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Gravity flow of blasted rock within tall stopes

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Abstract

The Alternative Mining Methods Project, conducted in collaboration between Luleå University of Technology and Boliden, investigates the feasibility of a hybrid mining concept aimed at improving productivity and reducing development requirements in Boliden's underground operations, with Garpenberg mine selected as the initial test site. The proposed concept is constrained by the need to maintain the existing mass balance between ore production, waste rock development, paste filling capacity, and tailings storage facility capacity. As a result, a hybrid stoping approach has been developed in which primary stope heights are increased, while secondary stopes are extracted using deck blasting and shrinkage-like retention of blasted ore within the stope.

In this concept, blasted ore remains stored in the secondary stope until the full stope height has been reached. Final extraction is then carried out from the production level while rockfill is continuously introduced from the top. This creates a constrained gravity-flow system in which ore recovery and dilution are strongly influenced by stope height, production-level layout, drawpoint geometry, fragmentation, and fines migration. To evaluate these effects, a series of discrete element method models were developed using the YADE framework. The models examined several design variants, including 100 and 50 m secondary stopes, different production-level layouts, drawpoint widths, and the use of drawbells.

The modelling results show that taller stopes generally promote more favourable gravity-flow development and improved recovery. In the 100 m stope cases, dilution typically entered the draw column at approximately 80% extraction, whereas reducing the stope height to 50 m caused dilution entry to occur as early as 50% extraction. Wider drawpoints improved recovery in the 50 m case, but did not fully compensate for the reduced stope height. The most significant improvement was obtained by incorporating drawbells, which promoted faster development of the gravity-flow and shifted dilution entry to approximately 75% extraction in the reduced-height configuration. Overall, the study indicates that dilution entry point, rather than cumulative dilution alone, should be considered the key operational limit for evaluating the proposed method. The results also highlight drilling accuracy, fragmentation control, fines migration, and drawbells as critical factors that must be addressed before the concept can be advanced toward full-scale implementation.

Keywords: *gravity flow, blasting, hybrid mining methods*

1 Introduction

Underground mining operations are increasingly challenged by greater mining depths, rising development costs, and growing productivity demands. Many existing underground mines continue to rely on traditional and well-established mining methods, which must now operate under increasingly constrained technical and economic conditions. These pressures highlight the need for alternative approaches that can improve productivity while controlling development requirements and operational costs.

Both caving and stoping mining methods face significant challenges as mining depths increase. In caving operations, higher stress conditions often lead to increased seismicity and associated operational risks. In addition, surface subsidence frequently becomes a limiting factor for environmental acceptance and

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land-use compatibility. In areas with strict environmental or infrastructure constraints, the application of caving methods may therefore be restricted. Under such conditions, highly productive stoping-based alternatives may need to be considered to maintain economic viability while minimising surface disturbance.

Stoping mining methods face a different set of challenges at increased depths. Stope stability becomes progressively more difficult to maintain, particularly under elevated stress conditions and increased seismicity (Hudyma et al. 2010; Potvin et al. 2019). These factors often require stronger backfill systems, leading to increased cement consumption and higher operating costs. Furthermore, increasing stope dimensions, particularly stope height, becomes more difficult while maintaining acceptable stability conditions. As a result, mines often experience increasing development requirements, greater operational complexity, and higher costs associated with planning, maintenance, and ground support.

To address these limitations, hybrid mining method concepts have been proposed that combine elements of different mining methods with the aim of achieving improved productivity while maintaining or enhancing stability conditions. One example is demonstrated at Newmont's Subika underground mine (Kwaku Yeboah & Quainoo 2024), where sublevel shrinkage mining (Mackay et al. 2014) was applied to control hanging wall stability while maintaining continuous rock filling from the top of the mining block. This approach enabled controlled extraction while maintaining stability of the surrounding rock mass.

Another example of alternative mining method evaluation is presented in the context of the planned underground transition of the Svappavaara mining operation (Sormunen & Saiang 2022). In that study, both caving and stoping alternatives were assessed for underground development. The challenges in this case were strongly influenced by land-use constraints and the requirement to achieve a high production rate while maintaining acceptable environmental impact.

Despite these examples, hybrid mining approaches introduce additional complexity during feasibility assessment and mine design. Gravity-flow behaviour in caving operations is relatively well understood (Castro et al. 2007; Pierce 2010; Castro & Pineda 2015) and supported by an extensive knowledge base used during design and operational planning. In contrast, hybrid mining concepts often require case-specific evaluation of gravity-flow behaviour under constrained conditions. Key influencing factors include stope geometry, orientation, and size, spatial distribution of blast fragmentation, and rock mass behaviour during extraction. In addition, dynamic stiffness changes within the stope may occur during material flow, particularly when hang-ups of rock material occur, which further complicates stability assessment. Consequently, reliable evaluation of gravity-flow behaviour represents a critical component in the design and feasibility assessment of hybrid mining methods, if such concept is applied.

In this context, a hybrid mining concept is currently being investigated for potential implementation across Boliden's underground operations. The objective is to achieve substantial improvements in productivity while simultaneously reducing development requirements and operational costs, without compromising safety standards. The study focuses on evaluating gravity-flow behaviour under different mining configurations as a key factor influencing the feasibility and design of the proposed mining method.

2 Alternative Mining Methods Project

With a strong portfolio of stoping mining methods, Boliden partnered with Luleå University of Technology to investigate opportunities for improving operational performance through the application of alternative mining methods. This collaboration led to the Alternative Mining Methods Project, which aims to identify a mining method capable of significantly improving efficiency while reducing operational costs across Boliden's mines. The project's objective was clearly defined: to investigate a mining method capable of delivering substantial improvements in productivity, cost efficiency, and development reduction, while maintaining high standards of operational safety.

Garpenberg mine, Boliden's flagship operation, was selected as the initial test site for the project. However, the scope extends beyond modifying the mining method at Garpenberg alone; the intention is to develop a solution that could potentially be implemented across multiple Boliden operations. Garpenberg is a polymetallic underground mine producing zinc, silver, lead, copper, and gold, and currently operates using sublevel open stoping, with an annual production of approximately 3.5 Mt of ore. Mining is conducted using alternating primary and secondary stopes, where primary stopes are backfilled with paste fill, followed by low-strength paste or rockfill placement in the secondary stopes. A typical stope is approximately 25 m high, with spans of about 10 m for primary stopes and 15 m for secondary stopes. Under favourable rock mass conditions, double stopes are excavated, representing the current upper limit of stope size and productivity on a per-stope basis. The operation follows a conventional drill-and-blast approach, with downward longhole drilling and material handling performed from loading drifts developed longitudinally along the stope floor.

The selection of Garpenberg as the test site introduced several constraints influencing the mining method design process. Significant water bodies located above the orebody in the form of lakes effectively ruled out the application of caving methods early in the project. Caving-induced subsidence could compromise lake floor stability and pose a substantial risk of underground flooding. In addition, the rock mass is characterised by pronounced foliation within the dominant mica quartzite host rocks, which further limits the applicability of caving methods.

Backfill management also represents a critical constraint from the perspective of the mine's overall mass balance. Eliminating paste fill would increase the volume of tailings requiring disposal in the tailings storage facility (TSF), potentially necessitating expansion of TSF capacity. Such expansion would trigger a new permitting process and introduce significant delays. Furthermore, Swedish mining regulations limit the development of new TSF facilities unless dry stacking methods are employed. Rockfill availability is also limited, making substantial increases in its usage unlikely. Consequently, maintaining the existing mass balance between underground backfilling and surface tailings disposal constitutes a major constraint. Additional design requirements arise from the project's objective of reducing costs and development while maintaining high ore recovery and low dilution.

Increasing stope height within the current mining method introduces significant stability risks during secondary stope extraction. Exposure of tall paste walls may lead to instability and potentially disrupt operations. A key contributing factor is the formation of cold joints within paste columns, which create low-friction interfaces that increase the risk of paste column movement toward the open secondary stope. To address the constraints and risks identified above, a new hybrid mining concept has been proposed that satisfies the operational limitations while aiming to meet the project's performance targets.

The conceptual approach involves increasing the height of primary stopes to at least 50 m, or potentially higher depending on rock mass stability and longhole drilling capability using 89 and 115 mm hole diameters, while comparing both top-hammer and in-the-hole (ITH) drilling technologies. Following excavation of the first 50 m lift, the stope is paste-filled and allowed to cure. A second 50 m lift is then excavated and filled in the same manner. This sequence is repeated along the primary stope series, ultimately creating secondary stopes with a potential height of up to 100 m.

For the secondary stopes, the primary objective is to minimise paste wall exposure in order to reduce the risk of instability. To achieve this, the secondary stope is extracted in horizontal slices with thicknesses ranging from 5–15 m. The secondary stope is blasted in modified vertical crater retreat (VCR) manner (Villaescusa 2014), where a set of blastholes is completely drilled first, but only the bottom part of the holes are charged and blasted at once. From the production level, only the volumetric excess required to accommodate the next blast is removed. In this manner, most of the blasted material remains stored within the stope in a shrinkage-like configuration until the full stope height is reached. Once the final slice has been blasted, the stope is gradually drawn from the production level while rockfill is simultaneously and continuously introduced from the top of the stope. This process generates gravity flow of fragmented rock within the stope, the behaviour of which must be evaluated in terms of recovery and dilution performance.

The proposed concept (Figure 1) has the potential to address several of the project's key objectives by maintaining the mine's mass balance while reducing development requirements and increasing productivity. However, the hybrid approach also introduces several uncertainties, including the design of the production level, gravity-flow behaviour within the stopes, potential paste wall wear during material flow, and the ability to maintain drilling accuracy over extended longhole lengths. These factors significantly influence the feasible stope height and overall mining method performance, in addition to rock mass behaviour.

This paper focuses on the analysis of gravity-flow behaviour under different production-level layouts and stope heights. The presented results highlight key factors influencing the final mining method design and its feasibility.

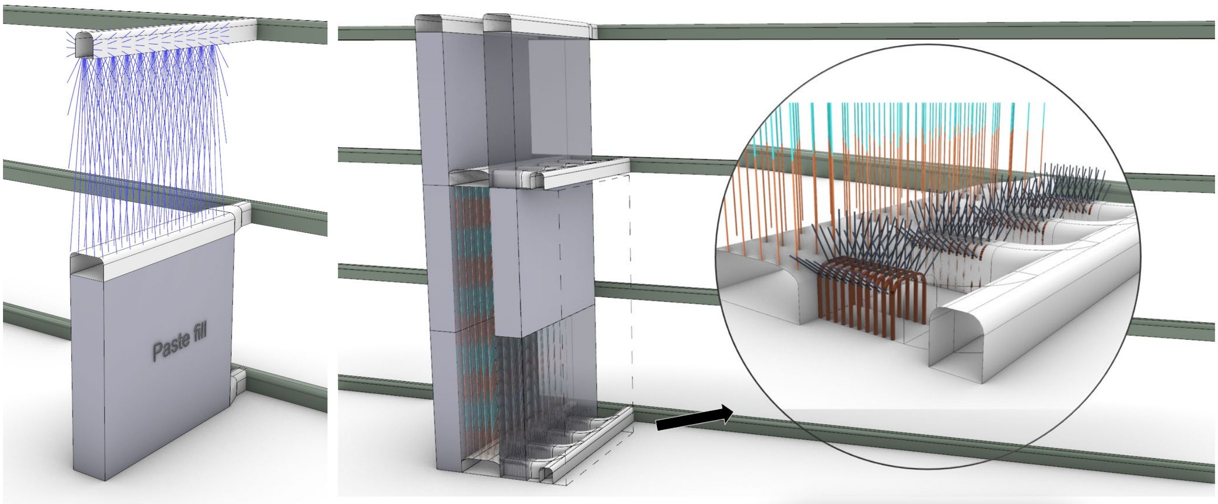

Figure 1 Proposed hybrid mining method layout

3 Methodology

Key aspects of the proposed concept related to gravity flow within the secondary stopes include the assessment of how the gravity-flow width develops with increasing stope height, how drawpoint spacing influences flow width and interaction between drawpoints, and the potential entry points for rockfill dilution. The discrete element method (DEM) has traditionally proven effective for evaluating gravity-flow behaviour in such systems and was therefore selected as the primary method for the initial stope-scale modelling. The open-source DEM framework YADE (Smilauer et al. 2023) was used for the simulations due to its flexibility and computational performance, as well as demonstrated wide application range (Angelidakis et al. 2024).

To ensure that the modelling aligns with the project's objectives, several design variants were developed, focusing primarily on differences in production-level layout and stope height.

3.1 General model setup and input data

To ensure that the results are directly comparable, all models were constructed using the same modelling approach and boundary conditions. This consistency ensures that the obtained results can be reliably used for decision-making and for narrowing down the mining method design options.

The stope geometry was represented using rigid meshes defining the external boundaries of the stope, with the entire simulation process conducted within these boundaries. This approach explicitly excludes analysis of paste wall abrasion as a source of dilution; however, quantification of dilution from the paste walls is planned for field trials. The YADE DEM framework allows the modelling of simple spherical particles, as well as more complex particle geometries using clumps or polyhedral elements. However, the latter significantly increase computational cost, particularly when large numbers of elements are required. Therefore, spherical particles were adopted for the initial modelling stage. Table 1 presents the material properties used in initial modelling stage.

Table 1 Material properties used in model

Material	Density, ρ (kg/m³)	Young's modulus, E (Pa)	Poisson's ratio, ν	Friction angle, ϕ (°)
Ore	2,700	10^7	0.20	45
Backfill	2,700	10^7	0.20	45

Fragmentation of both the ore and the rockfill is expected to have a major influence on the development of gravity flow. As the project is still ongoing, not all required data were available at the time of modelling. In particular, fragmentation data must be obtained from dedicated blast tests, which had not yet been conducted during the initial modelling phase.

Therefore, particle size distributions used in the initial models were assumed. These assumptions were made considering that the rockfill originates from development blasts and is therefore likely to exhibit a finer and less uniform size distribution compared with material produced from production blasting. Figure 2 presents the size distribution used for ore and backfill materials.

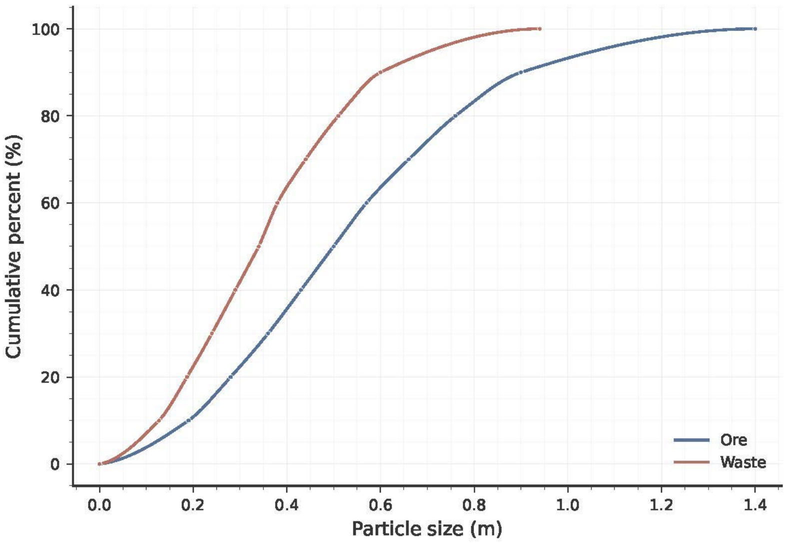

Figure 2 Particle size distribution used for the model

The spatial distribution of rock fragments is as important as the particle size distribution itself. Therefore, the model was prepared in several stages to ensure that the ore particle distribution realistically reflects excavation in horizontal slices. In practice, this means that particles representing the ore are sequentially packed in layers until the top of the external stope boundary is reached. Only after the complete packing stage is finished does gradual draw commence from the bottom of the stope, accompanied by continuous backfilling.

Backfill placement simulates a truck or loader dumping process. During this process, the spatial size distribution of the material develops naturally: coarser particles tend to accumulate farther from the tipping point, while finer particles concentrate closer to the tipping location

During the simulations, 3 primary parameters are recorded: overall ore recovery from the stope, cumulative dilution, and dilution per loader bucket. These parameters are defined as follows:

Ore recovery:

$$R = \left(\frac{m_o}{M_o}\right) \cdot 100 \tag{1}$$

Ore dilution:

$$D = \left(\frac{m_w}{(m_o + m_w)}\right) \cdot 100 \tag{2}$$

Dilution per bucket:

$$D_{bucket} = \left(\frac{m_{w,b}}{(m_{o,b} + m_{w,b})}\right) \cdot 100 \tag{3}$$

where:

m_o = extracted ore mass (t)

M_o = total ore mass (t)

m_w = extracted mass of waste (t)

$m_{o,b}$ = ore mass within single bucket (t)

$m_{w,b}$ = waste mass within single bucket (t).

4 Results

4.1 100 m tall stopes

4.1.1 Variant 1

The initial concept assumes that secondary stopes may reach heights of up to 100 m. The production level is designed such that the stope floor remains flat, while drawpoints are developed through the paste-filled primary stopes. The drawpoints are 5 m wide and spaced 15 m apart.

However, in the present model (Figure 3), only a single draw column is simulated. The effects of drawpoint spacing and drawpoint interaction are investigated separately in dedicated models.

The results indicate that dilution begins to enter the draw column at approximately 80% extraction, which corresponds to a similar level of ore recovery. Ore losses are primarily observed at the production level behind the drawpoint, where the gravity-flow zone does not fully develop. This limitation is also evident up to a height of approximately 35 m, which corresponds to the level at which the gravity-flow width reaches its maximum extent.

These observations formed the basis for investigating alternative production-level layouts aimed at improving the development of the gravity-flow zone and ultimately increasing ore recovery.

During the backfilling process, clear segregation of the material is observed. Coarser particles tend to accumulate on the side opposite the tipping point, while finer particles concentrate closer to the adjacent wall. As a result, finer material reaches the drawpoint more easily when both the tipping location and the drawpoint are positioned on the same side of the stope. This behaviour also indicates that the potential for controlling gravity flow through backfill fragmentation is limited.

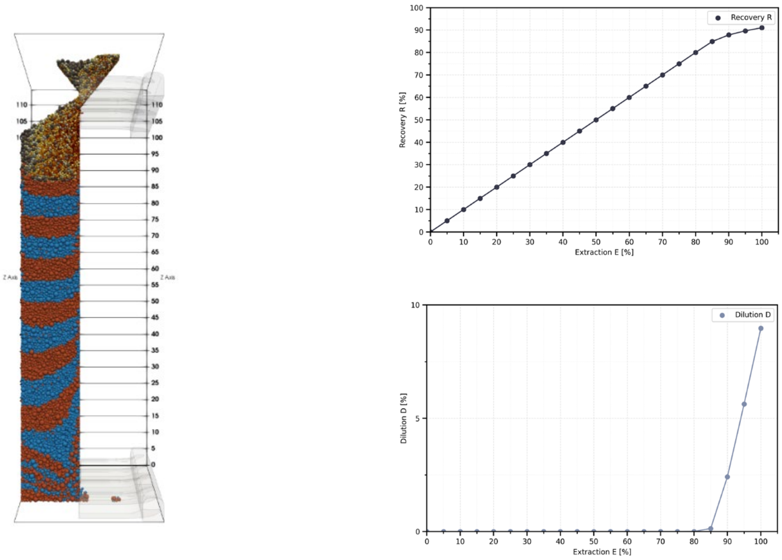

Figure 3 Variant 1 model overview and results

4.1.2 Variant 2

To address the shortcoming identified in Variant 1, where ore losses are influenced by the flat production level, Variant 2 (Figure 4) considers an alternative undercutting strategy within the secondary stope. In this approach, a material slope is introduced at the location where ore losses were previously identified. The purpose of this slope is to direct gravity flow toward the drawpoint, thereby promoting earlier development of the flow zone width during the initial stages of draw.

A key limitation of this approach is that the slope must be constructed through the placement of waste rock rather than through undercutting of the secondary stope. Undercutting would result in unacceptable ore losses within the slope itself and would therefore invalidate the concept.

Despite the additional operational implications associated with constructing the slope, the modelling results indicate that the dilution entry point remains largely unchanged. Dilution begins to enter the draw column at approximately the same extraction level as observed in Variant 1.

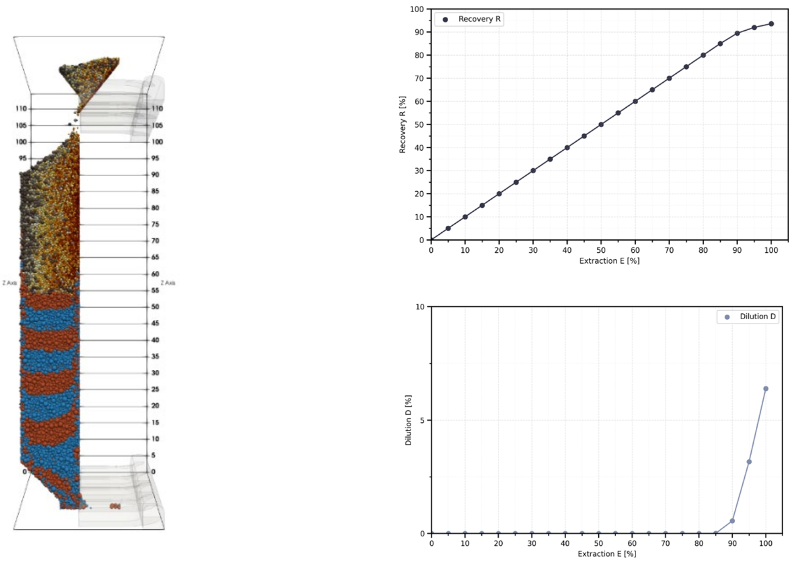

Figure 4 Variant 2 model overview and results

4.1.3 Variant 3

Both Variants 1 and 2 assume that drawpoints are developed as crosscuts through the paste-filled primary stopes. Since this configuration has been identified as a potential risk from the perspective of drawpoint stability and support requirements, additional alternatives were considered that could mitigate this issue while maintaining the overall mining concept.

In Variant 3 (Figure 5), the production level is positioned 15 m below the primary stope production level, placing the drawpoints within the surrounding rock mass rather than within the thickened paste fill. As a result, the total height of the secondary stope increases to approximately 115 m. This configuration also requires the development of drawbells, which act to funnel the material flow and may positively influence the development of the gravity-flow zone.

As expected, the presence of drawbells promotes faster development of the flow width, with the flow zone expanding almost immediately during the early stages of draw. This represents one of the key advantages of this approach. However, the simulations indicate that fines migration remains the dominant factor influencing the dilution entry point, which occurs at approximately the same extraction level as observed in the previous variants.

An additional risk associated with this configuration is the potential for drawbell hang-ups if the fragmentation of the blasted material is not adequately controlled. Unlike in caving operations, however, the fragmentation of the blasted material in this case can be designed and controlled during the blasting stage, providing an opportunity to mitigate this risk.

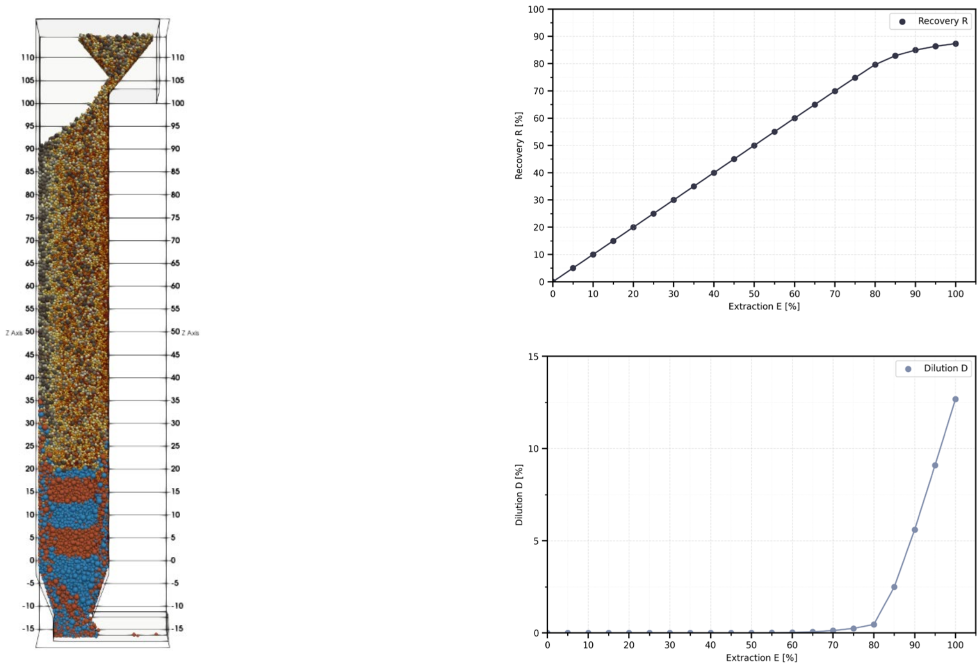

Figure 5 Variant 3 model overview and results

4.2 50 m tall stopes

4.2.1 Variant 4

During the conceptual development of the proposed mining method, gravity-flow modelling and drilling trials were conducted in parallel. The Lappberget orebody was selected as the primary test location, where the mineralisation is predominantly hosted in highly foliated mica quartzite rocks. Initial drilling tests indicated that rock foliation has a significant impact on drilling accuracy.

Drilling accuracy represents a critical parameter for successful implementation of the proposed concept. If not adequately controlled, drilling deviations could compromise the feasibility of the mining method. Consequently, it was concluded that if drilling performance proves to be a limiting factor, the gravity-flow behaviour associated with reduced stope heights must also be evaluated to assess the viability of the concept under more constrained conditions.

Variant 4 (Figure 6) follows the same configuration as Variant 1, but with a reduced stope height of 50 m. As shown in the results, stope height has a significant influence on gravity-flow behaviour. In this case, the dilution entry point shifts from approximately 80% extraction, as observed in Variant 1, to around 50% extraction. This results in an additional 30% of material losses.

Furthermore, instantaneous dilution increases sharply once dilution begins, exceeding 30%, and continues to rise progressively until the end of the extraction cycle.

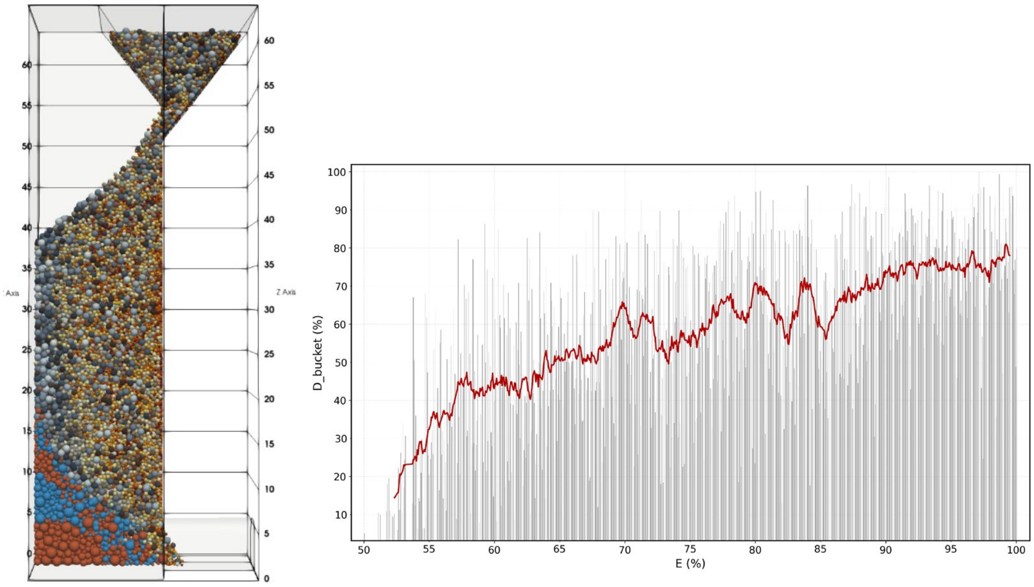

Figure 6 Variant 4 model overview and results

4.2.2 Variant 5

The results obtained for Variant 4 prompted consideration of an alternative approach for accessing the orebody through a longitudinal access drive developed along the stope. This configuration enables the implementation of a full-width drawpoint of 15 m, which has the potential to increase the flow width and improve overall recovery (Figure 7).

The modelling results indicate that the dilution entry point shifts from approximately 50% extraction in Variant 4 to about 65% extraction in this configuration. While this represents an improvement relative to Variant 4, significant ore losses are still observed. The 15% increase in recovery can be attributed primarily to the increased drawpoint width, as all other relevant parameters remained unchanged.

However, an additional observation is that instantaneous dilution increases even more sharply in this case, reaching approximately 50% and continuing to rise as extraction progresses.

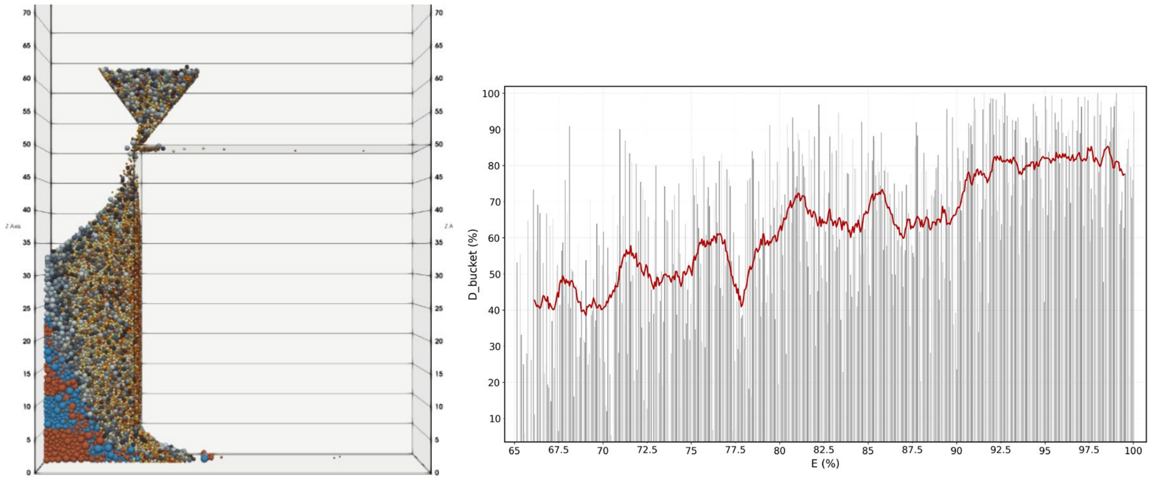

Figure 7 Variant 5 model overview and results

4.2.3 Variant 6

Based on the findings from the 100 m stope model simulations, Variant 6 (Figure 8) considers the implementation of drawbells beneath the secondary stope. This configuration effectively increases the total draw height to approximately 65 m while maintaining a maximum longhole length of 50 m, consistent with the limitations identified during the drilling campaign.

The modelling results show clear improvements compared to the previous variants. The dilution entry point shifts to approximately 75% extraction, demonstrating the positive effect of incorporating drawbells. These results indicate that such an approach may provide favourable conditions for improved gravity-flow control and enhanced overall recovery during secondary stope extraction.

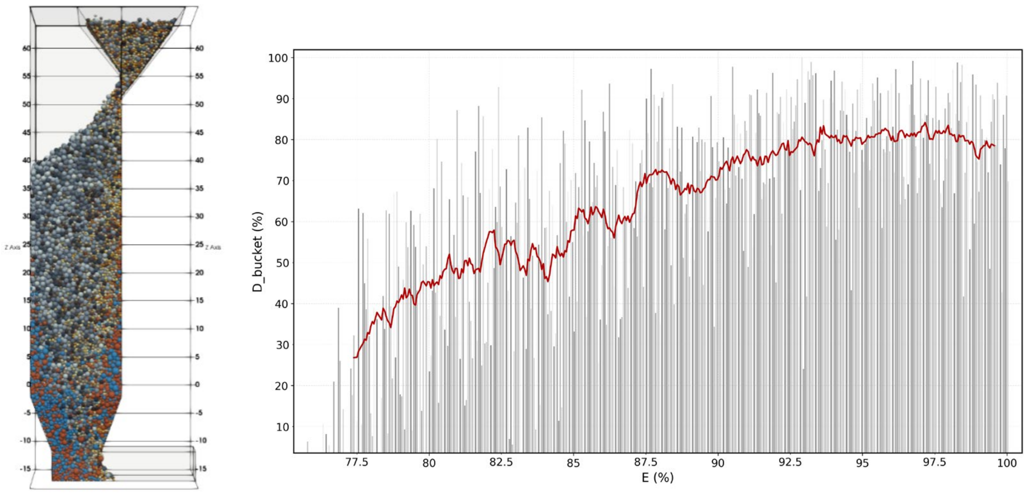

Figure 8 Variant 6 model overview and results

5 Conclusion

Given the objective of achieving radical improvements in mining method performance, a new hybrid mining concept has been proposed as a potential solution for application across Boliden's operations, starting from its flagship Garpenberg mine. The proposed approach must satisfy a strict set of constraints, particularly with respect to maintaining the mine's mass balance. Increasing stope height and introducing a new concept for secondary stope extraction have highlighted several key aspects that must be evaluated. Overall, the initial evaluation shows that the concept is technically promising, but its success is controlled by a limited number of critical factors: drilling accuracy, fragmentation, gravity-flow development, dilution entry, and the practical feasibility of drawbell construction.

The first key finding is that drilling accuracy is a governing constraint for the proposed concept. Increased stope heights and horizontal slice excavation can only be considered feasible if hole deviations remain within acceptable limits. This is closely related to the second key finding: because blasted material is intentionally retained within the stope until the final draw stage, gravity flow becomes the primary mechanism controlling ore recovery. Such flow behaviour is highly sensitive to fragmentation, and this sensitivity becomes even more pronounced under the constrained flow conditions within the stope. The modelling therefore shows that fragmentation and fines migration are central controls on dilution entry and recovery performance.

Variants 1, 2, and 3, which consider secondary stopes with a height of 100 m, demonstrate different levels of cumulative dilution as drawing continues toward full extraction. However, from a practical decision-making perspective these cumulative dilution values are of limited relevance on their own. Instead, the dilution entry point represents the critical parameter and should be considered the effective shut-off point for economic extraction. Once dilution enters the draw column, instantaneous dilution per bucket increases rapidly, often exceeding 50%, making continued mucking economically unjustifiable.

In Variant 3, which incorporates drawbells beneath a 100 m high stope, the results clearly demonstrate that drawbells promote faster development of the gravity-flow zone. This characteristic could significantly improve the overall performance of the concept by increasing flow width development and supporting improved recovery. Nevertheless, the initial modelling results indicate that fines migration remains a dominant factor influencing dilution entry and overall method performance, even when improved flow control is achieved through drawbell geometry.

The models with a reduced stope height of 50 m provided additional insights into the impact of stope height on gravity-flow behaviour. The results clearly show that reduced stope height leads to increased ore losses, indicating that such an approach is unlikely to meet the project targets. Even when the concept was modified to include longitudinal access drives, which enabled the use of wider drawpoints (15 m), the expected improvements in recovery were not achieved. In contrast, the introduction of drawbells beneath the stope significantly improved flow width development and recovery performance, highlighting the importance of this design element as the most effective geometry change evaluated in the modelling campaign.

Economic benchmarking will ultimately determine whether the operational benefits provided by drawbells justify the additional development and construction costs associated with this approach.

In summary, the modelling campaign indicates that taller stopes are generally more favourable for gravity-flow development, that dilution entry is a more relevant operational limit than cumulative dilution, and that drawbells provide the clearest improvement in recovery performance. At the same time, the results show that fines migration, fragmentation, and drilling accuracy remain critical risks that must be resolved before the concept can be advanced to full-scale testing. Considering the findings presented above, further design variants will be evaluated with the objective of incorporating the identified benefits while mitigating the associated risks and maintaining the project’s targets. One potential development path relates to drilling limitations. If drilling tests confirm that hole lengths greater than 50 m cannot be achieved with sufficient accuracy, the concept may evolve toward a multi-lift approach for secondary stope extraction. Such an approach would incorporate the observation that taller stopes exhibit more favourable gravity-flow behaviour and improved ore recovery. Furthermore, this approach aligns well with the current design framework at Garpenberg, as it allows stopes to remain within a single mining level without significantly disrupting the overall mine layout.

This paper presents the initial work conducted by the project team to rapidly evaluate key aspects of the proposed mining concept and to support the early stage narrowing of the mining method design. The focus of this study is limited to gravity-flow behaviour. The results obtained from the flow modelling campaign were used to benchmark different mining method variants and provide input for the economic evaluation of the proposed solutions. As the project is ongoing, the flow models will be revisited once more reliable input data become available, particularly with respect to fragmentation and rock mass properties such as strength and friction parameters. Due to the broad scope of the project, only a limited portion of the gravity-flow modelling results are presented in this paper.

Several additional research activities are currently underway or planned as part of the project. These include investigations into drilling deviation control measures aimed at improving drilling accuracy and achieving optimal fragmentation. Fragmentation assessment itself is a key component of the work, with active fragmentation surveys being conducted in both production stopes and development blasts, the latter serving as the primary source of rockfill. Modelling of fragmentation is also being carried out with the aim of developing a reliable and efficient predictive tool that could support full-scale testing of the proposed mining method.

In addition, in situ testing of horizontal slice blasting is currently under development. These tests are intended to evaluate fragmentation performance, overbreak behaviour, and operational feasibility. Diamond drilling of rock cores has also been conducted, and laboratory testing of rock strength and deformability is underway. These investigations aim to evaluate the stability of both the stopes and the backfill under the proposed mining concept. Together with the other research activities described above, these studies will play a critical role in defining the feasible stope height limits and identifying the key operational risks associated with the proposed method.

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