolvent; Mineral dust (granite, basalt, diabase, limestone, quartziferous stones) - < 100 µm (inhalable), < 5 µm (respirable)	**Mineral dust** Evaluation/assessment of hazards through employer; Moistening of travelways; Cleaning of vehicle cabins and closure of vehicle cabins; Permanent cleaning of working places, machinery, and devices; Dust suppression devices for machinery and cleaning of devices; Listing of rock types and mineral dusts: Investigation of dust-polluted working places or activities; investigation of necessary information regarding substances and activities e.g. amount of dust, physical and chemical propertied of dust; assessment of hazards (e.g. amount of dust, dust composition, physical and hazardous properties of dust) - checking of working environment, working place, activities and working techniques, and time and duration of dust liberation; fixation of protective measurements e.g. design of working procedure and usage of sufficient working tools, protective measurements at the hazard source, entry barriers, cleaning measures, working time regulations, personal protective equipment	**Chemicals/dangerous working material** Irritation/cauterization of skin, eyes, mouth, airway, and gullet; Long-term damage e.g. allergic reaction, cancer; Damage to internal organs e.g. liver, kidney, nerve system through poisoning; Daze and chocking hazard through oxygen deficit or high concentration of solvent fumes	**Mineral dust** Moistening of travelways; Cleaning of vehicle cabins and closure of vehicle cabins; Permanent cleaning of working places, machinery, and devices; Dust suppression devices for machinery and cleaning of devices

Number	Stage	Risk Issue	Risk Event/Issue	Causes	Preventative Controls	Impact	Mitigating Controls
30	**Safety**	**Organization**	Explosible atmospheres	Working with liquid gas, solvent glue, varnish, or paint; Charging of batteries and accumulators; Working in silos, containers, shafts, pits, and pipes; Storage of inflammable substances; Spillage of solvents	General: Creation of explosion document (VEXAT); application of substitutes; Evaluation of explosion hazards: Analysis of explosion risks and determination of ignition sources prior to mining activities; assessment of explosion hazards (working tools, working substances, working conditions) for each working place, production process and operating condition - questions to ask: Do inflammable substances occur? Are explosive atmospheres possible? Is a formation of an explosion-prone area possible? Can a formation of an explosive-prone area be prevented? Can an ignition in an explosive-prone area be prevented?; Accumulator charging station/battery rooms: Marking of charging rooms; placement of accumulators/batteries on isolated basis; natural or technical ventilation; usage of a locked, own room with opening outwards doors; openings for ventilation installed on opposite walls; free opening cross section "A" of intake and exhaust air openings $A = 28 * Q$ [cm^2] whereas Q is the per hour needed amount of air in [m^3/h] which can be calculated with	Injury to personnel; Damage to equipment; Standstill of production	General: Inerting through addition of inert gases (nitrogen, carbon dioxide, inert gases, combustion gases, water vapor, powder-like gases); monitoring of concentration (gas detection system with alert system, gas detection system with automatic triggering of protective measures, gas detection system with automatic triggering of emergency functions); elimination of ignition sources e.g. open flames, hot surfaces, sparks from electric facilities, friction induced sparking, static electricity, chemical reactions; Accumulator charging station/battery rooms: Stop of charging of batteries/accumulators in case of ventilation shutdown; Working in silos, containers, shafts, pits, or pipes: Knowledge of rescue measures of the person in front of the container; the person in front of container must be able to rescue accident victim by its own; due to impossibility of roping, the person in front of the container must fetching for help without leaving

					ÖNORM EN 50272-2; <u>Working in silos, containers, shafts, pits, or pipes:</u> Checking occurrence of oxygen deficit; checking occurrence of fire hazardous and explosive substances; checking occurrence of dangerous substances; instruction of protective measures in written form by supervisor prior to entrance and control of adherence by supervisor; prohibition of lamps with liquid fuels; prohibition of entrance due to occurrence of more than 50 % of UEX (lower explosion border) concentration of gases, vapors, or dust; guarantee of sufficient ventilation prior to entrance; usage of respirator due to oxygen deficit or exceeding of TLV values; permanent presence of person in front of the container; markings on endangered entrances		position (permanent eye contact to accident victim)

Number	Stage	Risk Issue	Risk Event/Issue	Causes	Preventative Controls	Impact	Mitigating Controls
31	**Safety**	**Organization**	Noise and vibrations	**Noise** Usage of machinery, drilling, or blasting; Exceeding of 85 dB (8 hours for 40 years); Exceeding of permissible exposure limit; **Vibrations** Usage of working tools with continuous and repeating movements e.g. motor-driven working tools, driving devices, rotating machinery; Exposure during working with Load-Haul-Dump (LHD), trucks, hydraulic excavators, front loaders, grinders, drilling machines, explosive-actuated working tools, hauling facilities, engines, or hydraulic hammers; High vibration intensity and long-term exposure	**Noise** Wearing of protective equipment (e.g. ear protection) due to exceeding 80 dB; Instruction of personnel about value of permissible exposure limit or triggering value due to exceeding of triggering value (triggering value for dangerous noise to hearing = 80 dB); Placement/Implementation of working tools and working methods in separate rooms; Keep noisy areas as small as possible; Submission of safety and health protection documents for approval request of facilities; Marking of dangerous areas; Usage of lists for harmed personnel due to exceeding of permissible exposure limit; Conduction of aptitude check prior to working due to exceeding permissible exposure limits; <u>Noise reduction at the source:</u> Usage of less noisy working methods; usage of less noisy working tools; sufficient maintenance of working tools; **Vibrations** Wearing of protective equipment e.g. anti-vibration gloves; Checking of triggering values and permissible exposure	**Noise** Constraints in communication or alert perception; Noise-induced deafness; Tinnitus; Loss of hearing; Noise depending load; Influences on cardiovascular system; **Vibrations** Raynaud's phenomenon (chronical disturbance of arms/hands); Backache; Damage to the spine	**Noise** Assessment of noise exposure in intervals; Collective measures due to exceeding of permissible exposure limit (usage of ear protection due to insufficient collective measure); Increase distance to acoustic source; Noise reduction through proper usage of working tools; Limitation of exposure times (breaks); Aptitude checks in intervals (every 5 years) due to exceeding permissible exposure limits; Aptitude checks (every 2 1/2 years) due to already existing hearing loss; **Vibrations** Instruction of personnel due to exceeding of triggering value; Sufficient maintenance in intervals; Limitation of exposure times; Ergonomic preferable posture; Prevention of heavy work (usage of auxiliary devices); Health monitoring due to exceeding of triggering values;

					limits in manuals; Conduction of vibration measurements due to lack of information (manual, calculation methods, comparison data); Usage of alternative working methods; Usage of low-vibration working tools e.g. vibration damping stock, electronic adjustable velocities on electro working tools, buffers on drilling working tools; Sufficient maintenance in intervals		Whole body vibrations: Reduction of ground problems on travelways; adjusting of driving velocity; usage of proper tires on vehicles; usage of vibration damping seats and cabins; damping floors; Hand/arm vibrations: Usage of vibration damping stock

Number	Stage	Risk Issue	Risk Event/Issue	Causes	Preventative Controls	Impact	Mitigating Controls
32	**Safety**	**Organization**	Maintenance (1)	Maintenance (preservation of proper condition, control of proper condition, assessment of proper condition, improvement of proper condition, secure of proper condition) of machinery/facilities	Maintenance and cleaning of working places/sanitary equipment/social services that consist of electrical facilities, working tools, protective equipment, fire alarm/firefighting installations, first aid equipment; Controlling of proper condition of above named equipment, working tools, and facilities; Securing facilities with maintenance locks; Liberation of facility through supervisor; Usage of proper materials, working tools, and personal protective equipment; Checking of regulations e.g. MSV 2010; Planning of maintenance; Usage of personal lock for safety switch (removal of key) from each working force; <u>Usage of maintenance strategies with the objectives:</u> High reliability of facilities; high level of security of facilities; low shut down costs; low maintenance costs; Switching off machinery/facility prior to work; <u>Switching off not possible due to technical reasons:</u> Arranging of sufficient technical protective measures; working of only instructed and competent personal; monitoring of work through further person	Major bruises; Injury through sharp devices; Falling from heights; Damage to equipment/machinery; Standstill of production	Liberation of facility after finishing work and removal of working force

Number	Stage	Risk Issue	Risk Event/Issue	Causes	Preventative Controls	Impact	Mitigating Controls
33	**Safety**	**Organization**	Maintenance (2)	Maintenance (preservation of proper condition, control of proper condition, assessment of proper condition, improvement of proper condition, secure of proper condition) of machinery/facilities	Hierarchy of measures (with increasing hazard from 1 to 4): 1) Conduction of maintenance only without hazard through machinery 2) Conduction of maintenance on running machinery only by presence of specific protective devices (grids, light curtains, pressure mats, enabling device) 3) Conduction of maintenance without protective devices only by presence of additional devices (magnetic gripper, pliers, enabling device, portable emergency stop, slowing down of working velocity) 4) Conduction of maintenance without auxiliary devices only by presence of special measures; Hierarchy of measures against dangerous machinery movements: 1) Starting of maintenance only due to absence of hazard through machinery (standstill of dangerous movements, no possibility of starting the machinery, prevention of dangerous movement due to stored energy); 2) Conduction of maintenance on running machinery only by using special protective devices (separating protective devices (covers, enclosures), portable protective devices (two-hand control device, enabling device), command devices with automatic reset device	Major bruises; Injury through sharp devices; Falling from heights; Damage to equipment/machinery; Standstill of production	Liberation of facility after finishing work and removal of working force

					and protective devices with proximity sensor (light curtains, light barriers, pressure-sensitive mats)) - emergency shutdown buttons and pull-cord switches are not suitable; 3) Implementation of maintenance without protective devices only by presence of specific additional devices that e.g. enabling fast shutting down (emergency shutdown buttons, enabling device), enabling slowing down of velocity, barriering dangerous areas (covers); 4) Possibility of maintenance without named measures (1 - 3) only by presence of competent and qualified personal and one person standing at the emergency shutdown button		

Number	Stage	Risk Issue	Risk Event/Issue	Causes	Preventative Controls	Impact	Mitigating Controls
34	**Safety**	**Organization**	Rail operation/railway sidings	Hazards due to vehicle operation and electric facilities (catenaries, feedlines) in relation with tracks	Usage of security guards due to impossibility of safeguard measures; Prohibition of working start prior to instruction through supervisor of train operator; Prior to work: Instruction of personnel; checking of hearing and visibility under certain conditions; Safeguard measures: Protective fixed barriers between operation track and working area; usage of derails; usage of automatic crew alert (Rottenwarnanlage); Machinery and automotive usage: Usage of track-bound machinery only through qualified person; prohibition of machinery movement due to constrained sight; usage of proper places as co-driver; protection of parking wagons with skids; usage of earth-movers or cranes on tracks only due to command of supervisor; activation of overhead line and feeder line; Mine siding and industrial siding: Validity of special duties for industrial sidings e.g. authorization requirement, technical and organizational regulations; validity of rail-juridical and worker protection-juridical regulations; operation of industrial siding through an enterprise (not public); possibility of rail vehicle	Damage to equipment; Standstill of production; Injury to personnel	During work: Wearing of high-visibility clothing; checking for hazards at darkness; prohibition of leaving ensured working place unauthorized; immediate abidance of warning signals; prohibition of security guard distraction; leaving of the tracks at determined side; entering the tracks after supervisor command; keep distances to rail vehicles during entering the tracks; leaving of building machines only on track-free side; storage of working tools and devices in a certain distance to tracks and not in safety rooms; separation of tracks only if bypass for bridge current exists; proper behavior of security guards; clearing of tracks due to lack of planned safeguards requirement; Machinery and automotive usage: Prohibition of jumping up/off driving track vehicles; cowered walking between buffers of standing automotive; keeping distances to overhead line and feeder line due to impossibility of activation

					transition; approval of mine siding erection and operation through approval of e.g. local mining office; industrial siding enterprises are regarded as employers; exception of industrial siding without in-house operation from duty of plant manager; duty of operating instructions creation; adherence of technical regulations (rail-juridical approvals, maintenance regulations, cleaning instructions and auditing standards) for industrial sidings; reporting obligation of accidents or operational disturbances to accident investigation authority of Ministry of Transport by industrial siding enterprises; reporting obligation of lethal or heavy working accidents to working inspectorates		

Number	Stage	Risk Issue	Risk Event/Issue	Causes	Preventative Controls	Impact	Mitigating Controls
35	**Safety**	**Organization**	Alcohol and addictive drugs	Abuse of alcohol, medics, addictive drugs	Prohibition of alcohol/addictive drug consumption during work; Prohibition of working place entrance of employees under alcohol/addictive drug influence; Expel of employees under alcohol/addictive drug influence; Informing of employee organization	Damage to equipment; Standstill of production; Injury to personnel	Ingesting only antialcoholic drinks during work; Drinking of enough water; Monitoring of employee conditions e.g. residual alcohol; Prohibition of heavy medic indication during work
36	**Safety**	**Personal protective equipment**	Personal protective equipment	Risky/dangerous conditions during working activities	Wearing of head protection, hearing protection, safety glasses, safety masks, breathing protection, hand/arm protection, skin protection, safety boots, personal protective equipment against fall, personal protective equipment against drowning, high-visibility clothing, and weather protection if necessary; Introduction of safety culture within company	Injury to personnel	Monitoring of working conditions; Communication within company
37	**Safety**	**Personal protective equipment**	Risk of falling (1)	Working conditions (e.g. open-pit operations, exposed places) including risk of falling	General: Usage of personal protective equipment e.g. safety belt, safety harness, safety rope, karabiner, fall damper, rope shortener, height protective device; instruction of device-using personnel in usage of protective equipment in intervals (every 1 year); usage of safety ropes only in combination with safety belts or safety harness; fall protection (e.g. dams, boulders, barriers, safety	Injury to personnel; Death	Monitoring of roped up person by minimum one additional person; Live-saving equipment and their usage during rescue: Guarantee of secure absorption of falling body load (minimum 7,5 kN) through stopping point; placement of stopping point orthogonal above user; dumping of belts and ropes after a fall

					nets) required at each working place/travelways; usage of fall protection for entries, facilities, processing site starting at 1 m falling height for all stationary areas, stairs, wall openings, operation places for machery and their accesses; <u>Retaining/catching systems:</u> Usage of retaining/catching system (safety harness (EN 361), fall damper (EN 355), rope shortener (EN 353-2), height protective device (EN 360), stop device) due to impossibility of technical fall protection or catching facilities installation;		

Number	Stage	Risk Issue	Risk Event/Issue	Causes	Preventative Controls	Impact	Mitigating Controls
38	**Safety**	**Personal protective equipment**	Risk of falling (2)	Working conditions (e.g. open-pit operations, exposed places) including risk of falling	Live-saving equipment and their usage during rescue: Provision and maintenance of sufficient live-saving equipment (e.g. descendeur, lifting device, lifebelt) and means of escape by employer; checking of user manual prior to rescue; checking conditions of ropes, belts, accessories prior to rescue; storage of live-saving equipment on proper places or under proper conditions (free-hanging in dry rooms, certain distance to heatings, preventing connection with aggressive substances, protection against sunlight, protection against sparking); proper marking (manufacturer's logo, type, year of manufacture, serial number or number of manufacture, CE marking) of devices; conduction of control (minimum every 1 year) through qualified person; dumping of damaged devices; adherence of 7 essential rules: priority of collective protective measures, providing proper education/instruction, checking equipment, proper preparation of work, usage of secure stopping points, individual adaption of equipment, guarantee of secure; Fall protection in open-pit mining/mountains - behavior	Injury to personnel; Death	Monitoring of roped up person by minimum one additional person; Live-saving equipment and their usage during rescue: Guarantee of secure absorption of falling body load (minimum 7,5 kN) through stopping point; placement of stopping point orthogonal above user; dumping of belts and ropes after a fall

					rules: Regulation of responsibilities and authorities; ensuring of proper communication in all situations; subdividing of hazard zones in sectors; systematic analysis of terrain and definition of local safety goals; conduction of evaluation; exposure time constraints; creation of safety/secure concept prior to work; investigation of systematic hazards; mapping of hazards; planning of measures (entry to open-pit, definition of escape ways/safety areas/assembly points, working shut down circumstances, signals and barriers, protection of/from third party, checking influence of changing conditions)		

Number	Stage	Risk Issue	Risk Event/Issue	Causes	Preventative Controls	Impact	Mitigating Controls
39	**Safety**	**Personal protective equipment**	Risk of drowning	Working on/above/in waters	Usage of sufficient protective equipment (e.g. life jacket); Knowledge of minimum one present person about reanimation Life jacket: Proper storage/transport of life jacket; reconstruction of life jacket only through qualified person; checking of lifetime and maintenance intervals in manufacturer information; checking of CE marking; conduction of practical exercises; recommendation of using an automatically vest	Injury to personnel; Death	Knowledge of minimum one present person about reanimation; Monitoring of working conditions
40	**Safety**	**Workmanship and working process**	Geogene hazards	Emission of mineral dust due to mineral extraction; Hard rock hazards: Falling of joint bodies caused by external influences (joint water, ice pressure, material/geometry changes due to weathering, erosion and mining activities); sliding of joint body along discontinuity/discontinuities; sliding of multiple bodies along a polygonal sliding plane; tilting/sliding of towerlike/platy joint bodies at the edge of a competent joint body on a incompetent base; rotation of singular joint bodies;	General: Investigation of geogene risk potential followed by a risk identification and planning stage; sufficient design for bench height/width and travelways; usage of measures for improving rock mass conditions; illustration and marking of geogenic danger areas; Drainage: Usage of surface drainage, drains (prohibition of construction at slope foot/slope area parallel to slope), drainage drill holes (inclined in direction of dewatering), drainage adits); Geological adaptions: Engineering-geological planning prior to designing of slope; Monitoring of benches (daily observation through plant manager/qualified person);	Occurrence of impacts mentioned before - "causes"; Injury to personnel; Damage to equipment; Standstill of production	Technical measures: Reduction of slope angle at working places and travelways; rehabilitation of dangerous areas; scaling of slope faces; adaption of bench orientation/working direction due to geological conditions; adaption of mining method; Drainage: Usage of surface drainage, drains (prohibition of construction at slope foot/slope area parallel to slope), drainage drill holes (inclined in direction of dewatering), drainage adits); Topographical adaptions: Stabilization through dumping at slope foot; excavation of slope crown; reduction of slope

				kinking of column-shaped/tabular-shaped joint bodies; tilting of column-shaped/tabular-shaped joint bodies; Loose rock hazards: Sliding of a failure body on a shell-shaped sliding plane; slope creep; flow (solid/water mixture); Slope stability: slope stability is influenced by specific weight of slope ground, grain size distribution, grain size and grain abrasiveness, porosity and bulk density, moisture content, angle of internal friction, consistency, shear strength, shape change behavior, degree of saturation, cohesion, structure, structural strength of slope ground (undisturbed, grown, disturbed), slope inclination and slope height, ground water table, external water, unsteady flowing mechanisms, mass forces; operational loads through drilling and blasting or mineral extraction, erosion	Organizational measures: Fixing of off-times; prohibition of entrance/access for certain areas; fixing, blocking and marking of dangerous areas; dumping of walls in front of slopes/benches due to rock fall hazards (minimization of movement); usage of sufficient self-driving working tools (Falling Object Protection Structure (FOPS), Roll Over Protective Structure (ROPS))		inclination; planned failure due to blastings; Geological adaptions: Adaption of slope on existing discontinuity system; Design measures: Erection of supporting walls, gravity walls, cantilever retaining wall and slope stabilization through shotcrete, rock bolts; Recultivation: Sufficient recultivation;

Number	Stage	Risk Issue	Risk Event/Issue	Causes	Preventative Controls	Impact	Mitigating Controls
41	**Safety**	**Workmanship and working process**	Blasting operation	Handling of explosives; Incorrect/incomplete detonation of explosives	Investigation and evaluation of existing hazards; Creation of drilling plan, charging plan, and initiation plan based on investigations and evaluations prior to blasting; Creation of blasting pattern (drilling pattern, charging pattern and initiation pattern) due to many comparable blastings; Attachment of blasting patterns on health protection and safety protection	Absorption of dangerous substances through skin/airways; Occurrence of blasting fumes (NO_x, CO, CO_2); Occurrence of fly rock and ground vibrations; Intolerance regarding explosives, devices, means; Impacts from environment (rock fall, avalanche, water inflow, explosive gases, high/low temperatures); Impacts on neighboring working places; Damage to equipment; Standstill of operation	Monitoring of blasting procedures; Adaption of blasting parameters e.g. charge per delay, burden between rows, burden to free surface, initiation sequence, delay times, initiation system, spacing between boreholes, stemming to separate cartridges; Surveying of boreholes; Usage of other type of explosives; Usage of blasting mats against fly rock
42	**Safety**	**Workmanship and working process**	Crusher	Removal of blockage at crusher feeding; Hurling of material out of crusher; Sticking, bruising and catching of body parts at moving machine parts; Noise during operation; Dust exposure during comminution; Hazards due to maintenance/repair	Blockage against falling into crusher; Turning off and locking machinery during maintenance/repair; Sufficient planning of maintenance implementation (e.g. usage of proper working tools); Checking of manuals and maintenance instructions; Checking machinery conditions e.g. static placement on floor, electrical connections, condition of connector sockets, installation of protection covers, secure of views and takings against reaching into, condition of air pipes, condition of couplings, condition of emergency stop facility, condition of rebound	Damage to equipment; Injury to personnel; Death	Chain curtains at crusher feedings against hurling out material; Water sprays at crusher feedings and dust collection devices due to reduction of dust emission; Monitoring of crushing operations; Communication within company

					protection, marking of dangerous area, condition of transmission covers, condition of hydraulic lines		

Number	Stage	Risk Issue	Risk Event/Issue	Causes	Preventative Controls	Impact	Mitigating Controls
43	**Safety**	**Workmanship and working process**	Belt conveyor	Catching of body parts through rotating belt; Wrapping around of auxiliary working tools due to pulling into entries of machine; Fall due to walking over conveyor belt; Hazard due to slipping off of belt; Hazard of being pulled into conveyor at driving drum, tension roller, deflection pulley, pressure roller, carrier roller at belt bending, roller at belt turns; Hazard of being pulled into conveyor due to impossibility of belt dodging e.g. at carrier roller below feed hopper, carrier roller during conveying material, or carrier roller below belt;	Cover of dangerous areas due to danger of being pulled into conveyor; Protection of protection facilities at operation roller/drop roller against hazards due to being pulled into, catching, or spooling; Usage of non-hindering protection facilities at tension roller due to regular maintenance; Secure of under-belt carrier roller up to a height of 2,50 m against catching	Injury to personnel; Damage to equipment	Monitoring of machinery; Communication within company
44	**Safety**	**Workmanship and working process**	Fastening of loads (1)	Transportation of loads; Handling with loads	Transport: Transportation of loose pieces only inside load handling devices e.g. stone basket, material box; leading of long pieces with leading ropes; fastening of loads with additional protection; instruction of work force prior to transportation; Lifting means: Permanent and clearly visible marking of lifting means; permanent and clearly visible naming of load capacity up to an inclination of 60° (except single-thread	Damage to equipment; Injury to personnel	Lifting means: Protection of lifting means during lifting near sharp edges; assumption of existence of only two load bearing ropes at multi-rope suspension gear; Chains: Straight pulling of chains

					ropes, bands and chains due to naming of load capacity through tables); preventing deformation of load hook mouth in lifting means; prevention of more than 5 % deterioration in load hook mouth; testing of lifting means in intervals (minimum on yearly basis) through qualified person; Steel wire ropes: Minimum diameter of 8 mm; regular maintenance of steel wire ropes; dumping of ropes due to rusting, heavy deformation, breaking of many wires in small areas, or buckling of rope; prohibition of straight-pulling of steel wire ropes with carrying load; Rope end connections: Prevention of ferrule bending; usage of valid rope locks; proper allocation of wedge and lock; securing of rope end against pulling out; prevention of wire rope clips for rope end connections		

Number	Stage	Risk Issue	Risk Event/Issue	Causes	Preventative Controls	Impact	Mitigating Controls
45	**Safety**	**Workmanship and working process**	Fastening of loads (2)	Transportation of loads; Handling with loads	Chains: Cleaning of chains (must be corrosion-free); usage of valid working tools for shortening of chains; mitigation of load capacity during freeze; dumping of chains due to extension (whole chain or one link) of more than 5 %, reduction of chain width at one position of more than 10 %, increase of hook mouth of more than 10 %, or contact with live material; Fiber lifting slings: Minimum diameter of 16 mm (fibre ropes); presence of markings with information about load capacity during various fastening methods; prohibition of natural fibre ropes out of cotton as lifting gear; storage of fibre ropes in dry and ventilated rooms; dumping of ropes due to heavy deformation, damage through wrong storage, or breakage of lace; Load handling device: Permanent marking of device (company, name, inclination angle, length of 4 strand hanger, stacking height, load capacity, weight, content, build year, article number); delivery together with manual by manufacturer; permanent attachment on device of important manual parts; regular testing of load handling devices regarding abrasion, deformation, fractures, pollution, and marking	Damage to equipment; Injury to personnel	Lifting means: Protection of lifting means during lifting near sharp edges; assumption of existence of only two load bearing ropes at multi-rope suspension gear; Chains: Straight pulling of chains

Number	Stage	Risk Issue	Risk Event/Issue	Causes	Preventative Controls	Impact	Mitigating Controls
46	Safety	**Workmanship and working process**	Transport/load restraint (1)	Insufficient load restraint; Transportation of dangerous goods e.g. loads for petrol and diesel, battery acids, fluid gas, or oxygen	General: Tensioning of lashing strap and chains; dumping of damaged lashing trap and chains; internal driver license for driver; secure of load against drop and movement on loading platform; Load restraint: Secure and storage of load against heavy movements during transport; secure of load in driving direction with a counterweight (minimum 80 - 100 % of load weight); secure of load against driving direction with a counterweight (minimum 50 % of load weight); secure of load on both sides with a counterweight (minimum 50 % of load weight); reduction of friction due to usage of anti-slide mats; positive-lock securing of loads with e.g. scantlings, wedges for blocking, loading skids, nets, or paddings; correct direct lashing (e.g. through lashing of load, head lashing, bay lashing, diagonal lashing, or tilted lashing in longitudinal/cross direction); correct tie-down lashing (considering weight of load, friction coefficient, lashing angle, lashing means, pre-tensioning, and distribution of pre-tensioning on both ropes of lashing means); correct combined load restraint (usage of anti-slide mats + tie-down lashing + zero space between front side of load and headboard); 7 basic rules of	Damage to transport means, vehicle, or stranger facilities	Monitoring of load restraint; Twice-checking of regulations due to transportation of dangerous goods; Twice-checking of stability of load restraint

					load restraint: 1) usage of sufficient vehicles 2) prevention of exceeding whole weight and load on axes 3) keeping barycenter as low as possible and in the middle longitudinal plane 4) secure and storage of load against slipping, rolling, dropping, and tilting 5) usage of sufficient securing devices 6) prevention of damaging the load through storage or secure 7) adjusting of driving velocity due to traffic conditions		

Number	Stage	Risk Issue	Risk Event/Issue	Causes	Preventative Controls	Impact	Mitigating Controls
47	**Safety**	**Workmanship and working process**	Transport/load restraint (2)	Insufficient load restraint; Transportation of dangerous goods e.g. loads for petrol and diesel, battery acids, fluid gas, or oxygen	Liability law and transportation of dangerous goods: Checking of liability law (StVO, KFG, FSG); checking of legal regulations due to transportation of dangerous goods (GGBG, ADR, GGBV); Small quantity exception: Declaration of total quantity each carriage category on carriage paper; calculation of transportation limit (point rule) due to transportation of various dangerous goods altogether (≤ 1000 points = small quantity transport, > 1000 points = subject to marking transport of dangerous goods); Transportation of small quantities of dangerous goods: Prohibition of loading goods of class 1 together with other dangerous goods; usage of a danger label, the letters "UN" and the UN number on each excepted package; usage of container for diesel fuels with additional marking on container; sufficient load restraint against movement; separate storage of dangerous goods; sufficient ventilation due to transport of class 2 gases; prohibition of smoking (also e-cigarettes) and usage of fire during loading of goods; switching-off engine during loading and unloading; observance of accompanying documents and equipment (fire extinguisher)	Damage to transport means, vehicle, or stranger facilities	Monitoring of load restraint; Twice-checking of regulations due to transportation of dangerous goods; Twice-checking of stability of load restraint

Number	Stage	Risk Issue	Risk Event/Issue	Causes	Preventative Controls	Impact	Mitigating Controls
48	**Safety**	**Machinery, devices and facilities**	Safety of machinery	Uncertified machinery; Requirement mismatching of machinery; Inadmissible modifications	Adherence of European Standards during designing and manufacturing of a machinery (declaration of conformity and CE marking); Equipment requirements for old machines: Fulfilling of certain uniformly designated requirements; presence of operating manual in German; Certifications, safety requirements: Guarantee of matching safety requirements by manufacturer; Additional safety through voluntary tests conducted by certificate authorities; Maintenance: Focusing maintenance on safety facilities; creation of sufficient plan regarding systematic maintenance; implementation of maintenance by qualified persons; Modification: Usage of modified machines only due to conduction of a hazard analysis and implementation of measures; combined usage of working tools only due to compatibility agreement and implementation of a hazard analysis; clarifying of intention (modification or exchange)	Damage to equipment; Injury to personnel	Duties of employers: Regular maintenance of machinery; regular testing of machinery by qualified persons; presence of operating manual at site; Tests during operation: Testing of working tools due to regulations arranged by employer; issuing of test results; Maintenance: Usage of maintenance books for cranes, power-operated working tools for load lifting, winches and towing equipment, goods cable lifts, excavators and LHDs for lifting of single loads, load carrying facilities and lifting means for loads or work cages, self-driving working tools, and working tools for lifting employees;

Number	Stage	Risk Issue	Risk Event/Issue	Causes	Preventative Controls	Impact	Mitigating Controls
49	**Safety**	**Machinery, devices and facilities**	Risk of tipping-over, falling, and rock fall	Unstable benches; Slippery surfaces; Unstable working position	ROPS as a protection during rolling over; FOPS as a protection against falling rock blocks; Tip-over protective structure (TOPS) as a protection against tip-over for small excavators	Falling rock blocks from bench; Falling from the edge of the bench during operation; Tilting during operation	Monitoring of working area; Visual contact between workers; Watching out for gesticulations;
50	**Safety**	**Machinery, devices and facilities**	Danger zone of working tool	Blind spot of working tool; Inaccurate adherence of safety zone around working tool	Prohibition of walking under lifted loads and lifted parts of working tools e.g. boom, bucket; Prohibition of staying in driving/slewing direction of working tool; Adherence of safety distance between moving machinery and solid parts of the surrounding; Sufficient field of view (visibility of crouched person in the range of 1 m around the working tool)	Damage to equipment; Injury to personnel; Death	Observation of surrounding area by working tool operator; Usage of driving cameras during driving; Measures due to insufficient field of view e.g. separation of trafficways, technical barrier of working place, driving cameras, signaler, person identification systems;
51	**Safety**	**Machinery, devices and facilities**	Hydraulic excavator, loader	Loading process; Unstable benches; Maneuverability of machinery; Slippery surfaces	Checking of safety devices (brakes, warning devices, emergency stop) prior to lifting work; Usage of automatic overload control for hydraulic excavators; Prohibition of load lifting above persons; Leading of fastened loads with ropes	Falling during getting in and getting out of excavator/loader; Collision between loading machine and truck during loading; Falling down of rock blocks during loading with excavator; Falling during turning machinery on benches; Slipping with excavator/loader on slippery surfaces	Usage of climbing helpers (e.g. ladder, stairs, handrail) during getting in; Turning of machinery only within sufficient areas; Keeping visual contact during access; Switching off trucks during loading; Usage of honks for communication during loading process (truck, excavator)

Number	Stage	Risk Issue	Risk Event/Issue	Causes	Preventative Controls	Impact	Mitigating Controls
52	**Safety**	**Machinery, devices and facilities**	Trucks	Loading process; Dumping areas; Driving on trafficways	Prohibition of walking on operating benches; Getting out of machinery only during visual contact to workers; Staying inside machinery during loading; Secure of dumping areas; Proper position of loading trough (totally lowered) during driving; Prohibition of exceeding valid load on axes; Regulation of priority in traffic with markings	Falling during getting in and getting out; Overloading machinery; Tilting at dumping areas;	Usage of climbing helpers (e.g. ladder, stairs, handrail) during getting in; Observation of dumping areas; Watching out for gesticulations
53	**Geology**	**Mineral deposit conditions**	Inaccurate size/shape/grade of deposit	Lack of exploration; Lack of collection/documentation of drill cores; Insufficient application of deposit models	Increasing exploration; Collecting and documentation of drill cores (depth, photo)	Wrong decision making (mining method); Problems with ground control	Creation of deposit models and permanent updating of data due to exploration; Comparing of real data with modelled data
54	**Geology**	**Rock strata conditions**	Faulting	Tectonic setting	Observing geology; Application of investigation tests (e.g. Markland Test)	Loss of orebody direction; Mining the wrong areas; Different ore grades to processing	Manifold exploration of (geological) important areas
55	**Geology**	**Rock strata conditions**	Presence of water	Inflow of water in abandoned mine workings; Accumulation of water above impermeable layers; Decreasing of shear parameters	Investigation of water bearing formations; Water control by pumping; Creation of hydrogeological maps; Drainage of water bearing formations; Looking out for leakage areas	High costs due to de-watering; Flooding of important working areas; Damage to equipment; Injury to personnel; Failure of small to large structures	Drainage of water bearing formations; Secure observation of water run-outs: Prevent working in dangerous areas; Drainage of water bearing formations

Number	Stage	Risk Issue	Risk Event/Issue	Causes	Preventative Controls	Impact	Mitigating Controls
56	**Geology**	**Rock strata conditions**	Hard rock strata	Geological formation of competent rock	Exploration and observation of mining area; Investigation of geological maps; Getting information of neighboring mines	Low to severe damage to BWE	Pre-splitting/Pre-blasting of more competent layers/zones
57	**Geology**	**Rock strata conditions**	Soft rock strata	Geological formation of less competent rock	Exploration and observation of mining area; Investigation of geological maps; Getting information of neighboring mines	Overestimating of rock conditions; Too high investment costs for BWE	Choosing of sufficient cutting tools
58	**Environment**	**Working conditions**	Dust exposure	Loading; Transportation; Crushing	Dust suppression facilities during drilling; Ongoing tests due to dust exposure; Moistening of transport and driving routes during summer; Covers for waste dumps; Using water sprays for trucks	Suspended solids; Disturbance of public society/environment; Health problems (Quartz, Silicosis)	If no quality control is needed, using of minimum transport ways is suggested; Installation of dust suppression devices on drilling machines; Increasing of watering during hot summer days
59	**Environment**	**Working conditions**	Vibrations	Blasting; Crushing; Transportation	Usage of vibration mitigating basis for crushers; Accurate blast pattern (burden, spacing, delay times, scaled distance); Measurements of vibrations (geophones)	Disturbance of public society/environment; Damage to buildings/facilities	Optimization of initiation/charging/blasting plan; Positioning of geophones at various distances from blast;
60	**Environment**	**Working conditions**	Noise exposure	Blasting; Crushing; Secondary breakage activities; Transportation	Noise reduction barriers (plant trees, dumping a wall); Orientation of mining operation	Disturbance of public society/environment	Measurements of noise level during blasts (microphone)

Number	Stage	Risk Issue	Risk Event/Issue	Causes	Preventative Controls	Impact	Mitigating Controls
61	**Environment**	**Working conditions**	Water pollution	Acid Mine Drainage from sulfide rich minerals; Suspended solids; Dissolved solids; Nutrients; Toxic compounds	Accurate dumping of tailings (dam material, inclination of dams, impermeable layer below); Cover for waste dumps to prevent erosion; Reduction of erosion; Biological processing treatment; Site preparation for heap leaching and tailing dams	Low to severe damage to public society/environment	Prediction of acidic regions and prevention of oxygen contact; Vegetation/soil stabilization; Reduction of erosion, monitoring mine dewatering; Using another treatment for gold and silver processing; Monitoring of solutions, reduce contact to wildlife
62	**Environment**	**Working conditions**	Release of toxic compounds	Excavation; Dust emissions	Geochemical investigations of ground conditions/rock mass	Contact of arsenic, pyrite with water -> generation of arsenic acid/sulfuric acid; Recultivation problems: Missing nutrients in ground for flora; Hazard for health conditions of fauna, humans; Pollution of environment (lake, river, soil)	Blockage of affected area; Regular sampling of affected area
63	**Environment**	**Working conditions**	Emissions of CO, NO_x, CO_2	Utilization of diesel-powered machinery	Presence of CO_2 certificates	Restrictions from mine inspectorates; Governmental disputes	Utilization of electrically powered machinery; Monitoring of emissions
64	**Environment**	**Working conditions**	Accumulation of CO_2	Very deep open-pit mine (bowl design)	Sufficient ventilation	Accumulation of CO_2 on open pit floor -> lethal at content of 10 %	Monitoring of CO_2 content
65	**Environment**	**Working conditions**	Tailings	High-volume waste; Containment of toxic metals (Pb, As, Cd); Dumping in the next suitable location	Long-term tailings disposal plan; Prevention of mobilization of tailings and release of toxic components	Occupation of large surface areas; Pollution of groundwater, river, and soil; Destroying habitats	Tailings disposal in underground openings; Usage of tailing ponds

Number	Stage	Risk Issue	Risk Event/Issue	Causes	Preventative Controls	Impact	Mitigating Controls
66	**Environment**	**Working conditions**	Recultivation/Site Reclamation	Suitability of area after mining activity; Slope stability of open pit; Too shallow rootage of flora	Early start of recultivation; Comparing own mine conditions with other mines;	Disturbance of landscape; Slope failure due to insufficient recultivation; Extinction of animal species, plant species	Using fast growing plants/trees; Gather information of experts; Monitoring of growth progress
67	**Environment**	**Legislation**	Environmental restriction	Restraints due to legislation	Previous checking of international constraints and framework conditions	Standstill of mining activities due to negotiations with government; Loosing of extractable areas due to seldom animal occurrence; Prohibition of mining at certain areas	Following restrictions; Searching for improvements due to working conditions; Good relationship with responsible persons
68	**Financial**	**Economics**	Underestimation of costs	Forgetting about unexpected costs e.g. changing diesel price, changing water price	Twice-checking of costs; Stay updated regarding price development	Budget too low; Getting dismissed	Balance sheet checking; CAPEX/OPEX checking
69	**Financial**	**Economics**	Overestimation of income	Changing of prices for metal ores/exporting coal on the market	Twice-checking of revenues; Checking of commodity prices (e.g. daily basis)	Budget too low; Getting dismissed	Balance sheet checking; CAPEX/OPEX checking
70	**Financial**	**Economics**	Unfavorable development of exchange rates	Changing of currency on currency market	Checking the currency market	No profit (costs higher than revenues); Getting dismissed	Balance sheet checking
71	**Financial**	**Economics**	Changing of commodity prices	Changing of prices for metal ores/exporting coal on the market	Checking markets (LME, NYMEX, COMEX)	No profit (costs higher than revenues); Getting dismissed	Balance sheet checking
72	**Financial**	**Economics**	Lower plant performance	Disturbance e.g. strike, accident; Damage to equipment	Good relationship with employees; Considering tribal laws and customs; Checking national risks and priorities	Loss of money due to production standstill; Kidnapping	Living in peace with public society; Prevent damage to native people; Secure areas against usurpers
73	**Financial**	**Economics**	Taxation changes	Change in politics and legislation due to governmental change	Keep yourself informed; Investigation of political system and legislation prior to mining; Stay up to date	Loss of money	/

Number	Stage	Risk Issue	Risk Event/Issue	Causes	Preventative Controls	Impact	Mitigating Controls
74	**Maintenance**	**Application**	Ignorance of maintenance	Carelessness of customer	Description of most important regulations in user guide (e.g. maintenance intervals, maintenance if extreme heat/freeze occurs); Motivation of customer for implementation of maintenance	Damage to machinery; Operational accidents; Injury to personnel	Maintenance in accurate intervals; Documentation of problems, observations; Communication with responsible person
75	**Maintenance**	**Application**	Implementation of maintenance	Carelessness of customer	Monitoring of maintenance (send data to headquarter); Check lists for maintenance; User guide for maintenance; Instruction of personnel;	Damage to machinery; Operational accidents; Injury to personnel	Maintenance in accurate intervals; Documentation of problems, observations; Communication with responsible person; Monitoring of maintenance
76	**Maintenance**	**Application**	Adjustment of machinery	Wrong adjustments of machinery	Instruction of personnel; Monitoring of machinery functions	Wrong application of machinery; Wrong production output; Damage to machinery; Quality impact; Injury to personnel	Monitoring of machinery; Production control; Quality control; Communication with personnel
77	**Maintenance**	**Application**	Updating machinery/facility functions	Updating software/hardware by responsible company/manufacturer	Training of operating and maintenance personnel; Checking of changes due to operation; Checking of technological changes on market; Stay up to date	Production standstill; Ignorance of personnel; Wrong handling of machinery; Quality impacts	Building up stockpiles; Communication with personnel; Alternative production in case of a shutdown;

Number	Stage	Risk Issue	Risk Event/Issue	Causes	Preventative Controls	Impact	Mitigating Controls
78	**Repair**	**Implementation**	Mechanical hazards	Falling objects; Leakage of fluids or fluids under pressure; Sharp edges/parts/surfaces of machinery; Uncontrolled/controlled movements of machinery parts; Slippery surfaces; Stumbling	Wearing of safety clothes during repair; Fix machinery against uncontrolled movements; Checking/cleaning of surfaces prior to repair; Disposal of damaged safety clothes; Usage of intact equipment/working tools for repair; Monitoring of critical points/areas; Hazard identification; Repair implemented by qualified person; Saving against restart of machinery	Injury to personnel; Damage to equipment; Standstill of production	Available first aid equipment; Emergency response; Blockage of hazard zone
79	**Repair**	**Implementation**	Electrical hazards	High voltage of machinery; Damaged wires; Sparking; Welding	Familiarizing with safety regulations; Monitoring of critical points/areas; Hazard identification; Wearing of protective equipment during repair; Usage of intact equipment/working tools for repair; Repair implemented by qualified electricians	Injury to personnel; Damaging of equipment; Standstill of production	Available first aid equipment; Emergency response; Blockage of hazard zone
80	**Repair**	**Implementation**	Fault finding	Complexity of system; Hiding of system components	Keep systems as simple as possible; Implementation of repair by qualified person; Training of more than one person for repair; Proper installation of machinery/equipment/system	Standstill of production; Hiring of experts -> high costs; Shutdown of system	Alternative operation method(s) in case of disturbances; Long-term manufacturer contracts

Number	Stage	Risk Issue	Risk Event/Issue	Causes	Preventative Controls	Impact	Mitigating Controls
81	**Repair**	**Implementation**	Unplanned movements of machinery	Lack of fixing machinery against movement prior to repair	Fixing of machinery against movement	Injury to personnel; Damage to equipment; Standstill of production	Emergency response; Shutting down of machinery
82	**Repair**	**Implementation**	Protective equipment	Repair under dangerous circumstances	Wearing of protective equipment during repair	Injury to personnel	Emergency response
83	**Repair**	**Implementation**	Adherence of regulations	Working without thinking on consequences; Endanger fellows during repair	Going through regulations prior to repair	Injury to personnel; Damage to equipment; Standstill of production	Emergency response
84	**Repair**	**Implementation**	Appropriate spares	Insufficient spares; Lack of spares	Checking of machinery user guide; Keeping spares on stock	Injury to personnel; Insufficient operating conditions; Damage to equipment; Standstill of production	Emergency response; Alternative operation system/method
85	**Repair**	**Implementation**	Trial	Wrong repair implementation	Twice-checking of repair results	Damage to equipment; Injury to personnel	Emergency response; Prevent operation with maximum load to machinery
86	**Repair**	**Implementation**	Unplanned starting of machinery	Technical failure; Activation through personnel	Saving against restart of machinery; Identification of repair actions	Injury to personnel; Damage to equipment	Easy reachability of kill switch
87	**Repair**	**Implementation**	Problem with solution finding	Lack of enrollment	Proper enrollment of personnel	Damage to equipment	Asking fellows for help; Communication within company
88	**Repair**	**Implementation**	Entry of ignorant person	Lack of barrier	Proper barrier installation	Injury to personnel	Ordering person away from working place

Number	Stage	Risk Issue	Risk Event/Issue	Causes	Preventative Controls	Impact	Mitigating Controls
89	**Reliability**	**General**	Appropriate construction of machinery	Usage of wrong information for construction by manufacturer; Delivering of wrong information for construction by company; Not finished construction of machinery; Bad working conditions in manufacture	Monitoring construction process in manufacture by manufacturer; Checking of manufacture processes by manufacturer; Detailed investigation of mine conditions and delivering information to manufacturer; Monitoring of working conditions in manufacture	Problems during operation; Damage to machinery; Standstill of production	Appropriate contracts with manufacturer (fine print, long-term guarantee); Alternative operation method(s) in case of disturbances
90	**Reliability**	**General**	Regularity of maintenance	Ignorance to maintenance; Wrong chosen maintenance intervals; Wrong user guide information	Instruction to personnel; Choice of responsible persons for monitoring implementation; Usage of a maintenance handbook (date, time, persons included and so on)	Damage to equipment; Standstill of production; Injury to personnel	Alternative operation method(s) in case of disturbances
91	**Reliability**	**General**	Machinery design	Inappropriate design of e.g. BWE, Spreader Bad working conditions in manufacture	Monitoring design process in manufacture by manufacturer; Checking of manufacture processes by manufacturer; Detailed investigation of mine conditions and delivering information to manufacturer; Monitoring of working conditions in manufacture by company	Bad working conditions; Damage to machinery; Injury to personnel; Standstill of production	Alternative operation method(s) in case of disturbances; Appropriate contracts with manufacturer (fine print, long-term guarantee)
92	**Reliability**	**General**	Quality of assembly	Bad quality of assembly; Bad working conditions in manufacture	Monitoring of assembly process in manufacture by manufacturer; Monitoring of working conditions in manufacture by company	Damage to/failure of machinery; Operational accidents; Injury to personnel	Alternative operation method(s) in case of disturbances; Appropriate contracts with manufacturer (fine print, long-term guarantee)
93	**Reliability**	**General**	Handling of machinery	Wrong handling of machinery by operator; Bad instructions by manufacturer	Instruction of operator; Training of operator; Regular observation of operational implementation	Standstill of production; Damage to machinery; Injury to personnel	Appropriate contracts with manufacturer (fine print, long-term guarantee); Switching of machine operator

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94	**Offer**	**General**	Technical and financial risks	Liquidity of customer; Wrong transmission of information; Security of country/state	Checking of customer's creditworthiness; Collecting of information about country/state; Looking at markets; Looking for other partners of customer and collecting information; Implementation of safeguarding measures (contract-based, insurance)	Wrong basis for projects; Failure of the project	Safeguarding measures (insurance, contract-based measures)
95	**Offer**	**General**	Feasibility of technical solution	Lack of knowledge; Lack of equipment range; Environmental conditions; Economical conditions; Operational conditions e.g. work force, infrastructure	Gather information regarding environmental/economical conditions; Working on an alternative plan (Plan B); Describe uncertainties for safeguarding reasons; Compare conditions with existing projects	Wrong implementation of solution; Failure of the project; Loosing of customer	Brainstorming regarding feasibility of solution; Consulting of experts; Adaptability of solution
96	**Offer**	**General**	Approval of offers	Approval through non-qualified person	Strict rules regarding approval of offers	Problems during project or failure of the project; Problems during handling of an offer	Approval chain within company
97	**Availability**	**General**	Weather conditions	Occurrence of storm, flood, earthquake, avalanche, or fire	Accurate investigation of climatic conditions in destination country; Looking for similar projects with similar conditions; Speaking to domestic people; Resistance of machinery against weather conditions; Design of machinery; Auxiliary installations e.g. early warning systems, cover for machinery; Protective equipment for personnel	Disturbance of the operation; Production standstill; Destroying of facilities/machines; Injury to personnel	Early warning systems; Checking weather warnings on TV; Emergency response plan; Auxiliary protective equipment for personnel; Limiting number of decision makers

Number	Stage	Risk Issue	Risk Event/Issue	Causes	Preventative Controls	Impact	Mitigating Controls
98	**Availability**	**General**	Availability <-> Reliability	Relationship between availability and reliability	Guarantee of reliability	Process/machinery/equipment not available	Monitoring of availability/reliability; Responsible person in company e.g. works supervisor
99	**Availability**	**General**	Engagement of personnel/customer	Carelessness of personnel; Value setting of enterprise	Organizational rules; Development of working culture in enterprise; Checking experiences with customer	Delay of project/operation; Damage to equipment; Bad working conditions e.g. condition of BWE teeth, energy supply problems; Lack of communication between instances	Appropriate contracts with customer; Communication within company; Monitoring of work force