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Key issues related to oreflow in raise caving

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Abstract

Oreflow was identified as a key issue for the successful implementation of the novel raise caving (RC) method. Critical excavations for the method are narrow de-stress slots and large production stopes. During extraction, slots and stopes are filled with blasted ore, which supports the excavation walls. To extract the ore, it needs to flow properly towards the drawpoints. Otherwise, voids can form, which serve as space for the hangingwall to cave into and cause dilution. Another critical aspect of oreflow is the avoidance of hang-ups in narrow slots. These can interfere with the predefined draw strategy, can form stress bridges which weaken the de-stress effect and are difficult to remove, especially in higher regions of the slot. Additionally, an even lowering of the bulk material should be achieved to form a free surface on top of the slot and stope. The surface is important to allow a subsequent blast conducted from raises above, which are an essential part of the infrastructure. For a beneficial environment of oreflow, a well-planned mine design and draw strategy are essential.

The emphasis in this paper is to highlight the key issues related to oreflow. The key issues, namely avoiding dilution, avoiding hang-ups and the creation of a free surface are individually defined, outlined and described. For this purpose, the oreflow in the large drawbells, which are utilised in raise caving, is analysed further with numerical simulations. The drawbell design is intended to be approached on two sublevels which is beneficial for a complete covering of the stope. Further, such a drawbell design may show positive effects on stability due to a lower amount of infrastructure on each level.

The simulations are done by means of the discrete element method (DEM). One part of the work considers the influence of drawbell shapes on the oreflow. It shows that an inclination for the large drawbell of around 60° is advantageous to enlarge the extraction zone. Additionally, the spacing of drawpoints is varied to investigate the effect of proper spacing on the overall flow situation. Thereby, a positive influence of the large drawbell on the interaction between the drawpoints could be shown. The results of the models and outcomes are presented in this paper to highlight the advantages of large drawbells for oreflow.

Keywords: *oreflow, raise caving, mine design, discrete element method simulation, drawpoint spacing, drawbell inclination*

1 Introduction

Increased mining depth using current mining methods like sublevel caving (SLC) inevitably leads to unfavourable rock pressure conditions. These rock pressure related problems are described in this paper with reference to the Kiirunavaara iron ore mine in Sweden. The novel raise caving (RC) method can provide a solution to address upcoming rock pressure problems and to ensure a safe mining environment (Ladinig et al. 2021). A critical aspect of a successful RC layout is to adequately handle the flow of the broken ore inside the stopes. A brief comparison between the present SLC and the planned RC needs to be done to fully understand the importance of oreflow in future mining operations.

Both mining methods use drilling and blasting to break the ore. In SLC mining, the orebody is prepared for extraction by developing drifts along strike in the footwall (FW) of the orebody. From these drifts, so-called crosscuts are developed to and through the orebody right to the hangingwall (HW) contact of the orebody. From these crosscuts, steeply inclined blasthole fans, so-called blast rings, are drilled and blasted on retreat. The blasted ore is loaded in the crosscut and transported to a system of ore passes through which the ore is gravitated to the main level, from where it is transported to a shaft system and hoisted to the surface. The overall direction of mining is top-down. The HW above the active sublevel is allowed to cave. The important point is that the vertical distance which the ore moves before it is transported to the orepass is typically the height of one, or maximum, two sublevels. A critical issue in SLC is to prevent dilution of the blasted ore with the caved waste rock, which is situated directly above and in front of the blast ring. Control of the oreflow is mainly done by coordinating drawing and loading operations in neighbouring crosscuts. A problem with SLC at great depth are the unfavourable stress conditions in the abutment zones, which endanger the mine infrastructure.

The situation with RC is different (see Figure 1). Here, long raise boreholes are drilled from a main level several hundred meters above the level where mining of the orebody commences. Starting at the bottom of the raise borehole, slightly dipping fans of blastholes are drilled and blasted. These drill fans are near horizontal, and the slices of ore are dropped by the explosives action into the void below. At the bottom of the raise stopes, there are drawbells with drawpoints from where the ore is loaded and transported to the main shaft system. Ultimately, there can be several hundreds of meters in the vertical direction over which the blasted ore has to gravitate to reach the drawpoint at the extraction level. The control of oreflow in the RC situation cannot be compared to that of SLC mining and is crucial for the success and performance of the RC mining system. Two different types of RC stopes must be distinguished. The first group of stopes are the relatively narrow 'de-stress slots', which are planned to have a strike width of 30–80 m, a thickness of 5–25 m and a vertical extent of several hundred meters. The second group of stopes are the 'production stopes' established in the stress shadow of the de-stress slots. The production stopes are of squared or circular cross-section, with a span of about 30–60 m.

In contrast to the de-stress slots, some of the production stopes are completely situated in the orebody while slots are at the HW contact of the orebody. To support the HW and prevent early caving, the slots and stopes are not emptied completely and, therefore, always filled with bulk material in order to be run in a shrinkage stoping mode. The fact that the orebody in Kiruna mine is reasonably flat dipping at an angle of about 60°, together with the great vertical extent of the stopes, complicates matters further.

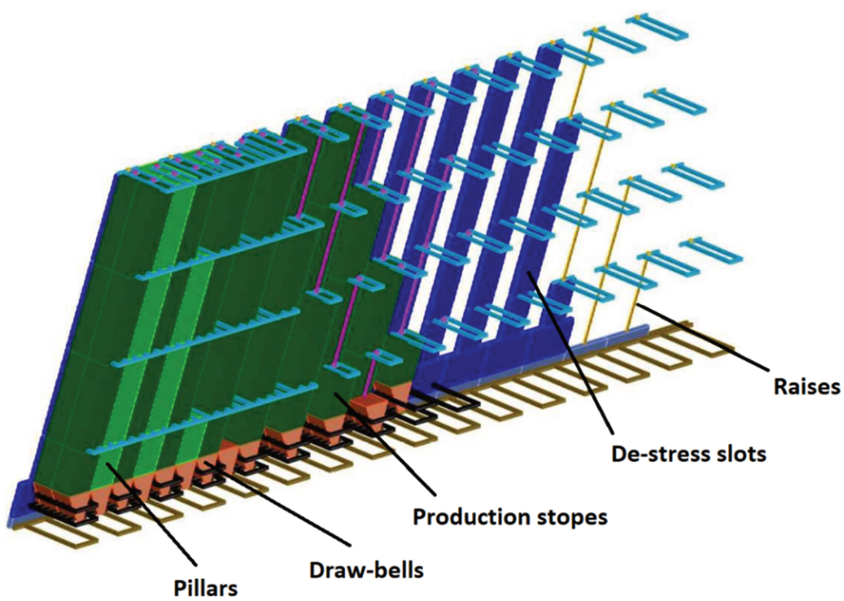


Figure 1 **Raise caving design: De-stress slots (yellow) are blasted from raises (light green), which then form favourable stress conditions for the production stopes (turqoise). These are extracted from drawbells (red) at the bottom, which are drawn via sublevels. In a later stage, also pillars (dark green) in between the stopes are mined (Ladinig et al. 2021)**

1.1 Key issues for a successful operation

To enable a successful mine operation, several key issues need to be considered:

- Maximum reliable extraction of the ore.
- Keep high production volumes despite the depth.
- Minimum dilution of ore with waste rock.
- Safe ore production at an acceptable cost.
- Stability of infrastructure in the FW area.
- Enabling a sustainable mining operation.

For the oreflow, various questions arise in terms of the mining method, the mine design and the draw strategy. These questions need to be investigated. To extract most of the ore in a caving operation and to delay dilution entry, the broken material needs to be extracted to allow even lowering of the top of the material pile. This situation is called mass flow, where the upper portion of the cave subsides uniformly in a way that particle trajectories are nearly vertical (Laubscher 2000). Mass flow can be achieved by smart mine design and a proper draw strategy. That means the drawpoints need to be spaced strategically and that the right amount of material is extracted from the right positions. It needs to be kept in mind that a system of stopes, de-stress slots, and possible pillar extractions are interacting at some point. Therefore, a global sequence needs to be established based upon subsidence control, stress management, production requirements etc.

As the dimensions of the two mentioned RC geometries (slots and stopes) are very different, the oreflow needs to be investigated separately for each situation.

1.1.1 Key issues in slots

The slot is characterised by a significant width and height, but a limited thickness (see Figure 2). The bulk material cannot flow freely as the narrow walls form frictional constraints. High stresses at great depths can further cause deformation and convergence of the slot walls. Hang-ups could form in higher regions of the slot, which can be difficult to resolve. Hence, a crucial point for the de-stressing slot is to prohibit the ore from clogging. To prevent these hang-ups, the minimum slot thickness needs to be investigated. A proper oreflow can be achieved by positioning the drawpoints at the bottom strategically, and enable a uniform lowering of the ore. To guide the material downwards despite the dipping angle, intermediate draw levels can be used for loading on higher elevations. A second important point for the slot is to lower the material and create a void on top of the rock pile. This acts as a free surface for the subsequent blasted ring. Additionally, the free volume must be prevented from getting too large, as the HW might otherwise cave and lead to early dilution. Potential difficulties in drilling and blasting need to be considered for the narrow geometry of the de-stress slots.

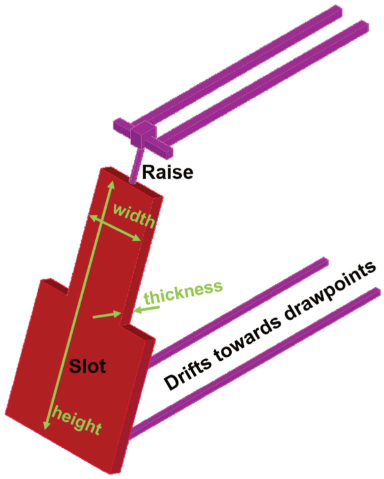


Figure 2 Thin de-stressing slots form favourable stress conditions for the infrastructure behind them

1.1.2 Key issues in stopes

In contrast to the de-stressing slot, the stopes have large dimensions in all directions (see Figure 3). Hang-ups and wall convergence play a minor role. The target is to lower the blasted and caved material uniformly to avoid dilution and thus to extract the entire volume as completely as possible. The drawpoints need to be placed strategically for a good interaction of their particle movement zones. Because the RC system is flexible, there are several possibilities to construct the layout. A part of the solution is to place the drawpoints at two or more sublevels to achieve an ideal interactive flow within the stoping area. By maintaining a planned draw strategy, good control can be maintained for a uniform oreflow. Analogous to the slot situation, a void is required for the subsequent blast ring.

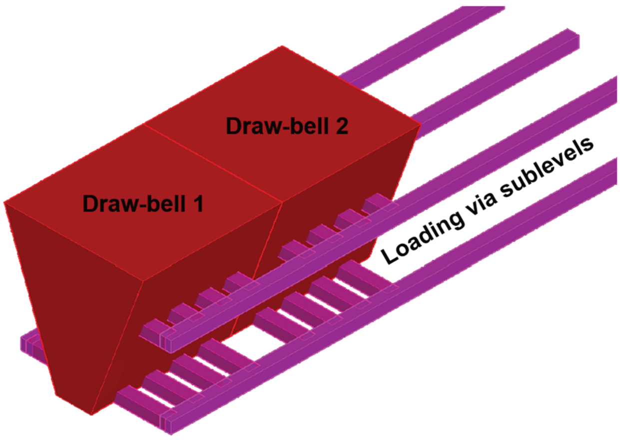


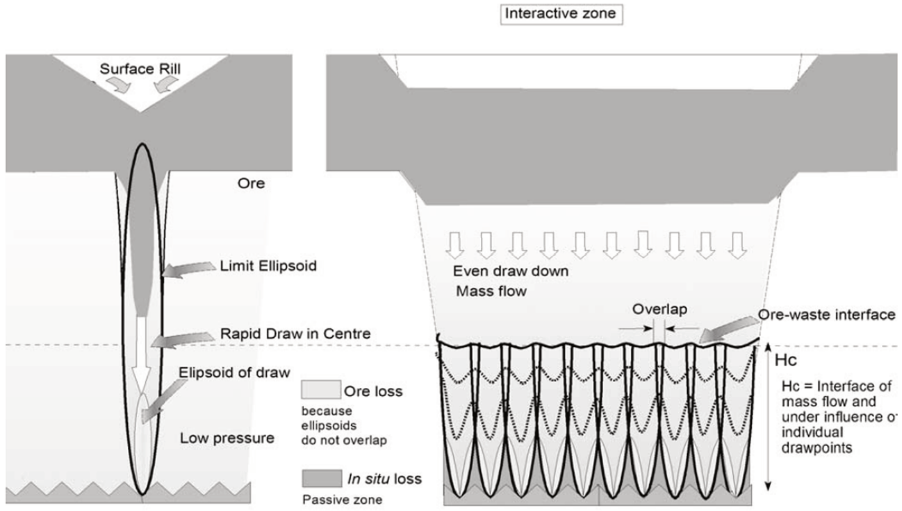
Figure 3 Large drawbell design can be developed in RC via sublevels for a flexible and efficient covering of the stope

1.2 Flow principles

The following principles apply to rather 'ideal' and unconstrained flow conditions, such as in sand models and block caves. Such conditions resemble the RC situation. In SLC, like in Kiruna, the confined blasting and restrained flow conditions lead to different effects which dominate the flow situation.

The first discovery in the early days of oreflow investigation with sand models was the ellipsoid theory (Kvapil 1965; Janelid & Kvapil 1966). It states that material extraction forms an ellipsoidal-like draw zone whose dimensions are dependent on particle size, particle size distribution and amount of material drawn. In Figure 4a, the principle is schematically drawn to allow a better understanding. The ellipsoid of the isolated draw zone (IDZ) describes the limiting outline of the original location of the drawn material. Another ellipsoid is defined by the isolated movement zone (IMZ), thus by the border between stationary material and material that had been mobilised (Hancock et al. 2010). As the drawpoint is mucked, the ellipsoids get higher and eventually form a cylindrical funnel, called a chimney that progresses upwards (McCormick 1968).

Another important recognition was that the isolated draw zones overlap if the openings are sufficiently close together – the so-called interactive draw (Heslop & Laubscher 1981; Laubscher 1994). Further, it was found that there was an even lowering of the sand on the top of the model when the drawpoints were spaced properly, and the material was extracted uniformly (see Figure 4b). Hence the interaction of draw zones resulted in a mechanism known as mass flow (Laubscher 2000). The height of interaction is the height at which the interacting movement zones transition to mass flow. This means that a uniform draw can be promoted by strategic spacing and mucking the drawpoints.

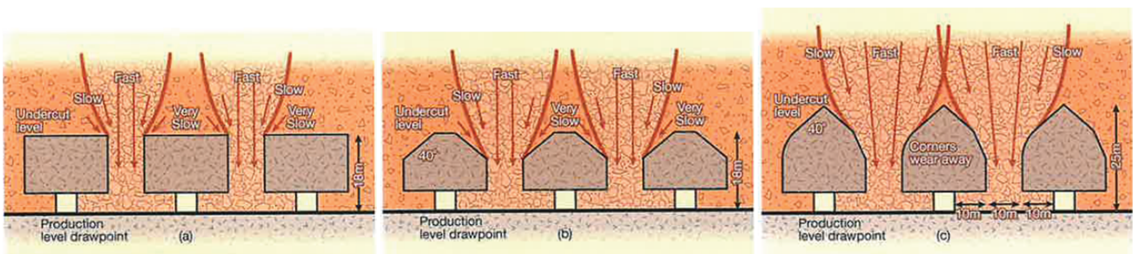


(a) (b)

Figure 4 Flow zones developing above drawpoints (a) A drawpoint worked in isolation where the 'Ellipsoid of draw' is the IDZ and the 'Limit Ellipsoid' the IMZ; (b) When the drawpoint spacing is designed so that the draw ellipsoids overlap, an even draw (mass flow) can be realised (Heslop 2010)

1.3 Drawbell design and drawpoint spacing

The drawbell allows the material to flow towards the drawpoints where it is drawn. The shape and geometry of the drawbell generally play an important role in developing the overlying movement zone. It was found that shaping the drawbell above the brow increases the width of the movement zone (see Figures 5b and 5c). A drawbell without inclined walls is more stable but also restricts the movement zone above the pillar (see Figure 5a). Hence, a compromise for a good material flow and a strong brow with stable major and minor apices needs to be found (Laubscher et al. 2017). The undercut level layout of block caving (BC) mines already predetermines the potential shape of the drawbell.



(a) (b) (c)

Figure 5 Different drawbell shapes and their influence on the oreflow (a) Without shaping; (b, c) Shaped drawbells increase the flow width (Laubscher et al. 2017)

Due to the flexible RC method, there are alternative possibilities to construct the layout. A part of the solution can be to place the drawpoints at two or more sublevels to achieve an ideal interactive flow within the stoping area. Therefore, a drawbell has not only two drawpoints at the bottom, but several, depending on the design of the drawbell. A schematic representation of this large drawbell design can be seen in Figure 3. In BC there are several solutions to position the drawpoints, an equal distancing in all directions and therefore perfect covering of the stoping area is altogether not possible. An advantage of the RC design is that the area of the draw can be covered more completely. To accomplish this, the drawpoints need to be positioned strategically in the horizontal and vertical directions around the drawbell to support the oreflow. A further advantage of the flexible design is the possibility of building the lower extraction level upfront while the upper sublevel can be established later in de-stressed ground.

For optimal positioning of drawpoints, the dimensions of their individual movement zones above need to be known to space them accordingly. The previously mentioned flow zones of the individual drawpoints interact and increase to some extent (see Figure 6). The challenge is to find the balance between a short drawpoint spacing to embrace the interaction of the movement zones and a large drawpoint spacing for less infrastructure and more stability due to a larger pillar between adjacent drawpoints. Therefore, the oreflow investigations are complemented by rock mechanical considerations on the stability in a later stage of the project.

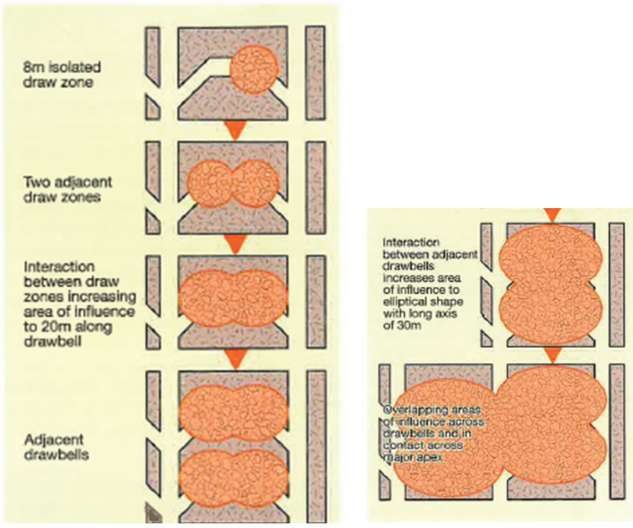


Figure 6 Progress of drawpoint interaction and growth of draw zones as adjacent drawpoints are drawn (Laubscher 2000)

2 Methodology

As seen above, a proper mine design is crucial to allow beneficial circumstances for the oreflow. This paper focuses on the mine design of drawbells and stopes and their influence on the oreflow. The first part investigates the influence of the drawbell shape on the oreflow. Thereafter, the spacing of the drawpoints is investigated to understand its effect on the overall flow situation.

2.1 Approach

The first oreflow investigations were done by means of sand models, which provided good insight into possible flow mechanisms in shallow cave mines (Heslop 2010). As mines extend deeper, the theories derived for shallow cave mines cannot predict the flow behaviour accurately, because more complex mechanisms occur. Especially in SLC operations, the flow differs due to the confined blasting situation and the restricted flow zone. To resolve the issue, full-scale tests such as marker tests were conducted, which provided valuable information (Campbell 2020). The disadvantage of these marker tests is that they are expensive and time-consuming. Therefore, different numerical simulations have also been used to study gravity flow (e.g. Beck et al. 2011; Sharrock & Hashim 2009; Castro et al. 2016; Sellden & Pierce 2004). Observations made in the first two approaches can be useful to set up meaningful numerical models for realistic results. Different mine designs can be compared, and the draw strategy optimised with such numerical models. The main advantage of simulations is the speed, the simplicity and the repeatability compared to full-scale trials. Furthermore, the physical limitations of the sand models are not present as scale and gravity are properly considered. Especially because modern caves are larger, deeper, and operate in stronger rock, numerical methods will become increasingly important in the future.

There are different calculation methods in the numerical approaches. A frequently used approach to predict the behaviour of granular materials is the discrete element method (DEM) (e.g. Sellden & Pierce 2004; DeGagné & McKinnon 2005, 2006). The idea of DEM is to simulate models with millions of interacting discrete particles where physically relevant information is exchanged. Particle dynamics can evolve freely under gravity and can be visualised. The high computational requirements are the main limitation of DEM models.

Rapid advances have been made in flow simulations, but the inclusion of every aspect in a cave mine is not feasible. An inclusion of the exact geometry of fragments and walls would increase the calculation time excessively. Some of these aspects are not even known adequately. This investigational issue necessitates to mimic the real cave mine oreflow behaviour with a simplified model. Simultaneously, it is important to maintain the analogous oreflow behaviour.

Measures to accelerate the simulations comprise upscaling or neglecting certain aspects, explained in Section 2.3. In order to decrease the computational demand, the model can additionally be split into sub-models where each describes a different aspect of the problem. The task is to find a way to analyse these aspects separately without changing the overall conditions of the model.

For simulations with a reasonable calculation time, an adequate software with efficient parallelisation possibilities in the algorithm is furthermore necessary. The investigations done in this paper are conducted with the DEM software EDEM from Altair (DEM Solutions Ltd. 2021). The software offers the possibility to calculate the models with the help of powerful graphic cards.

2.2 Used material

Realistic results from DEM simulations are achieved by first calibrating the material in the model. The idea of calibration is to obtain a modelled granular material that possesses the same behaviour as the real granular material in the mine. The calibration thus establishes the connection between the idealised material used in the simulation and the real-world bulk flow behaviour. A calibration usually consists of a physical test and a virtual replica. The test should be characteristic for the task, thus resemble a similar situation as in the actual application. For this reason, the present calibration is based on the experiences of flow dimensions of isolated draw zones in BC by Laubscher (1994). This approach is taken as the BC flow situation, it is comparable to the RC flow situation in the stopes. As explained above, the constrained flow situation in SLC differs strongly from that one in RC. In the calibration, the angle of repose is additionally checked, if it is in a realistic range.

In the calibration process, the most important parameters are calibrated, namely the rolling and sliding friction between ore and ore, as well as the ore and wall. Additionally the material density, the particle size distribution, coefficients of restitution and shear modulus with the corresponding Poisson's ratio are input parameters. It is nearly impossible to implement an exact representation of the particle shape and size distribution, and experience shows that it is also not necessary to model the bulk behaviour realistically (Coetzee 2016). To mimic a realistic material geometry, several particle shapes consisting of multi-sphere-clumps are included. The particle size distribution is chosen from the Kiruna SLC situation (Wimmer et al. 2015). Particle sizes range from 50 mm to 1,500 mm.

2.3 Simplification and calibration

On an actual mine, the particle sizes vary from fines to boulders. The proportion of fines is very large and it is not feasible to model these large amount of fines due to the enormous computational demand. Boulders are the largest particles and they do not drastically influence the overall flow behaviour in a wide stope as their number is very low. However, a very wide particle size distribution (PSD) in DEM models reduces the speed of simulation markedly. For these two reasons, the smallest (<50 mm) and largest particle groups (>500 mm) are neglected in the stope simulations to maintain the computational effort in a feasible range. The neglection of boulders is considered reasonable, as the material is blasted in RC in a favourable free-face situation, so fewer boulders are expected compared to the SLC situation, where the PSD is taken from.

To further speed up the simulation, the particles are upscaled. Thereby the particles are sized up in diameter by an upscaling factor by concurrently maintaining the particle behaviour of the original particle size. This procedure is a common approach for DEM simulations but needs to be maintained within a certain limit (Coetzee 2019). In the calibration process, an upscaling factor of 3 is identified as reasonable and implemented. For this reason, a PSD of 150–1,500 mm was used instead of the original 50–500 mm.

The calibration resulted in a rolling friction coefficient of 0.12, a static friction coefficient of 0.72 and a damping coefficient of 0.5. Further, the density of the material is set to 4,700kg/m³ with a Poisson's ratio of 0.25. Sivakugan and Widisinghe (2013) found for very rough walls that the wall-particle friction can be taken as the same as the inner-particle friction. Therefore, the above mentioned parameter-set was used for particle-particle as well as for particle-wall parameters. It was found in the past that the shear modulus does not have a large influence on the result of DEM simulations, but that it must be kept within certain limits to prevent too large an overlap of the particles (Lommen et al. 2014). A lower shear modulus than the original allows for a larger timestep and therefore accelerates the simulation. Hence, it is aimed to set the shear modulus on the lower end of the before-mentioned limit range. After test simulations, a shear modulus of 5 GPa is found reasonable for the material.

3 Model description

3.1 Model for investigation 1: Drawbell inclination

The first investigation deals with the inclination of a drawbell underneath a stope. Four models of drawbells with different inclinations (90°, 75°, 60°, 45°) are filled with the calibrated material and material is then extracted from the drawpoint at the bottom. A schematic drawing of the model can be seen in Figure 7. For the drawing process, an extraction zone is predefined in front of the brow of the drawpoint. As soon as the material enters this extraction zone, it is deleted from the model. This continuous extraction differs from the real situation, because the material does not get time to settle before the next extraction cycle begins. The continuous approach is chosen to obtain a qualitative output, as a realistic extraction process over several months or even years overshoots the computational capabilities of DEM simulations. The resulting flow and extraction zones are then compared to find the effect of the inclination on the oreflow.

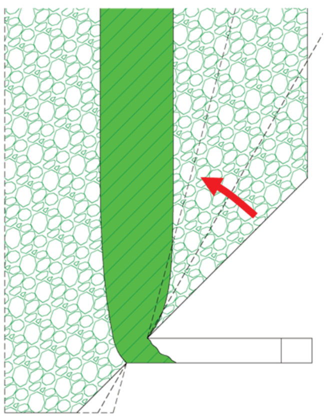


Figure 7 First model to investigate the influence of the drawbell inclination on the oreflow. The inclination was switched from vertical (90°) to 45° in 15° steps

3.2 Model for investigation 2: Drawpoint spacing

The second investigation targets the proper drawpoint spacing at the bottom of a stope. Three models with spacings of 10, 20 and 30 m are simulated to find a maximum possible drawpoint spacing, which still enables that the whole area between drawpoints can be extracted. Figure 8 presents a drawbell, and its drawpoints over two sublevels in a side view. To keep the model simple, only two drawpoints across from each other are modelled.

To begin with, all model geometries for investigating the effect of drawpoints spacing are again filled with the described particle mixture. To mimic the extraction process, the material is deleted from the model as it enters a predefined zone, beginning at the brow of the drawpoints. This zone is opened and closed by a movable plane. The particles have five seconds to settle before the next extraction cycle. This procedure enables a more realistic, discontinuous extraction by maintaining the computational effort in a feasible dimension. Investigations into the impact of drawpoint spacings in other directions will follow in future work.

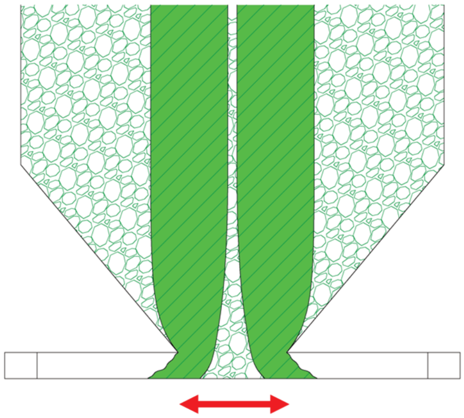


Figure 8 Second model to investigate the horizontal drawpoint spacing on the oreflow. Only two adjacent drawpoints are modelled, their flow zones are displayed with a green fill

4 Results

To visualise the isolated draw zone (IDZ) and isolated movement zone (IMZ), figures are generated with the particles at their initial position. Extracted particles are thereby coloured in black, which marks the IDZ. The remaining particles are coloured by their travel distance towards the drawpoint, which indicates the IMZ within the stoping area. Dark blue regions have less than 1 m of movement during the full extraction process, which is considered as quasi-static (no significant movement takes place).

4.1 Investigation 1: Drawbell inclination

In Figure 9, the four models of the drawbell inclination investigations are shown. The dimensions of the IDZs and IMZs are evaluated and can be found in Table 1. The vertical drawbell wall of 90° resulted in the narrowest IDZ and IMZ. For the model of 75° it can be seen that the inclination favours an increase of the zones in width. This leads to the conclusion that a certain inclination is favourable for the enlargement of the flow zones. An explanation for this effect can be that particles are led towards the drawpoint from more distant positions. Especially pronounced is this effect in the IDZ and IMZ of the drawbell with 60° inclination. The model with 45° inclination shows a similar IDZ, but the IMZ is again narrower than at 60° wall inclination. This observation raises the question of whether a too flat drawbell decreases the widening effect again.

The extraction rate of 2 kt for these models is relatively low as the target was to show a qualitative trend of flow zone development. However, it was expected that more flow takes place along the drawbell walls in the up-dip direction, and hence longer simulations are planned to provide a more detailed analysis.

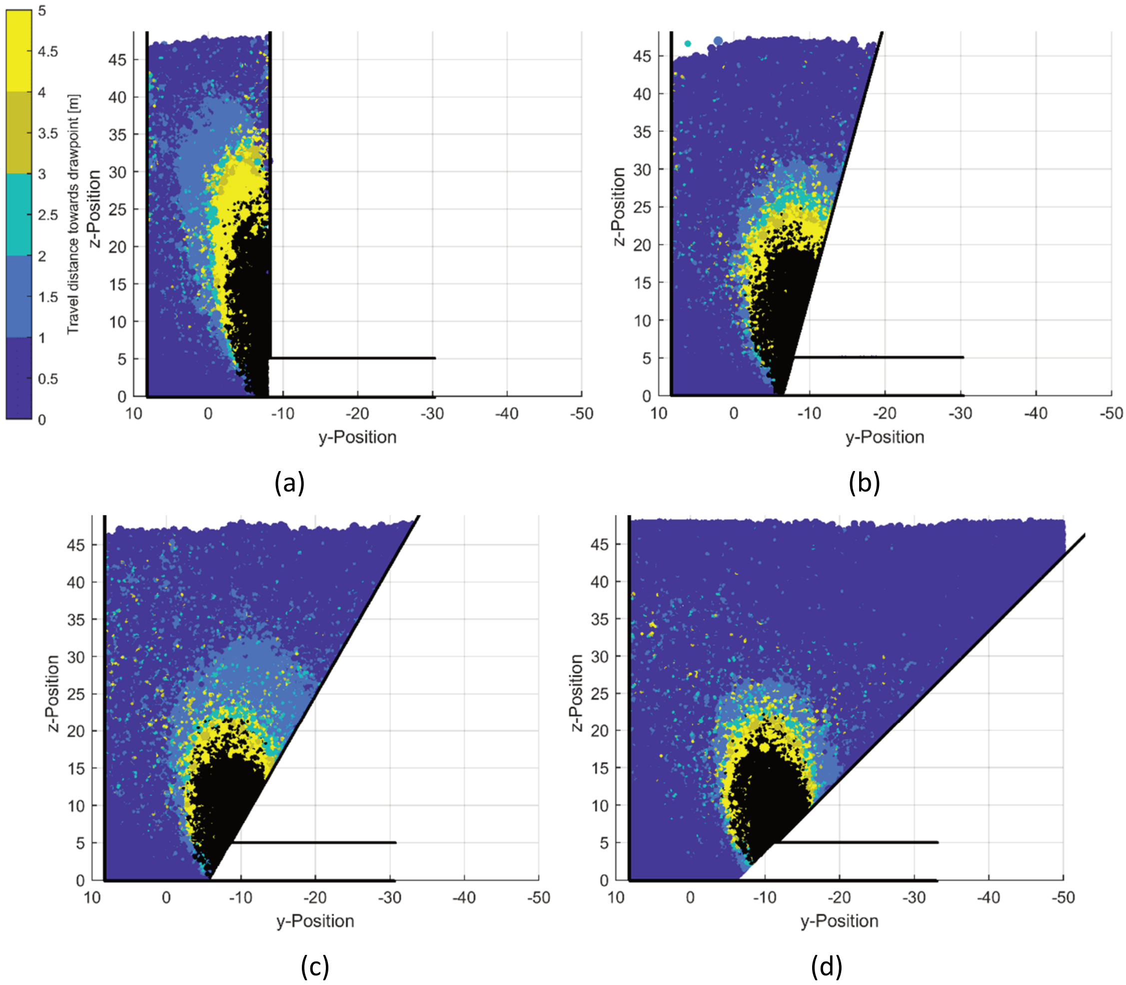


Figure 9 Side view of a cut through the drawbells. Four inclination angles were compared on their draw zones after 2 kt (kilo-tons) of extraction. Black particles have already been extracted, while the colours indicate the travel distance of individual particles. (a) 90°; (b) 75°; (c) 60°; (d) 45°

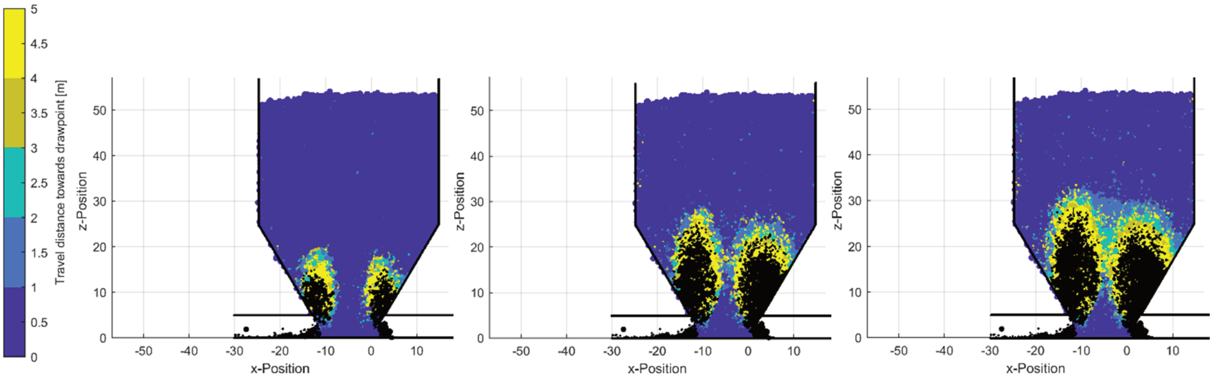
Table 1 Comparison of the extraction and movement zones of different inclined drawbells

Drawbell inclination (°)	Width of extraction zone (m)	Width of movement zone (m)
90	6.0	13.0
75	9.0	15.2
60	10.2	19.5
45	10.9	16.5

4.2 Investigation 2: Drawpoint spacing

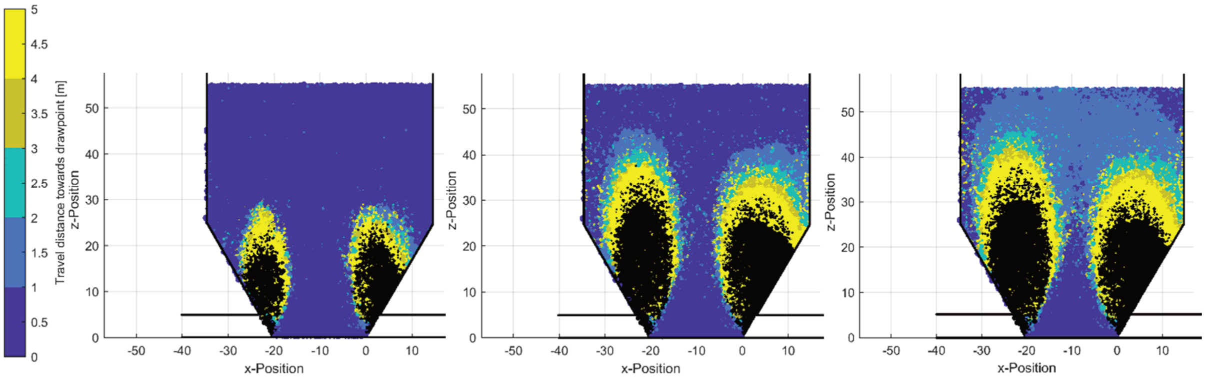
The three models with drawpoint spacings of 10 m, 20 m and 30 m can be seen at progressive extraction states in Figure 10, Figure 11 and Figure 12 respectively. It needs to be noted that the flow zones of the models are not symmetric as the wall above the right drawpoint is completely even. The left side comprises a macroscopic unevenness, as particles are rigidly fixed in the wall for modelling reasons. It can be added for future investigations that the left side might display a more realistic situation concerning the wall-particle contact.

The IMZs of the drawpoints grow together at an early stage at 10 m drawpoint spacing. At an extraction state of 6 kt, the interaction can be observed. For 20 m drawpoint spacing, the flow zones grow upwards before interacting at an extraction state of 14.5 kt. In the 30 m drawpoint spacing analysis an extraction of up to 22 kt results in a clear isolated draw situation with a large inactive region between the flow zones. An interaction can therefore not be detected at first sight. However, a finer resolution of the colour bar in Figure 13 reveals that material from the middle is also mobilised to a minor extent. A long-term simulation is planned to see whether the flow zones grow together more strongly in a later extraction stage. In summary, it can be seen that the drawbell design favours large flow zones which can interact over wide spacings of 20 m or more. Laubscher (1994) suggests the critical distance of drawpoint spacing with 1.5 times the width of IDZ for fine to medium rock. In the present case this would be 1.5 × 10 m and thus around 15 m. Comparing this to the results of the simulations indicates an advantage of the large drawbell design.



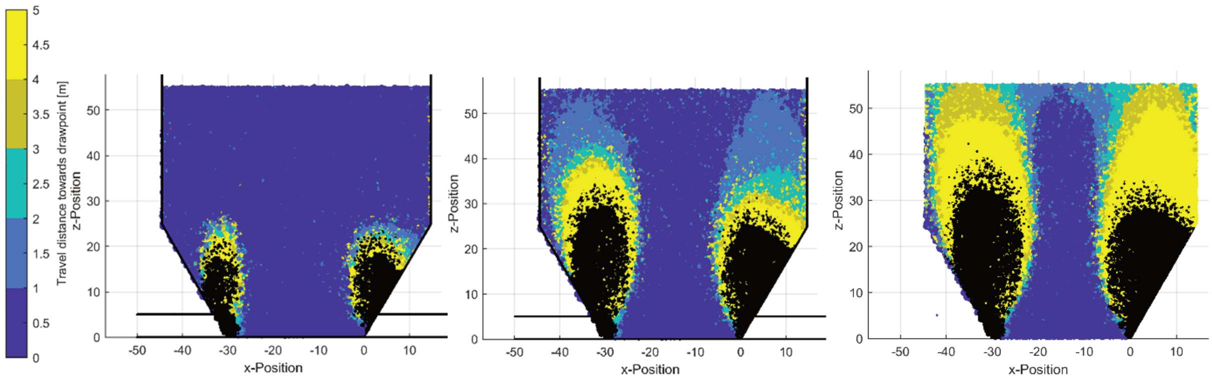
(a) (b) (c)

Figure 10 10 m drawpoint spacing at different extraction states (a) 1 kt; (b) 4 kt; (c) 6 kt



(a) (b) (c)

Figure 11 20 m drawpoint spacing at different extraction states (a) 4 kt; (b) 12 kt; (c) 14.5 kt



(a) (b) (c)

Figure 12 30 m drawpoint spacing at different extraction states (a) 4 kt; (b) 14 kt; (c) 22 kt

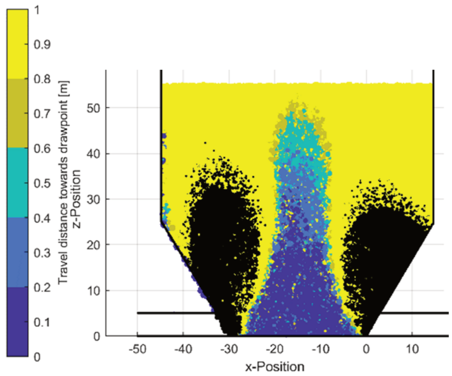


Figure 13 30 m drawpoint spacing at 22 kt extraction stage with finer colour-resolution

Drawpoint spacings of 15 m have been commonly used by block and panel cave mines. The spacings have been increased in newer mines to 17–18 m, as they operate in more coarsely fragmented rock (Brown 2007). The comparison shows the potential of the large drawbell design for a large drawpoint spacing of 20 m or more. Therefore, this point needs to be investigated further to find the maximum possible drawpoint spacing dependent on the fragmentation size.

5 Conclusion

As mining progresses to greater depths than in the past, hazards relating to high rock stresses get larger and new ways of mining need to be found. Raise caving (RC) is a novel mining technology developed to address crucial issues of cave mining at great depths. One central part in achieving a successful RC operation is to control the oreflow. The main target of oreflow in cave mines is to prevent early dilution and extract a high percentage of the deposit. Therefore it is necessary to lower the broken material in a stope evenly towards the underlying drawpoints, which is called mass flow. Mass flow can be achieved by proper mine design and draw strategy. The flow zones above each drawpoint can then interact and mobilise the ore uniformly.

The target of this work is to investigate the effects of shape and drawpoint spacing on the design of large drawbells, which are planned to be used in RC. To address these issues, large discrete element method simulations are conducted. The material is scaled up, simplified, and calibrated to enable the computationally demanding simulations in a reasonable time.

In the first investigation, four inclinations of the large drawbell are analysed to understand their effect on the flow zone above the drawpoint. It can be shown that the vertical (90°) drawbell design resulted in the narrowest flow zones. The inclined model of 75° shows a wider isolated extraction and movement zone (IEZ and IMZ), and an inclination of 60° improves the result further. An inclination of 45° results in a slightly larger IEZ than 60°, but the IMZ is again narrower. It can be concluded that an inclined drawbell design improves the width of the flow zones. This might be because the ore is guided towards the drawpoint from regions being situated further away. As the inclination gets too low, this effect might be weakened again to some extent.

The second investigation in this paper targets the spacing of two drawpoints across from each other at the bottom of a large drawbell. The simulations shows a strong interaction at 10 m spacing at a 6 kt extraction state. At 20 m drawpoint spacing, the flow zones grow together at a 14.5 kt extraction state. For 30 m, a strong interaction cannot be detected, even though the material between the flow zones is slightly mobilised at higher regions. It is not known if the flow zones would grow together more strongly for the 30 m drawpoints spacing as extraction progresses. This point is still under investigation. In BC and PC mines, a drawpoint spacing of 15 m is commonly used, but 17 m and 18 m are spacings are also used for coarser fragmentations. The large drawbell design can therefore be advantageous to increase the spacing further and decrease development in infrastructure.

To sum up, a positive influence of the inclined large drawbell design on the flow zones can be shown. It favours the interaction of drawpoints at wider spacings, which is shown with the investigation of drawpoint spacings. Future investigations should include a different particle size distribution to investigate the effect of particle size on the flow zones. The other directions of drawpoint spacing also need to be investigated to ensure mass flow over the full stoping area. The drawing via sublevels needs to be looked at to prove the interaction with vertically spaced drawpoints, which is the main advantage of RC drawbell design.

Another major point to investigate is a proper draw strategy to guide the ore uniformly along the dipping stopes. The target is to decrease the hazard of hang-ups and early dilution, and create a free surface on top of slots and stopes for subsequent blast rings. It is planned to perform large-scale physical model tests for further investigation of oreflow in the RC design and to confirm the results from the simulations in this paper. The research will be used as a guideline for mine design and draw strategy to enable successful RC operations at greater depth.

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