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Critical Issues of Ore Flow for the Raise Caving Method

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Abstract: Ore flow has been identified as one of the critical points of developing the novel mining method Raise Caving (RC). The focus of this contribution is on the key issues of ore-flow and on how to encounter them to enable a safe, efficient, and economic mining operation.

In the de-stressing phase of RC, narrow, tabular de-stressing slots are developed via raises, only the blast swell is drawn, and hence they stay filled with blasted material at all times to support the hanging wall in order to prevent early caving and dilution ingress. To simultaneously enable a free surface at the top for blasting, the extracted amount from the bottom needs to be monitored consistently. Another point in the narrow de-stressing slots is to prevent hang-ups by an adequate slot thickness. Hang-ups in higher zones are especially critical as they are difficult to resolve and may lead to unnoticed hanging wall caving.

In the following production phase, production stopes are developed in the de-stressed area behind the slots. During this phase, the stopes are always filled with blasted material as a support for the hanging wall. They are only drawn-empty at a later point after the stopes are fully established. The most important issue for production stopes is to prevent early dilution in order to extract the deposit economically. Additionally, the free surface needs to be prepared for upcoming blasts. To optimize the extraction, a uniform flow towards the draw-points needs to be created. The mentioned points can be addressed by a proper mine design and draw strategy. The parts of the mine design include the draw-point spacing, the draw-point position, and the draw-bell layout. Further on, the draw strategy must enable a uniform draw, guide the ore down the inclined stope, and prevent early dilution. The critical points mentioned in this contribution are approached by the R&D with empirical, numerical, and analytical means.

Keywords: Ore-flow, Raise caving, Dilution, Hang-ups, Free volume

Schlüsselfragen des Erzflusses im Raise-Caving Verfahren

Zusammenfassung: Der Erzfluss wurde als einer der kritischen Punkte bei der Entwicklung des neuartigen Bergbauverfahrens des Raise-Caving (RC) identifiziert. Der Schwerpunkt dieses Beitrags liegt auf den Schlüsselfragen des Erzflusses und darauf, wie man ihnen begegnen kann, um einen sicheren, effizienten und wirtschaftlichen Abbau zu ermöglichen.

In der Entspannungsphase des RC werden über Raise-Schächte schmale, tabulare Entspannungsschlitze gesprengt. Von Abzugspunkten am Boden der Schlitze wird das Schwellvolumen des gesprengten Erzes abgezogen. Um gleichzeitig ein freies Volumen an der Oberseite für die Sprengung zu ermöglichen, muss die abgezogene Menge von unten ständig überwacht werden. Die Schlitze sind ansonsten stets mit Sprenggut gefüllt, um das Hangende zu stützen und so ein frühzeitiges Eindringen von Verdünnung zu verhindern. Ein weiterer Punkt in den engen Entspannungsschlitzen ist die Vermeidung von Aufhängungen des Schüttgutes. Besonders kritisch sind Aufhängungen in höher gelegenen Zonen, da sie schwer zu beheben sind und zu unbemerkten Einbrüchen des Hangenden führen können.

In der Produktionsphase entstehen im entlasteten Bereich hinter den Schlitzen Abbaukammern. Die Abbaukammern bleiben in dieser Phase immer mit gesprengtem Material zur Unterstützung des Hangenden gefüllt. Sie werden erst zu einem späteren Zeitpunkt leergezogen, wenn die Abbaukammern vollständig hergestellt sind. Bei den Kammern kommt es vor allem darauf an, eine frühzeitige Verdünnung zu verhindern, um die Lagerstätte wirtschaftlich abbauen zu können. Außerdem muss ein freies Volumen für anstehende Sprengungen gegeben sein. Um die Gewinnung zu optimieren, muss ein gleichmäßiger Fluss zu den Entnahmestellen geschaffen werden. Die genannten Punkte können durch die Bergbauplanung und Abzugsstrategie erreicht werden. Bestandteile der Bergbauplanung sind die Abstände und Positionen der Abzugspunkte und das De-

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sign der Ziehglocke. Des Weiteren muss die Abzugsstrategie einen gleichmäßigen Abzug ermöglichen, das Erz in den geneigten Kammern führen und eine frühzeitige Verdünnung verhindern. Die in diesem Beitrag genannten kritischen Punkte werden in der Forschung und Entwicklung mit empirischen, numerischen und analytischen Mitteln bearbeitet.

Schlüsselwörter: Erzfluss, Raise Caving, Verdünnung, Aufhängungen, Freies Volumen

1. Introduction

1.1 Raise Caving

Developing a new mining method like raise caving (RC) implies detailed research to gain a profound knowledge on the critical factors for a successful and safe operation. Pillars, hanging wall behavior, raise stability, seismicity, and ore-flow have been identified as critical aspects to be investigated. A detailed explanation of the overall RC system is given by [1–3]. In the following, the RC system is briefly described to subsequently show the most critical issues of the ore's movement inside the slots and stopes, which is called ore flow.

There are three different stages in the RC system. As rock stresses are very high at deep levels, a de-stressed area needs to be created in the beginning. This is done by creating narrow de-stressing slots which are separated by long dip pillars. The slots can be efficiently developed via automated drill and blast from raises. This is high stress mining. The pillars attract the stresses, which causes the de-stressing slots to create stress shadows behind them. The required infrastructure like production raises and drifts can be placed in this de-stressed area. All other mining operations are performed in the established stress shadow as far as possible.

The initial phase is followed by the production phase, where stopes are established to extract large parts of the deposit. The construction of the stopes is again conducted via drill and blast from raises. Slots and stopes are filled with bulk material at all times during the first two phases to support the hanging wall and prevent it from early caving. Between the slots and stopes, highly stressed dip pillars form, which either yield and crush after some time on their own or need to be preconditioned to achieve yielding and crushing. In the final draw-empty phase, the crushed pillars are extracted together with the rest of the stopes. The extraction of slots, stopes, and pillars is conducted via draw-bells, which are placed at the bottom of the structures.

Each stage provides different conditions for the ore flow and needs to be distinguished when investigating the topic. The important point of the RC method is that, with the exception of is the first step, all other mining operations can be performed in a de-stressed ground. Figure 1 gives an overview of the evolution of the RC mining system.

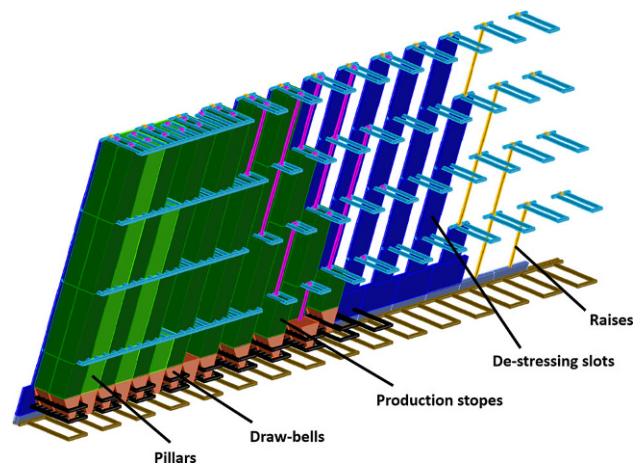


Fig. 1: Raise caving design: De-stressing slots (*dark blue*) are blasted from raises (*yellow*), which then form favorable stress conditions for the production raises (*pink*) and the production stopes (*dark green*). These are extracted from draw-bells (*orange*) at the bottom, which are drawn via sublevels. In a later stage, also pillars (*light green*) in between the stopes are mined

1.2 Ore Flow

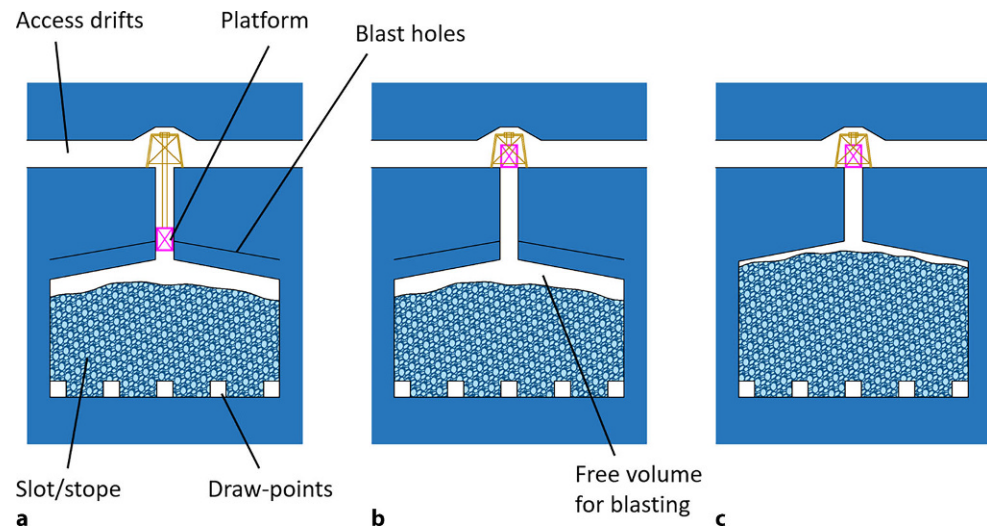
The term ore flow describes the movement of the broken ore from the time of blasting or caving until the moment of extraction from draw-points. In RC the production stopes are filled with a high pile of broken ore, which is extracted from the bottom by load haul dump (LHD) vehicles. As soon as material is pulled from a draw-point, the other particles in the stope are mobilized by gravity and flow towards the draw-point. The mobilized particles form a zone of movement, which is called isolated movement zone or flow zone of a draw-point. The width of the flow zone increases with the fragmentation size and consequently allows draw-points to be spaced further apart [4]. The basic theory behind the dimensions of the movement zones is that they grow during the operation progresses until they reach their final width and only grow vertically upwards [5].

The overall target for a complete extraction is to space the draw-points and extract the material in a way to mobilize the whole mining area, which is called mass flow [6]. Concluding, the draw-points need to be spaced according to the mechanics of ore flow. Additionally, the rock mechanical stability of draw infrastructure needs to be considered.

2. Key Issues of Ore Flow in RC

The overall target of ore flow in RC is the safe, as complete as possible and economic extraction of the deposit. To fulfill this target, various questions need to be investigated. These questions influence the new mining system, mine layout, and draw strategy. The most critical points are ensuring the free surface for blasting, blocking the ore-flow through hang-ups and dilution in connection with the hanging wall caving. Controlling each of the points defines the success of this novel mining method. The de-stressing slots of small thickness will hereby show a different behavior than the stopes of a much larger dimension. Hence,

Fig. 2: View in transverse direction on the blasting situation in RC **a** the platform is lowered down the raise and blast holes are generated and charged autonomously. **b** the platform is raised again to prepare for the blast **c** the successful blast fills the free volume with bulk material



slots and stopes are differentiated for the research on the critical points (described in Sect. 1.3).

2.1 Free Surface for Blasting

Bulked material always captures a larger volume than the compact form in its origin. This swelling happens due to the bulking when the material piles loosely on the ground. Therefore, as compact ore is blasted and gets dissolved from its in-situ rock mass, it needs a free volume to be able to break and expand. The blasting situation in the RC system can be seen in Fig. 2. The free volume above the blasted and caved ore inside both the de-stressing slot and the stope needs to be large enough for the next blast to be conducted. That can be done by drawing uniformly from draw-points in strike direction at the bottom, so the material lowers evenly and a free surface forms over the whole area (see Fig. 3a).

In reality, the uniform draw is not always possible as certain draw-points are sometimes blocked by hang-ups.

Neglecting hang-ups and extracting excessively from adjacent draw-points can lead to an uneven surface for the next blasting or even to the forming of a funnel to the hanging wall (see Fig. 3b). Furthermore, an unbalanced draw strategy can lead to an uneven lowering, which restricts the upcoming blast ring from breaking properly (see Fig. 3c). By maintaining a pre-planned draw strategy, a good control for a uniform ore flow can be anticipated.

2.2 Hang-ups

A hang-up is a phenomenon where material is accumulating, arching, and clogging between two or more solid walls. The location of the hang-up is important and defines the severity of the consequence. Hang-ups may occur directly at the draw-points in both slots and stopes (see Fig. 4a). These hang-ups usually can be visually observed and accessed to be released again. A common practice is to use water cannons or explosives to dissolve hang-ups. The practice to draw from adjacent draw-points, as the ore

Fig. 3: View in transverse direction on the flow zones of adjacent stopes. **a** Even lowering of bulked material (mass flow) through a proper draw strategy. **b** neglecting hang-ups while drawing from adjacent draw-points can form funnels and subsequently pull waste. **c** unbalanced draw strategies lead to an uneven lowering of the material

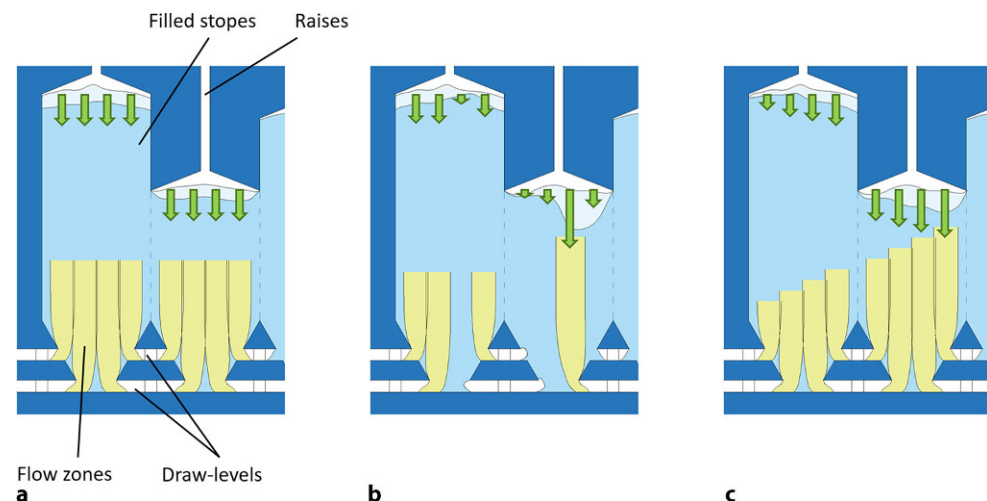
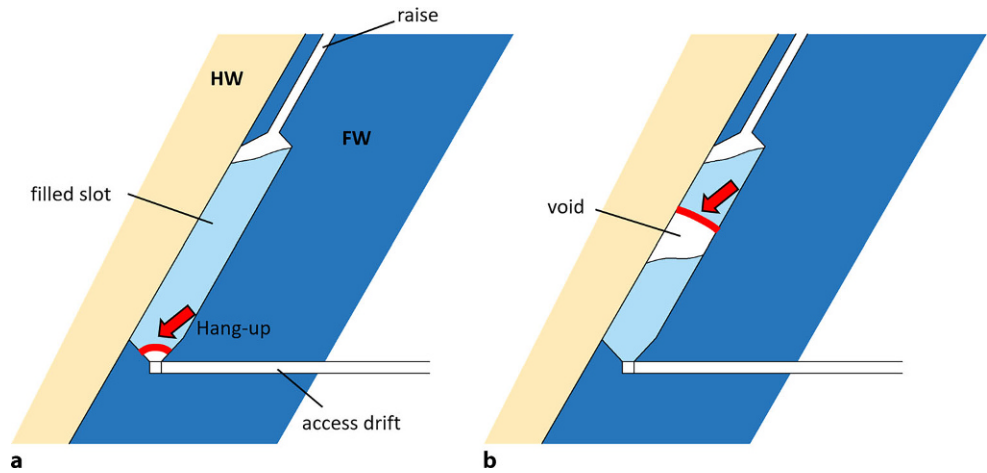


Fig. 4: View in strike direction on hang-ups in de-stressing slots. The position of a hang-up defines the severity of consequences **a** a hang-up near to the draw-point leads to a challenging removal process but is accessible **b** a high up position inside the slot cannot be accessed easily and leads to a dangerous situation



is flowing out easier there, is a hazard in operations. This practice hinders a uniform flow towards the draw-points, interferes with the production targets, and possibly ends in pulling dilution from the hanging wall [7]. Consequently, the recovery is negatively affected, and the draw-point cannot be worked, which causes an economic loss. The dilution may also be difficult to stop again as paths to the hanging wall are then already formed.

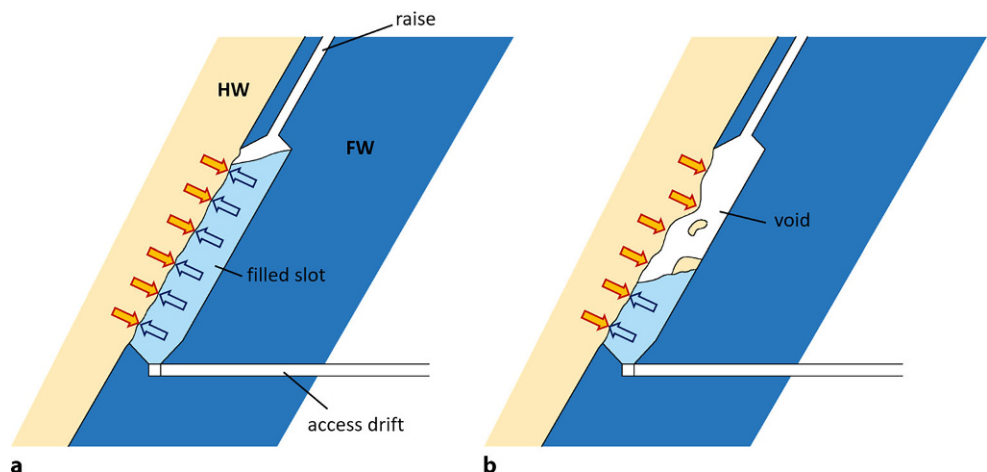
An even more critical situation is a hang-up further up the narrow slots (Fig. 4b). If this hang-up is not noticed and released, the free surface on top of the slot cannot form and production will come to a halt. If a hang-up like this is not released or is discovered too late, the hanging wall may cave into the free volume and endanger the operation. High hang-ups cannot be accessed easily, and a release can turn out to be difficult as it is enclosed by bulked ore below and above. To prevent this, a method to monitor routinely the height of broken ore in the de-stress slot should be developed and incorporated in the operating procedures. In higher up regions of the production stopes, hang-ups are rather unlikely due to the large dimensions of a stope. Arches cannot form in a stable manner as the distances between the walls of the stope are very large.

Summing up, hang-ups at the draw-point may occur in slots and stopes and can be critical if neglected for longer periods. Hang-ups further up in the slot need to be prevented even more as they are difficult to access and any neglect has serious consequences. Dimensions, like the thickness and inclination of the de-stressing slot, play a major role in preventing higher-up hang-ups. In stopes, these types of hang-ups are rather unlikely due to the large dimensions of the structure. The investigation on hang-ups therefore focuses on slots and the required dimensions to enable a successful operation.

2.3 Dilution in Connection with Hanging Wall Caving

A further important point is the prevention of early dilution originating from hanging wall caving. This is especially important during the blasting-phase as the free surface cannot form if mostly waste material from the hanging wall is pulled. In the later stage of the system when stopes are drawn empty, dilution with waste material leads to economic losses but is less severe in terms of the overall applicability of the system. To prevent early dilution, the ore flow

Fig. 5: View in strike direction on a de-stressing slot. **a** Slot filled with bulk material (light blue) to prevent the hanging wall (orange) from caving. **b** a too large void above the bulk material removes the support and leads to an undesired hanging wall caving



needs to be guided uniformly towards the draw-points at the bottom by means of a proper draw strategy. The draw strategy plans the amount and position of ore extraction to create an environment for a uniform draw. That means that, from a specific height, the material moves downwards evenly over the whole mining area, leading to a mass flow situation. When diverging from the draw schedule, the mass flow may be disturbed and the risk of pulling waste arises (see Fig. 3b, c). Therefore, the draw-strategy needs to be followed strictly to prevent the forming of paths to the waste material, the so-called 'rat-holes' [7].

Another way to delay caving of the hanging wall as long as possible is to support it by the underlying material in the slots and stopes. Therefore the slots and stopes cannot be emptied completely but need to be filled with broken ore at all times. Thus, the bulk material exerts its support to the hanging wall to stabilize it. A second effect is that it prevents the disintegration of rock mass in low stress conditions (see Fig. 5a). Also the free space on top needs to be monitored to prevent it from growing too big and permit just enough free volume for the next ring to be blasted. A strong advantage in RC is the possibility to look inside the void at all times as the void is connected with the slot/production raise. With the help of this, an insufficient or oversized void can be detected, the draw strategy can be adapted, and the process can be controlled.

If excessive drawing is conducted regardless of a required next blasting, the hanging wall may bulge and cave eventually into the slot/stope. The waste rock would further be pulled towards the draw-points, which leads to major problems as it is difficult to hold back the created flow path. The effect of a too big void can be seen in Fig. 5b. The mechanisms of pulling waste rock to the draw-point result from bad draw management. A close look on the ore flow and draw strategy is therefore inevitable.

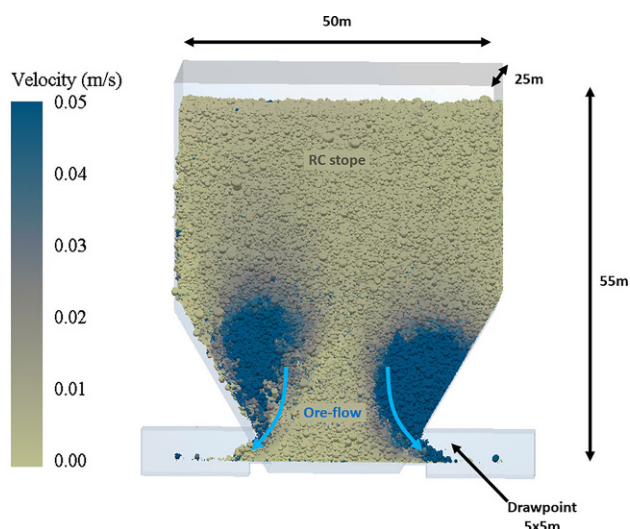


Fig. 6: Exemplary DEM model to investigate flow zones in stopes

3. Addressing Key Issues with R&D

The urge of gaining knowledge on ore flow mechanisms already developed in the beginnings of cave mines. Much research was then done in the 1960's for shallow cave mines, using simple sand models [8]. As the scale of caving operations increased over time and moved to further depths, the theories could not describe the actual ore flow found in the mine as precisely as before. This is due to violated reasons of similarity [9] and to ore flow mechanisms being more complex than shown in simple models [10]. Due to these issues, the ore flow characteristics of broken ore are still not well understood nowadays [11].

To develop a novel mining method like RC, the investigation approaches for ore flow need to be developed further for a better knowledge on the ore flow mechanisms underground. Empirical findings from within cave mines, full-size testings as well as numerical simulations are becoming more and more important. While large and full-scale measures can deliver good insights in the mechanisms of ore flow in cave mines, they are also time and cost intensive. Numerical methods provide a solution as they are comparably time efficient, cheap, and repeatable. Out of this reason, the R&D for ore flow combines the available empirical findings with numerical DEM models to simulate the flow of material in the cave mine, which can be seen exemplarily in Fig. 6. Thereby the mine design and draw-strategy are major parts to be investigated. An analytical approach is planned for the dimensions of the slot.

4. Summary

The contribution shows the most important critical issues for the investigation of the ore-flow for Raise Caving, namely preventing hang-ups, developing a free surface for blast rings, and preventing early dilution. For the investigation, de-stressing slots and production stopes are differentiated. Slots are the central excavation during the de-stressing phase. The broken ore is here located between two relatively narrow walls and the downward flow may be restricted. Hang-ups need to be prevented in advance by an adequate slot thickness. Especially hang-ups in higher zones may create major problems as this may lead to unnoticed hanging wall caving.

In the production phase, production stopes are developed. In contrast to the slots, they provide relatively free flow conditions for the ore due to their large dimensions. Yet, both geometries need to stay filled with bulk material at all times to support the hanging-wall and to prevent early caving and dilution ingress. Therefore the extracted amount from the bottom needs to be monitored consistently in order to generate sufficient free surface for blasting on top without letting it grow excessively. This is even crucial in the draw-empty phase when the excavations reach their maximum length.

The most important point for R&D is to gain a profound knowledge on ore flow in RC in order to avoid the mentioned issues. The investigations are conducted by empirical, analytical, and numerical means. Learnings and in-situ

data from related situations like Block or Sublevel Caving mines are combined with discrete element method simulations. An open point for future investigations is to establish an analytical model to assess proper slot dimensions. The understanding of the ore flow can then be used for the careful development of mine layout and draw strategy. The mine layout includes the draw-point spacing in horizontal and vertical directions and the draw-bell design in terms of shape and dimension. Further on, the draw strategy deals with a uniform flow and the inclination of the deposit to lead the material the right way from top to bottom.

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