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Enabling resilient long ore pass design for sustainable deep mass mining

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ABSTRACT

Our study addresses a significant knowledge gap by focusing on the design, construction, operation, and maintenance of long ore passes exceeding 300 m in length, in deep mining environments. Initiated by the International Consortium of Cave Mining 2040 Horizon One and further developed by CSIRO, this research serves as a technical guideline for ultralong and long ore pass design and highlights scenarios where their use should be cautioned against. The research journey began with a thorough desk study and a technical survey of Subject Matter Experts (SMEs). We summarise the conclusions from SMEs worldwide to identify the primary risk factors and critical design and optimisation parameters. These insights were carefully analysed to focus on the factors causing cascading effects and intensifying risk categories through the Rock Engineering System. After identifying the key risks and effective control parameters, we conducted a comprehensive examination of the effective factors to determine the control parameters for risk management and mitigation. This study presents considerations for the resilient design of long ore passes, noting the importance of statistically based design methods capable of sustainable operation and quick recovery from disruptions, aligning with our commitment to net-zero energy transitioning in mining.

1 INTRODUCTION

Efficient ore transport is crucial for achieving net-zero emissions in deep mining. Long ore passes, which are vital in mining methods such as Sublevel Caving (SLC), play a key role in reducing costs and energy consumption. Haulage is a major constraint in underground mining methods (Sellers and Salmi, 2020; Skawina, 2019). The design and implementation of ultralong (> 500 m) and long (>300 m) ore passes in proper locations can reduce the energy consumption in hauling, decrease the diesel needed for ore transportation, and improve the throughput of underground mining methods, such as deep SLC (Manzoor et al., 2023). However, their smooth operation is critical, as disruptions such as hang-ups, wall damage, or collapses can severely impact a mine's productivity and economics.

The industry typically uses passes with lengths of up to 300 m, seldom around 500 m, and extremes are approximately 650 m in both surface and underground operations (Emesent, 2021; Jarosz, 2008; McPherson and Pearson, 1997; Nelson and Rutter, 2018; Torres et al., 1981) as shown in Table 1. Limited information is available about the risks and issues associated with ultralong and long ore pass design, implementation, application, and maintenance in the public domain. Hang-ups, blockages, and scaling (overbreak) are among the key issues affecting the structural integrity of ore passes (Esmaeili, 2010). This causes an extended downtime, and the remediation costs become more expensive with length.

Ultralong ore passes can become critical production bottlenecks in mining operations because of the inherent technical complexity and cost associated with the inspection and clearance of hang-ups (Hadjigeorgiou and Lessard, 2007; Hadjigeorgiou and Lessard, 2010; Hadjigeorgiou et al., 2005; Sredniawa et al., 2023; Sredniawa et al., 2022). For example, the Andina Division Codelco in Chile experienced significant challenges due to damp minerals with clay-like characteristics and moisture content between 4% and 8%, resulting in numerous hang-ups (Torres et al., 1981). The likelihood of difficult ground conditions also increases with depth in several mines. Therefore, an increased risk of stress-induced issues (e.g., spalling, burst, and squeezing) appears (Edelbro et al., 2019; Sjöberg et al., 2015; Sjöberg et al., 2003; Stacey and Erasmus, 2005; Stacey and Harte, 1989).

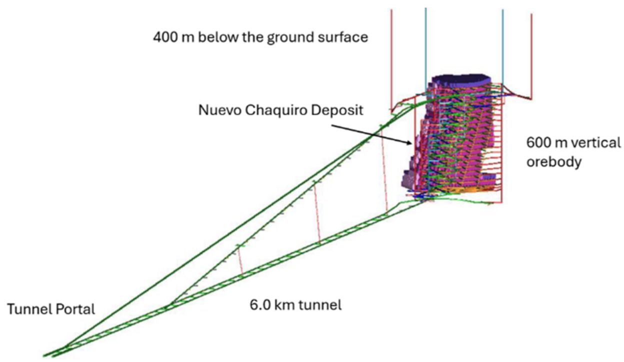

Figure 1 Access and long ore passes in a planned mine (Adopted from AGA (2019)).

Figure 1 shows how a mine design, in the project phase, can utilise a series of ore passes of approximately 400 to 500 m to transfer ore from the stopes into conveyors to be transported to the surface downhill of the mine, for a mine site located in a hilly area. Other mining projects will also face similar pressures on mine access because of the growing importance of renewable energy and the need for efficiency. This pressure arises from the need to selectively bring only the primary products that are essential for advancing towards a more circular economy to the surface (Batterham, 2017).

After a thorough desktop technical survey, we engaged global Subject Matter Experts (SMEs) to identify the primary risk factors and critical design parameters for the optimisation of long and ultralong ore passes. These insights were carefully analysed, focusing on the factors causing cascading effects and intensifying risk categories. This starts a discussion on the resilient design of long ore passes and leads to the identification of key risks and effective control parameters through the Rock Engineering System to enable mitigation and management. Then, statistical design methods are highlighted to enable robust design, sustainable operation, and quick recovery from disruptions, aligning with our commitment to net-zero energy transitioning in mining.

Table 1 Locations and lengths of known long and ultralong ore passes

Location	Length (m)
Chile	516
Canada	325
Indonesia	650
Colorado, USA	200
Sweden	350
South Africa	350

2 EXPERT SURVEY

The outcomes of the comprehensive gap analysis (Salmi et al., 2024b) showed that there is very little information documented and available regarding the design of long ore passes (with a length above 300 m to 500 m and approaching 1000 m). To address this issue, the research team conducted a technical survey of Subject Matter Experts (SMEs) from all around the world to identify the main risk factors in the design of long ore passes. SMEs with extensive ore pass design experience from various countries, including Canada, the US, Sweden, Chile, South Africa, Africa, Kazakhstan, Indonesia, and Australia, participated in the survey to assist in identifying and ranking key effective and risk factors. Further details related to the survey have been presented elsewhere (Salmi et al., 2024a) and will not be reiterated here. Such data are needed for the development of a methodology for the design and optimisation of ultralong and long ore passes in complex geological and geotechnical conditions, specifically in greenfield applications where limited data are available. The authors then took a practical step forward by compiling and processing the quantitative and qualitative survey results to distill and develop a comprehensive list of the key factors that matter most in the resilient design of ultralong and long ore passes and the main risks involved. Looking at the results of the dominant hazard problems identified (see Figure 2), the three highest factors are wall damage, frictional arching, and cohesive hang-ups. It became evident that there are some very slight trends in the responses from the survey, depending on the occupation of the respondents. Respondents from consulting companies place less importance on design, geological, and geotechnical factors than researchers do. However, this trend was not consistent for all the responses. Nevertheless, the analysis showed that these occupational biases were very minor and could be overlooked. In addition, the theory of the "Wisdom of Crowds" (Surowiecki, 2005) implies that the mean or median of the combined ratings could provide a much better estimation of the criticality of the parameters.

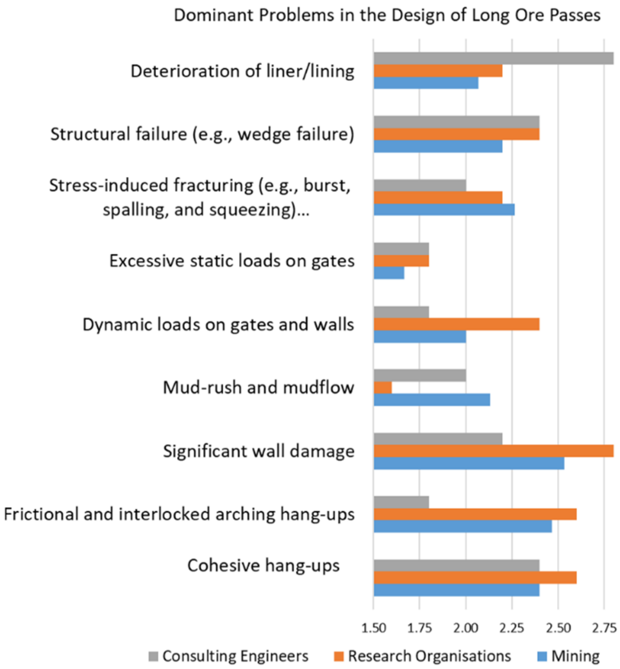

Figure 2 Dominant hazard problems in the design of long ore passes by expert discipline (3: most important, 2: important, and 1: least important).

From the survey, several pieces of information were found that have been confirmed to be correct and critical to the design of long ore passes. Several critical factors grouped into the "design and operational", "geological", and "geotechnical" factors were identified and rated in terms of their criticality by experts. The geotechnical parameters are shown in Figure 3. Several key research barriers were identified. The most critical is the lack of clear guidelines that are in place for designing and building ultralong and long ore passes, and the lack of data that is available when making decisions regarding the construction of such passes for SLC.

Some participants were also interested in expanding the technical survey to include information related to ore passes that were less than 300 m long. This interest can be assumed to be generated by a lack of guidelines or standards for ore pass construction, which have been previously identified by other scholars (Hadjigeorgiou and Stacey, 2013; Sjöberg et al., 2003). Considering how the length is a key factor in the ore pass life span, any information found to assist in long ore pass design would be relevant to shorter ore pass as well.

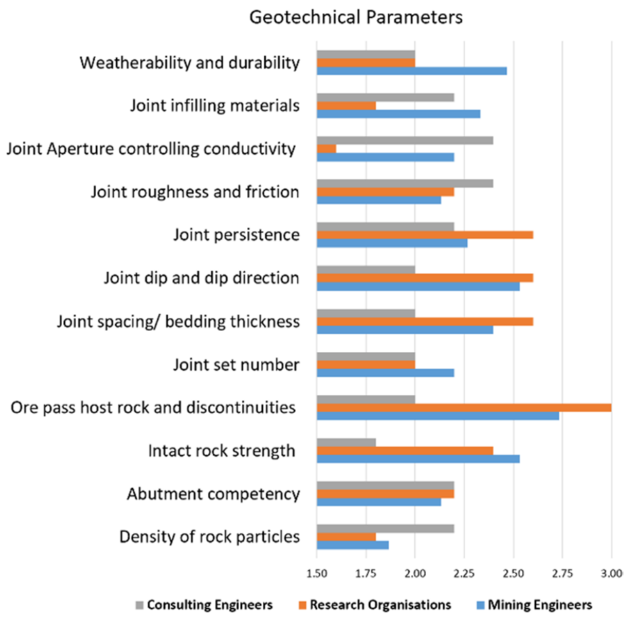

Figure 3 Geotechnical factor ratings in the design of long ore passes by expert discipline (3: most important, 2: important, and 1: least important).

Following this survey, the information can be used to carry out a second survey in which knowledge can be narrowed down to further determine the approaches that should be taken to develop and implement guidelines for ore passes of such length. It would also be beneficial to conduct research into the optimisation of the location, size, and geometry of ore passes regarding the shape of the ore body and the geology and geomechanics of the area. It might also be helpful to develop a database of ore passes to see what methods different mines have used for the design, implementation, operation, inspection, and maintenance of their ore passes to further expand the works initiated by Hagan and Acheampong (1999), Vieira and Durrheim (2005), Joughin and Stacey (2005), Lessard and Hadjigeorgiou (2003), and Hadjigeorgiou et al. (2005).

3 RESILIENCE

The mining operations are a complex system of multiple sub-systems. It was found that different elements of the mining value chain in mining systems are heavily interdependent, and the disruption of the mining infrastructure, such as ore passes, especially when coupled with production disruptions, may substantially impact the downstream (Manzoor et al., 2023; Sellers and Salmi, 2020). The idea of resilience and applying it to engineering designs in mining is a new development that is beginning to be understood and put into practice. In other branches of engineering, such as construction engineering, resilience refers to a structure or system's capability to withstand or prevent damage without completely breaking down. This is a goal of the design, maintenance, and restoration of structures, infrastructure, and communities. Resilience refers to the ability to react, endure, adjust, and bounce back from a disruptive event. A resilient system should withstand extreme events with minimal damage and operate properly during an event. If an incident takes place, the system must quickly restore its functionality, aiming to be as good as or even better than before the disruptive event occurred (Jackson and Ferris, 2013).

Figure 4 and Figure 5 schematically illustrate the functional degradation of a long ore pass, specifically characterised by ore pass productivity. Figure 4 illustrates a scenario in which productivity gradually diminishes owing to various factors, such as the accumulation of impact-induced damage, wear due to abrasive ore flow, or progressive closure of the pass caused by stress-induced failure (e.g., squeezing).

When ore pass productivity declines to a level incompatible with its intended function (see Figure 4), two primary options emerge: rehabilitation or abandonment in favour of a new pass. Choosing rehabilitation renders the pass nonoperational for a significant duration. Upon completion of rehabilitation, a relatively abrupt restoration of productivity is anticipated - a departure from the gradual recovery observed in the resilience evaluation of civil engineering structures (Koh, 2022). The loss and subsequent recovery of production during this period can be conceptualised as the "resilience polygon," like the "resilience triangle" described by Tierney and Bruneau (2007) and Koh (2022). To effectively model and optimise the recovery process mathematically, it is essential to find an approach that minimises the area enclosed by the resilience polygon (the area below the line of original capacity) while mitigating post-restoration productivity losses.

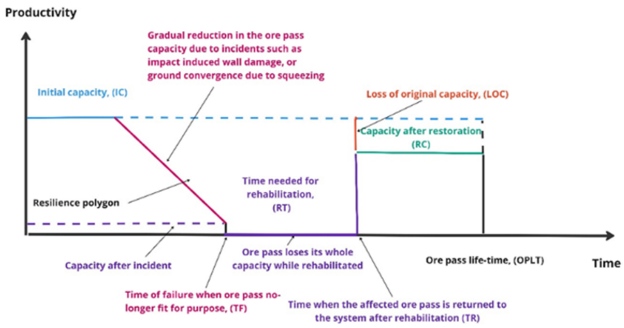

Figure 4: Schematic of resiliency polygon for long ore pass affected by impact induced damage or stress induced squeezing

Diving deeper into this analysis, it is crucial to mitigate the gradient of the red line (see Figure 4), which depicts the gradual decline in the ore pass capacity. This entails extending the time of failure (TF) to approach or even exceed the ore pass lifetime (OPLT), thereby preventing the pass from reaching an unacceptable capacity or functionality within its lifespan. This objective can be achieved by situating the ore pass within competent rock masses, distancing it from the impact of mining-induced stresses and strains, and implementing suitable liner and support measures. These measures aim to prevent any gradual deterioration that could compromise the pass’s functionality and reduce its productivity to an unacceptable level, thus necessitating potential rehabilitation. However, if deterioration cannot be avoided, the primary focus is to minimise the rehabilitation time (RT) to reduce the area enclosed by the resilience polygon (see Figure 4). Additionally, efforts will be directed toward restoring the pass's original capacity to mitigate the loss of the original capacity (LOC) observed during the decline. If the life span of the ore pass is very long, there will be potential for several cycles of these gradual declines in ore pass productivity during the pass lifetime, and after each restoration, there is a chance of capacity loss compared to its original capacity. The concept can, therefore, be amended to consider several disruption cycles within a given time span of ore pass life, and the proposed idea of minimising the resilience polygon will remain applicable, which is consistent with the mathematical modelling proposed for the resiliency assessment of civil engineering infrastructure (Kong and Simonovic, 2019).

In Figure 5, the resilient polygon (rectangle) represents the resilience dynamics of long ore passes, particularly when susceptible to various types of hang-ups such as cohesion and frictional blockages. To optimise the productivity of these long passes, minimising the area enclosed by the resilient polygon (the area of the polygons below the original capacity) is essential. Achieving this optimisation depends on several factors. First, it is necessary to reduce the occurrence of hang-ups. Second, minimising the time required for the recovery and release of hang-ups is crucial for the swift restoration of the pass functionality. Thus, efforts must focus on mitigating the decline in post-restoration productivity levels.

To achieve the first goal of minimising hang-ups, designing an ore pass that ensures unlimited ore flow is essential. This involves increasing the pass diameter to facilitate smooth flow and reduce irregularities in the ore pass geometry, which can induce turbulence and disrupt the flow dynamics, refining blasting practices to diminish fragmentation size while controlling the proportion of fines, installing grizzly screens to filter out oversized material, and implementing effective drainage methods to manage muck moisture content.

Note that Some of these solutions might be controversial and require optimisation. For example, increasing the dimensions of the long ore passes to ensure free flow of rock particles may increase the risk of geotechnical instability of the passes themselves.

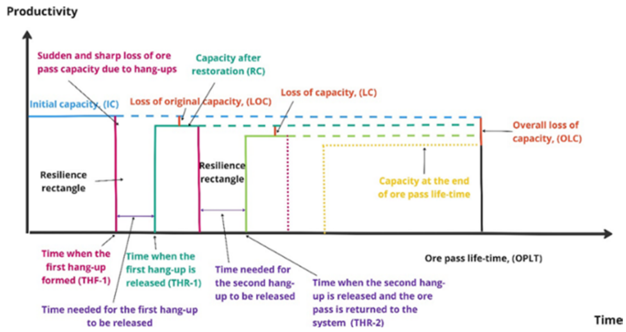

Figure 5 Schematic of resiliency rectangle for recovery from hang-ups.

For the second objective, swift hang-up recovery employing appropriate strategies and techniques is crucial. This entails having a skilled and experienced crew trained in hang-up release procedures and ensuring convenient access to hang-up locations. Lastly, to minimise productivity losses post-restoration, it is crucial to minimise the adverse effects of hang-up release methods, particularly during blasting, on the stability and functionality of ore passes. This involves carefully managing the impact of blasting or other hang-up releasing methods to prevent compromising the structural integrity and operational functionality of the passes. Achieving these objectives collectively contributes to reducing hang-ups, expediting recovery, and mitigating productivity losses in ultralong and long ore pass operations.

It is also noted that, depending on the rehabilitation of the passes, the productivity recovered may not necessarily return to the original (pre-disruption) level after an incident. However, a short-term increase in the ore pass system performance may be required after recovery to compensate for the loss that occurs during the disruption (Koh, 2022). An increase in functionality level may also occur when more advanced technology is incorporated during repair and rehabilitation works (e.g., if a new and more robust liner is applied or a new technology for the monitoring of passes and hang-ups) (Emesent, 2021; Van Heerden et al., 2005). In contrast, a reduction in productivity may be observed if recovery and rehabilitation efforts end before full recovery after an acceptable level of productivity has been regained.

Table 2 Representative effective factors (RFs) and Hazard Factors (HZs)

Factor	Definition
RF1	Orebody characteristics
RF2	Mining method
RF3	Mining production
RF4	Rock stresses
RF5	Water flow
RF6	Country rock characteristics
RF7	Construction method
RF8	Support method
HZ1	Hang-ups
HZ2	Mud-rush
HZ3	Air-blast/Back blast
HZ4	Wear and degradation of walls
HZ5	Structural failure
HZ6	Stress induced failure

4 EFFECTIVE FACTORS FOR RISK MANAGEMENT USING ROCK ENGINEERING SYSTEM

Efficient ore transport is crucial for achieving net-zero emissions in deep mining. Long ore passes, vital in methods like Sublevel Caving (SLC), play a key role in reducing costs and energy consumption. Their smooth operation is, therefore, critical, as disruptions such as hang-ups, wall damage, or collapses can severely impact a mine's productivity and economics.

Desktop study and Expert Elicitation information were used to identify the key factors affecting the stability and performance of ultra-long and long ore passes (Salmi et al., 2024a, b). Subsequently, Hudson's Rock Engineering System (Hudson, 1992) was applied to filter the parameters and identify the most critical factors.

Qualitative and quantitative Rock Engineering System (RES) analyses have been detailed elsewhere (Hudson, 1992; Salmi and Sellers, 2022), encompassing two distinct approaches: low-resolution with eight effective factors and detailed analysis with a more comprehensive set of 58 effective factors. We found it is important to integrate both effective factors and common hazards into the analyses. This multifaceted approach enables a comprehensive examination of the representative effective factors (see RFs in Table 2) and hazard factors (see HZs in Table 2) influencing ore pass design and optimisation, providing insights into both the inherent complexities of the system and the potential risks posed by common hazards.

The conducted RES analyses containing the interaction with hazards facilitate the ranking of hazard criticalities associated with the design and optimisation of ultra-long and long ore passes. The ranking definitions were as follows: 0, no interaction; 1, low interaction; 2, moderate interaction between parameters; and 3, strong interaction. The ranking matrix for the low-resolution approach is shown in Figure 6. Considering the relative values of the sum of rows (see Figure 6) and the sum of columns (Effect in Figure 6) offers valuable insights into prioritising risk management strategies and effectively allocating resources to mitigate the most significant hazards.

The priority factors that emerge are wear and deterioration of wall supports and liners due to impact-induced damage from abrasive ore, structural failure (e.g., wedge/block failure, cohesive and interlocking/frictional hang-ups, stress-induced failure, such as spalling, squeezing, burst, etc.), and mud-rush and mudflow. The following closely are gate failure, preferential flow in ore pass systems with branches and fingers, and air-blast and back-blast. These dominant hazards warrant particular attention in risk management and mitigation strategies for ultralong and long ore pass systems.

														Cause:
RF_1	3	3	2	1	1	2	2	3	2	3	3	1	1	27
1	RF_2	3	3	1	1	3	1	2	1	1	1	1	2	21
0	1	RF_3	3	1	1	3	2	2	1	2	3	1	1	21
1	1	2	RF_4	3	2	3	3	1	0	0	2	3	3	24
0	1	1	2	RF_5	3	3	3	2	2	0	3	3	3	26
0	1	1	3	2	RF_6	2	2	3	3	2	2	3	2	26
0	2	2	2	1	2	RF_7	3	3	3	3	3	3	3	30
0	1	3	3	3	2	1	RF_8	1	0	0	3	3	3	23
0	0	3	1	1	1	0	1	HZ_1	3	3	2	1	1	17
0	0	3	1	1	1	0	1	1	HZ_2	3	1	1	1	14
0	0	2	0	1	0	0	1	1	1	HZ_3	2	1	1	10
0	0	3	1	3	1	0	3	1	1	1	HZ_4	2	2	18
0	0	3	2	3	1	0	3	2	1	1	3	HZ_5	2	21
0	0	3	3	3	1	0	3	2	1	1	3	2	HZ_6	22
2	10	32	26	24	17	17	28	24	19	20	31	25	25	<Effect

Figure 6 Rankings of representative effective factors (RFs in Table 2) and the Hazard Factors (HZs in Table 2).

5 SYSTEMS THINKING

Long ore passes are subsystems of complex underground mining systems. Therefore, system thinking could be a useful approach for the design and optimisation of ultra-long and long ore passes within the larger context of underground mining systems. By adopting a holistic approach, engineers can consider how long ore passes interact with various components of the mining system, such as stope mining, scheduling, material handling, and support systems. Understanding these interdependencies enables identification of potential bottlenecks, inefficiencies, and safety risks. For instance, when designing ore passes, engineers must consider factors such as the rock mass properties, ore pass geometry, material flow dynamics, support measures, and liner characteristics. Each of these elements influences the performance of the ore pass, and consequently, the overall productivity and safety of the mining operation. By analysing the entire system and its subsystems, engineers can optimise the ore pass design parameters to enhance material flow, minimise hang-ups, reduce maintenance requirements, and ensure long-term structural integrity. This integrative approach maximises the efficiency and effectiveness of the entire underground mining system while mitigating the risks associated with ore pass operation.

6 STATISTICALLY BASED DESIGN

The stability of rock excavations, including long ore passes, is controlled by the rock mass condition, method of excavation, field stress state, and quality and quantity of the support measures applied. Jager and Ryder (1999) stated that one of the main aspects of the design of underground mining excavations is to control the field stress levels as much as possible to protect service excavations. To meet this goal, it is necessary to control the absolute stresses in the rock mass where service excavations have been located, to bearable levels. This can be achieved by locating ore pass excavations sufficiently remote from highly stressed areas and by properly designing layouts and sequences.

Wagner and Wiseman (1980) and Wagner (2019) proposed using a semi-empirical design criterion for the assessment of tunnel conditions and support systems, knows as the Rockwall Condition Factor (RCF). This approach was then used by Coetzer and Sellers (2003) to provide a tunnel design methodology to deal with a probabilistic in situ stress distribution. Joughin and Stacey (2005) also used this approach to investigate the stability of ore passes in deep mines in South Africa. The Rockwall Condition Factor (RCF) is defined in Equation 1 as

$$RCF = (3\sigma_1 - \sigma_3)/(F_m \times \sigma_c) \quad (1)$$

- If RCF < 0.7 good conditions prevail in the excavations
- If 0.7 < RCF < 1.4 average conditions prevail and typical support are needed
- If RCF > 1.4 the excavation conditions deteriorate rapidly

Here, σ_1 and σ_3 are the major and minor principle stresses, respectively. In addition, σ_c shows the intact rock strength, and F_m is a scaling factor that adjusts the intact rock strength to the rock mass strength.

In porphyry deposits typical for mass mining, geological formations and structures are often affected by the previous occurrence of hydrothermal alterations, leading to variations in the geotechnical properties of rock masses. Using geotechnical information from 6292 meters of drill holes associated with a proposed Columbian mining project (AGA, 2022; Perez Rodriguez et al., 2018), including UCS and Rock Mass Rating (RMR), and considering in-situ stress estimates from the provided landscape and rock density, it is possible to correlate RCF with depth for the mine location.

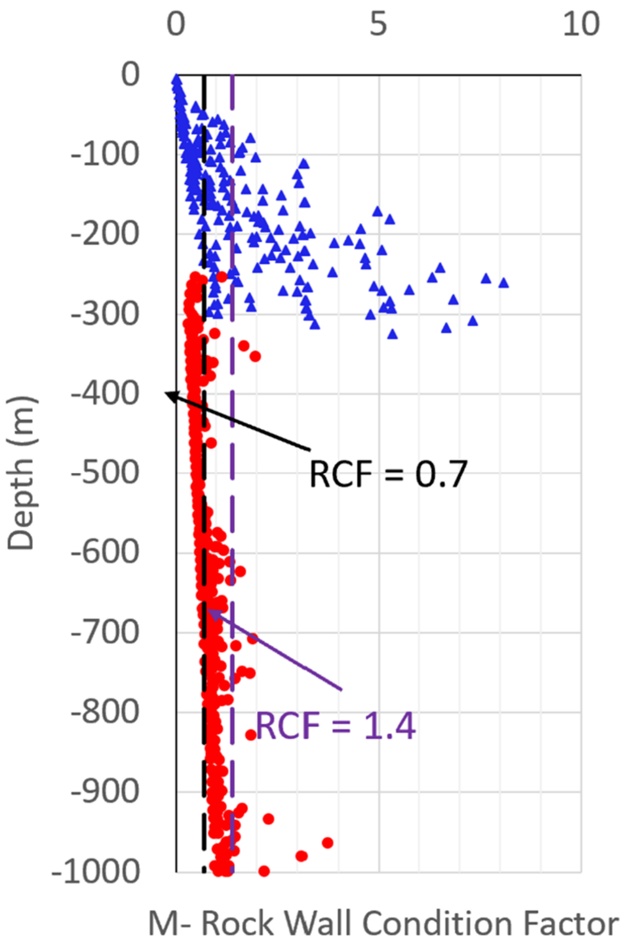

Figure 7: The Mean Rock Wall Condition Factor (RCF) based on the variation of rock mass characrtistics with depth

Considering the average values in Figure 7, the effect of the initial 100 m cover (with erosion, alteration, weathering, and deterioration, primarily influenced by the region's substantial rainfall and environmental conditions) and the next 200 m (characterised by the prevalence of sericite and chlorite-sericite rocks) create significantly weak rock formations. The rock quality improves significantly from approximately 400 m to 1000 m, encompassing the designated area for long ore passes, exhibiting a relative rock mass strength ranging from strong to very strong. The criterion for a typical support is met from a depth below 500 m and up to 1000 m depth (see Figure 7).

When we examine the lower bound rock mass properties predicted based on the coring data, there is a notable contrast, as shown in Figure 8. Throughout most of the ore pass length, the Rockwall Condition Factor (RCF) exceeds 0.7. Below 500 m, there is a notable possibility that the RCF surpasses 1.4, indicating the likelihood of significant stress-induced instabilities in those areas.

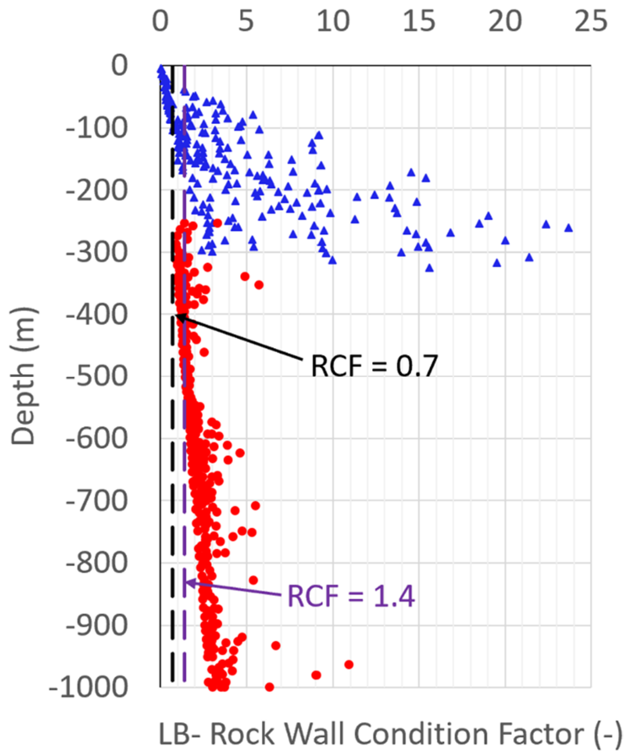

Figure 8: Lower Bound Rock Wall Condition Factor (RCF) based on the variation of rock mass characrtistics with depth

It is also noted that the methods proposed by Ramamurthy (1993) and Zhang and Einstein (2004) were used to estimate the F_m values needed for computing the variation of the average and lower bound *RCF*s, as shown in Figure 7 and Figure 8.

7 CONCLUSIONS

Effective ore transportation is essential for achieving net-zero emissions in deep mass mining operations. Ultralong and long ore passes, particularly important in techniques such as Sublevel Caving (SLC), are central to minimising costs and energy usage in material hauling. Nevertheless, ensuring their uninterrupted implementation and functioning is paramount, as interruptions such as hang-ups, wall degradation, or collapses can significantly hinder mine's efficiency and productivity. After a thorough desktop technical survey, we engaged global Subject Matter Experts (SMEs) to identify the primary risk factors and critical design and optimisation parameters. These insights were carefully processed and analysed, focusing on the factors causing cascading effects and intensifying risk categories. This starts with a discussion on the resilient design of ultralong and long ore passes and leads to the identification of key risks and effective control parameters through the application of the Rock Engineering system to enable mitigation and management. This research then introduces a novel approach for integrating the interconnectedness of key factors and primary geotechnical and operational hazards into the design and optimisation processes of ultralong and long ore passes. By considering different resolutions and scenarios, the analyses aimed to offer a holistic understanding of the critical elements that shape the performance and stability of ore passes. Ore pass lifecycle diagrams were also proposed to exemplify the degradation, blockages, and restoration cycles to qualitatively evaluate operational resilience. Simple statistical design methods were then highlighted to ensure that the full range of geotechnical data was considered during the design process to enable continuous and sustainable operation with quick recovery from disruptions, aligning with our commitment to net-zero energy transitioning in mining.

It is also noted that the lack of data was frequently raised by SMEs, especially regarding the identification of the best ore pass locations and the geological and geotechnical information required for the assessment of the potential of raise boring and stability analyses. These are difficult tasks for geotechnical and mining engineers because of the length and considerations that would need to be made during the early planning process of the ultralong and long ore pass.

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