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REVIEW ARTICLE

A review on the geotechnical design and optimisation of ultra-long ore passes for deep mass mining

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Abstract

Enhancing mine energy efficiency and productivity necessitates the implementation of longer ore passes, exceeding 300 m, to optimise material transport in underground mass mining. This research has revealed sporadic historical use of extremely long ore passes, stretching beyond 500 m and reaching up to 650–700 m, in both surface and underground settings. However, the scarcity of available data related to the primary engineering, geological, and geotechnical risks associated with the design, implementation, operation, and maintenance of long ore passes implies an urgent need for research into strategies to mitigate uncertainties in the design and optimisation of these passes. A comprehensive gap analysis from available ore pass projects worldwide, compiling various geological and geotechnical parameters affecting the ore passes' design and optimisation, identifies new techniques for designing these critical rock structures, highlights deficiencies in current methodologies, and shows areas for enhancement through expert elicitation techniques and risk assessment methods. Key utilisation scenarios for ore passes exceeding 300 m in length were also identified within the research and categorised into the design phase, emphasising stability, inclination, and gate loading, and the construction phase, including drilling, blasting, raiseboring, and support and lining, and the operational phase, encompassing flow dynamics, hang-ups, and ore fragmentation consequences. Insights gleaned from this comprehensive literature review and gap analysis provide a robust foundation for geotechnical engineers involved in the design of long and ultra-long ore passes for deep mass mining. These findings can empower engineers by enabling them to proactively anticipate, effectively respond to, and continually learn from the challenges inherent in the design, construction, operation, and maintenance of ultra-long and long ore passes. Further research is needed to facilitate energy-efficient material transfer in deep mass mining, including proper design and implementation of passes in uncertain geological conditions. This includes techniques for investigating the long-term stability of ore passes, enhancing the understanding of the risk of structural failure, improving characterisation of rock fragments, investigating flow dynamics, identifying better liner materials, methods for determining optimal pass placement, improving surveying and monitoring techniques, quantifying the rheological behaviour of muck and wet muck for flowability assessment, assessing the impact of mining-induced stresses on the stability of long ore passes, and developing safer and more efficient techniques for the mitigation and recovery of hang-ups.

Keywords Long and ultra-long ore passes · Sub-level caving · Deep mass mining · Gap analysis · Risk assessment · Resilient design

Introduction

All surface mining operations have a limited life which is often dictated by the so-called economic depth. At greater depths the costs of hauling the ore and removing waste via large diesel or electric trucks become prohibitive. To prolong the life of the current surface mines or to have access to deeper deposits, mining generally continues underground (Castro et al. 2023b; Hustrulid and Bullock 2001; Whittle et al. 2015). The backbone of most underground mining

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methods are ore passes, vertical or inclined, that serve as crucial conduits for transporting ore. For example, in sublevel cave mining, ore passes are used to transport ore and waste materials from the separate sublevels downward to the main haulage level (see Fig. 1). With the onset of the energy transition and saving, and the requirement for removal of diesel fumes (Salama et al. 2015; Skawina 2017; Skawina and Salama 2021), combined with deeper mines and wider spaced levels, it is anticipated that gravity feeds to shafts and conveyors may well become more popular mining solutions leading to the use of increasingly longer ore pass lengths. To enhance ore recovery, mines frequently locate ore passes into waste rock formations, as noted by Kvapil (1982, 1998), which possess varying rock properties. Unlike the ore body rock masses, waste rocks are often less thoroughly characterised in terms of their mechanical properties. This lack of characterisation diminishes the ability to make informed geotechnical decisions regarding the future stability of ore passes (Stacey and Hadjigeorgiou 2022).

The choice of using long ore passes, however, remains controversial, as truck operations offer high flexibility and reduce both capital costs and the amount of underground excavation, which can be complex (Greberg et al. 2016). The economic and energy response depends on the selected size of the mine openings and trucks, while emissions are strongly influenced by the choice of diesel or electric power (Greberg et al. 2016). The economic benefits of ore passes depend on their placement relative to the orebody (Koivisto 2017). Other forms of transport, such as high-angle conveyors, are now possible and become more economically advantageous with greater depth (Mahieu 2018). This paper will focus on identifying the advantages and disadvantages of long (lengths above 300–500 m) and ultra-long (lengths above 500 m) ore passes.

Despite the vital role of ore passes in mining, their design, implementation, operation, and maintenance have not received adequate attention, and they come with specific technical challenges. One significant issue is the potential for ore pass failure or blockage during material transport (Castro et al. 2016; Hadjigeorgiou and Lessard 2007; Iverson and Jung 2005; Sredniawa et al. 2023; Szwedzicki 2007). Such incidents can have a substantial impact on operational capacity and productivity. Hang-ups or blockages can render ore passes unusable, creating bottlenecks in the production cycle. When ore passes are no longer functional, they directly reduce mine production, underscoring their critical role in maintaining efficiency and throughput. Addressing these challenges is paramount for ensuring uninterrupted material flow and maintaining optimal operational productivity (Hadjigeorgiou and Lessard 2007; Manzoor et al. 2023a; Sredniawa et al. 2022; Szwedzicki 2007). Any malfunction or failure of an ore pass has the potential to instigate substantial disruptions in mine productivity (Skawina et al. 2018; Sredniawa et al. 2023) and recognising that ore passes can effectively serve as operational bottlenecks (Goldratt and Cox 2016), it becomes imperative to maintain their continual activity and efficiency throughout the entire mining operation for the optimisation of the mining value chain.

To date, there is very limited information available regarding the degradation and maximum throughput tonnage for ore passes having lengths greater than 300 m. A comprehensive industry benchmarking study on ore passes

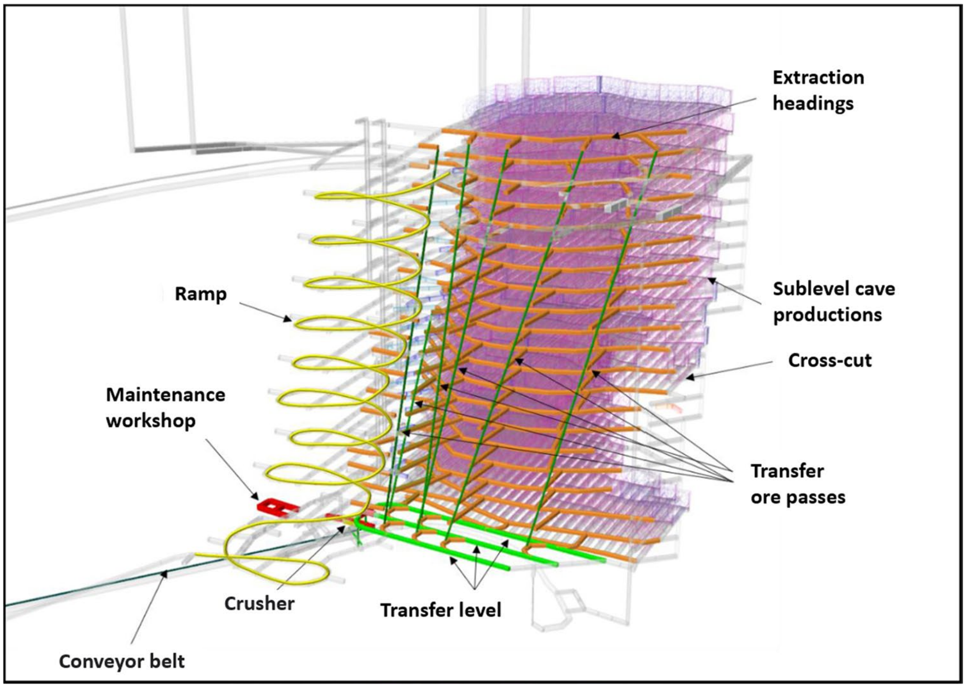


Fig. 1 An example of the application of long ore passes proposed for a sublevel caving operation in Colombia (Adopted and modified from AGA 2019)

in several deep and ultradeep underground mines in South Africa indicated a typical length of less than 200 m with only one pass exceeding 300 m (Joughin and Stacey 2005). Insights from Canadian and South African mines, as highlighted by Hadjigeorgiou and Stacey (2011), provide valuable perspective on the design and operation of ore pass systems. While mining operations have established clear goals for these systems over time, there remains a lack of well-defined strategies to effectively achieve these objectives.

The scarcity of publicly available information regarding the design, construction, operation, and maintenance of long and ultra-long ore passes is a critical issue, limiting the capability of the mining industry to design new, safe, and energy efficient operations where gravity flow operations supersede diesel powered trucking. The consequences of this scarcity are multifaceted. Firstly, the lack of standardised design guidelines and best practices for dealing with increased pass length increases the risk of future failures, compromising worker safety and causing costly production disruptions. The absence of comprehensive information also affects the ability of mining engineers and operators to make informed decisions regarding the new implementations of much longer ore passes in terms of design parameters, method of implementation, material selection for supporting, and maintenance strategies. As a result, mining operations will be unable to increase efficiencies, reduce downtime, and maintenance costs leading to conventional solutions that do not enhance industry productivity, competitiveness and sustainability. Considering these challenges, our research endeavours to address the knowledge gap surrounding ultra-long and long ore passes by systematically investigating key aspects of their design, construction, operation, and maintenance, focussing on the effect of length. By extracting the critical factors influencing ore pass performance and resilience design, we aim to provide valuable insights and practical recommendations to enhance safety, efficiency, and cost-effectiveness in deep mass mining operations. Through collaborative efforts between industry's engineers, academia, and consultant engineers we aspire to contribute towards the development of comprehensive guidelines and resources that will benefit the mining community in the design and optimisation of long-ore passes for the deep mines of the future.

The design and placement of ore passes in underground mining operations are critical decisions that impact safety, efficiency, and economic viability. For typical length passes, Stacey and Hadjigeorgiou (2022) underscore the complexity involved in these decisions, highlighting factors such as pass location, orientation, size, shape, and method of excavation. In high-stress environments, such as deep sub-level caving operations, the close proximity of ore passes to the orebody can lead to stress-induced failures and rock instability over time. While positioning passes closer to ore sources may seem operationally efficient initially, it can pose long-term risks to mine stability and productivity.

Moreover, the absence of comprehensive design strategies for ore passes, as observed by Hadjigeorgiou and Stacey (2013), is often due to the limited quantification of the overall, long term asset management costs associated with inadequate planning, design, and operation. This includes overlooked expenses related to hangup clearance, blast damage repair, and rehabilitation. Insufficient geotechnical data further complicates the situation, as noted by Joughin and Stacey (2004), resulting in a reliance on undocumented information and word-of-mouth communication among shaft personnel.

Our paper will begin by examining previous examples of ultra-long and long ore pass operations gathered from existing literature. Next, the paper aims to determine the key effective factors that must be considered in the design of long and ultra-long ore passes; the major issues associated with the design, implementation, operation, and maintenance of these systems; and the key triggers to identify when rock passes should be avoided. In this paper, a gap analysis of the work related to the design of ore passes conducted by Canadian, South African, Swedish, Australian, and US experts is also conducted to identify the issues and opportunities related to the design of ore passes and to use the lessons that can be distilled from previous studies for a resilient design of long ore passes for mass mining in great depth and challenging geological and geotechnical ground conditions. We will also carefully examine various facets of ore passes, including the following aspects:

Design of long and ultra-long ore passes This encompasses stability assessment, ore pass inclination, and static, and dynamic gate loads.

Construction methods We will delve into the techniques involved in the construction, including conventional drill and blast operations, support, and lining strategies, and raise boring methods.

Operation This section will cover some critical operational considerations such as flow dynamics, cohesive hang-ups, interlocking hang-ups, and ore fragmentation effects.

This comprehensive study identifies gaps in designing, implementing, and maintaining long ore passes in complex geological settings. To address these gaps, engaging Subject Matter Experts (SMEs) and using the "Expert Elicitation" methodology (Baecher 1999) helps pinpoint influential factors and key geotechnical risks. By gathering and processing existing knowledge, this research contributes useful insights for the robust and resilient ore pass design. Additionally, it develops the groundwork for further analysis using the Rock Engineering System (Hudson 1992) to understand how crucial engineering, geological, and geotechnical factors influence various risks, unveil cascading effects from disturbances, and identify effective controls for risk management and mitigation.

Prior implementations of long and ultra-long ore passes

The industry has used passes with lengths above 300 m and occasionally with lengths around 500 m and up to around 650 m in both surface and underground operations (Emesent 2021; Gresham and Turichshev 2016; Jarosz 2008; McPherson and Pearson 1997; Nelson and Rutter 2018; Torres et al. 1981). A summary of the main operations using long ore passes (length > 300 m) and the main technical issues they have been dealing with are presented in Table 1. Typically, these ultra-long ore passes have been used in mines situated on mountains e.g. Andina (Ascencio 1985; Torres et al. 1981) and Grasberg (Jarosz 2008; Parhusip et al. 2021) to transport ore to processing plants at lower level. The height difference and distance from the mountainside control the length of the ore pass. Unfortunately, there is limited information available about these ore passes in the public domain, especially about the risks and issues associated with their implementation, application, and maintenance. What information exists is compiled and processed. In other underground mines, (e.g. Brunswick, and Kiirunavaara), upper levels became depleted and mass mining blocks have been positioned at deeper and deeper levels leading to ore passes with substantial lengths (Esmaeili 2010; Hadjigeorgiou et al. 2008; Sredniawa et al. 2022, 2023). Another such mine is the Finsch diamond mine in South Africa that uses underground silos to transfer ore between levels or to redirect ore for load and haul to the surface Emesent (2021). Blockages, hang-ups, overbreak or scaling are among the main issues impacting the structural integrity of the ore passes and resulting in extended downtime and significant remediation costs. According to the findings of LiDAR scanning performed by Hovermap technology, the extensive wear and deterioration was caused by extended scaling and led to the irremediable condition of one of the long ore passes, compelling its abandonment. The outcomes of the Hovermap scan provided invaluable assistance to the mine manager in making this essential decision (Emesent 2021).

Ore passes of considerable length, exceeding 300 m, can potentially emerge as critical bottlenecks within mining operations due to the inherent technical complexity and cost associated with inspecting and clearing hang-ups that may occur deep within these extended ore pass systems. (Hadjigeorgiou and Lessard 2010; Hadjigeorgiou et al. 2005; Sredniawa et al. 2022, 2023; Sun et al. 2024). These types of hang-ups could result in delays in production and economic losses and can affect the entire process of mining. Restoring flow inside ore passes requires extensive rehabilitation and could lead to injuries and fatalities of workers (Hadjigeorgiou and Stacey 2013; Lessard and Hadjigeorgiou 2003a; Manzoor et al. 2023a; Nazeri 2001; Sredniawa et al. 2022).

For example, Andina Division Codelco, in Chile, experienced significant challenges in handling damp minerals in block caving mining with grizzlies, conveyor belts, and cohesive hang-up issues in ore passes (Torres et al. 1981), generated because of the melting of snow and the seepage of the water to the subsidence zones. Damp minerals, exhibiting clay-like characteristics and moisture content ranging from 4 to 8%, resulted in material cohesion and flow issues, leading to production stoppages and leaving up to 30% of reserves untapped. According to Ascencio (1985), the length of some of the ore passes used in this operation exceeded 500 m (Ascencio 1985).

Another illustrative example of the challenges encountered during the operation of long ore passes is the case of the deep sublevel caving operation at Kiirunavaara by LKAB, where stress-induced failures led to significant dilation and structural instability within the ore passes. Despite initial design considerations, the high-stress environment led to unexpected rock failures and passes deterioration and deformations, necessitating costly remediation measures and operational disruptions (Sredniawa et al. 2022, 2023). By examining the root causes of these failures and their impact on production efficiency and safety, mining operators can gain valuable lessons for mitigating similar challenges in their operations (Sjöberg et al. 2003).

Furthermore, the repeated blasting activities conducted during ore pass development and maintenance can exacerbate wear and structural degradation over time. Several case studies from large-scale underground mining operations demonstrates how frequent blasting operations in ore passes can lead to accelerated abrasive wear of ore passes walls and linings and support structures, resulting in increased maintenance requirements and downtime for repairs (Gustafson et al. 2016; Manzoor 2023; Sredniawa et al. 2023). Implementing proactive maintenance strategies, such as regular inspections and material upgrades, can help to mitigate the adverse effects of abrasive wear and prolong the service life of long ore passes' components (Brenchley and Spies 2006; Dunn and Menzies 2005; Hart 2006).

When the length of ore passes increases, there is a greater likelihood that the ore pass will encounter difficult ground conditions; also, the possibility that longer ore passes extend to deeper levels and, therefore, have a greater risk of stress-induced issues (e.g., spalling, burst, and squeezing) (Edelbro et al. 2019; Sjöberg et al. 2015; Stacey and Harte 1989; Stacey et al. 2005).

Table 1 A summary of existing long and ultra-long ore passes applications with main challenges

Mine site	Location	Maximum length of ore passes (m)	Method of excavation	Dominant problem	References
Río Blanco Division, Andina, Codelco	Chile	516	–	Hang-ups due to feeding wet muck	Ascencio (1985), Torres et al. (1981)
Brunswick	Canada	325	Raise-boring	Structural failure, Stress-induced failure	Esmaeili (2010), Hadjigeorgiou et al. (2008)
Grasberg	Indonesia	500 to 650	–	Severe air blast/back blast, dust mitigation issue, and serious wear which resulted in significant widening of some passes in the system	Calizaya and Duckworth (2007), Casten et al. (1999), Jarosz (2008), McPherson and Pearson (1997)
Henderson	Colorado, USA	Currently, 200 in full length. Mine may use passes with lengths beyond 300 in the future	Raise-boring	Flow dynamic issues and preferential draw in the ore passes' system, significant piston effect, and dust propagation in the system	Callahan and Gillon (2012), Gresham and Turichshev (2016), Nelson and Rutter (2018)
Kiirunavaara	Sweden	Around 350	Raise-boring	Significant wear and deterioration, stress and structural induced failures, issues with oversized fragments blocking ore passes	Manzoor et al. (2023a, b), Sjöberg et al. (2003), Sredniawa et al. (2022, 2023)
Finsch Mine Petra Diamonds	South Africa	350	Conventional drill and blast methods	Extensive wear and deterioration, resulting from prolonged scaling, rendered one of the long ore passes irreparable and necessitated its abandonment	Emesent (2021)

Review of state-of-the-art in the design, construction, and operation of ore passes

Design

In this section, we will provide a concise overview of the primary techniques employed by the industry for the design of ore passes. In the design phase of ultra-long and long ore passes, several critical factors must be considered. Firstly, the volume and rate of material transfer are crucial, ensuring the passes can accommodate the anticipated flow without blockages or excessive wear. Mining-induced stresses, influenced by the depth, surface topography, large structures, and the geometry of the ore body and the excavation, dictate the structural integrity requirements of the passes. The chosen mining method and levels also affect pass location and orientation relative to the ore body and drive-ways, and controlling the optimisation, efficiency and safety of the passes. The spacing between passes also influences the volume of materials transferred through them, and their alignment with geological features affects material flow and stability. Moreover, distances between mining levels dictate the length and gradient of passes, optimising haulage while minimising energy consumption and maintenance costs. Integrating these considerations ensures robust, efficient ore pass designs tailored to the specific mining operation's needs.

Stability analysis

Despite the critical importance of ore passes in underground mining operations, there has been relatively little emphasis on assessing the structural integrity of these vital rock structures, especially when compared to the more extensive investigation of rock flow dynamics within them. However, it is imperative to recognise that these two aspects are intricately linked and can significantly influence each other. Sjöberg et al. (2003) examined the primary failure mechanisms and modes observed in ore passes within the Kiirunavaara mine applying numerical models with empirical data and engineering expertise. They also aimed to identify the key controlling factors in the ore passes and find the main failure modes or mechanisms that govern failure and damage in ore passes. Sjöberg et al. (2003) developed a causal model, that effectively describes the mechanisms of failure and the progression of damage, and can be used to provide valuable insights into forecasting future ore pass stability and to recommend effective remedial measures (see Table 2; Fig. 2).

Key factors for designing a functional ore pass include:

- Structural instability (Stacey and Bartlett 1990; Stacey et al. 2005). The sliding of rock blocks can lead to rock falls and is among the dominant structural failures in rock excavations and ore passes. Discontinuities including joints, fractures, and faults should be carefully characterised and considered in the design of long ore passes. The orientation (between the discontinuities and the excavation and between discontinuities themselves), spacing, persistence, and thickness of discontinuities must all be included in the stability analyses (see Fig. 3).
- Orientation of the ore passes with respect to bedding (Esmaeili and Hadjigeorgiou 2012, 2014; Stacey and Swart 1997). Ore passes are more likely to suffer enlargement and degradation when they are developed sub-parallel to the rock foliation angle.
- Discontinuity filling (Barton 1995, 2016). The type of filling materials and their mechanical characteristics, as well as the shear strength of discontinuities, are also critical factors governing the mechanisms of failure and the formation of potentially unstable wedges or blocks.

Table 2 Analysis of failure modes, mechanisms, and influencing factors in ore pass failures and damage (Sjöberg et al. 2003)

Mode of failure	Mechanism of failure	Controlling factors
Slabbing and width increase	Spalling	High stress, and high-strength, brittle rock
Groove in floor and height increase	Wear and impact from transported rock	Wear, and boulder impact
Width increase and increase in width and height	Groove and shear failure in ore pass walls	Stress state, wear, and impact, non-brittle rock
Block fallouts, and height increase	Wedge failures along joints	Pre-existing joints, and stress state
Fallouts on the intermediate level	Wedge failures along joints and boulder impact	Pre-existing joints, and geometry and construction of intermediate level

Note that in Table 2, the mode of failure and the mechanisms of failure are different. The mode of failure is defined as the primary way in which rock materials around the ore passes break or become incapable of performing their intended function which is self-supporting the pass. Mode of failure is a broad classification of failure based on observable characteristics and is often categorised into modes such as tension, compression, shear, bending, buckling, or a combination of these. The mode of failure is concerned with the overall pattern of deformation and fracture exhibited by the rock materials. Conversely, the mechanism of failure delves deeper into the underlying physical processes leading to the observed mode of failure. It seeks to explain why and how the rock materials failed, on a more detailed level, considering factors like stress concentrations, crack propagation, rock mass properties, defects, and weak rock planes. The mechanism of failure provides insight into the fundamental processes that initiated and propagated the failure (Sjöberg et al. 2003)

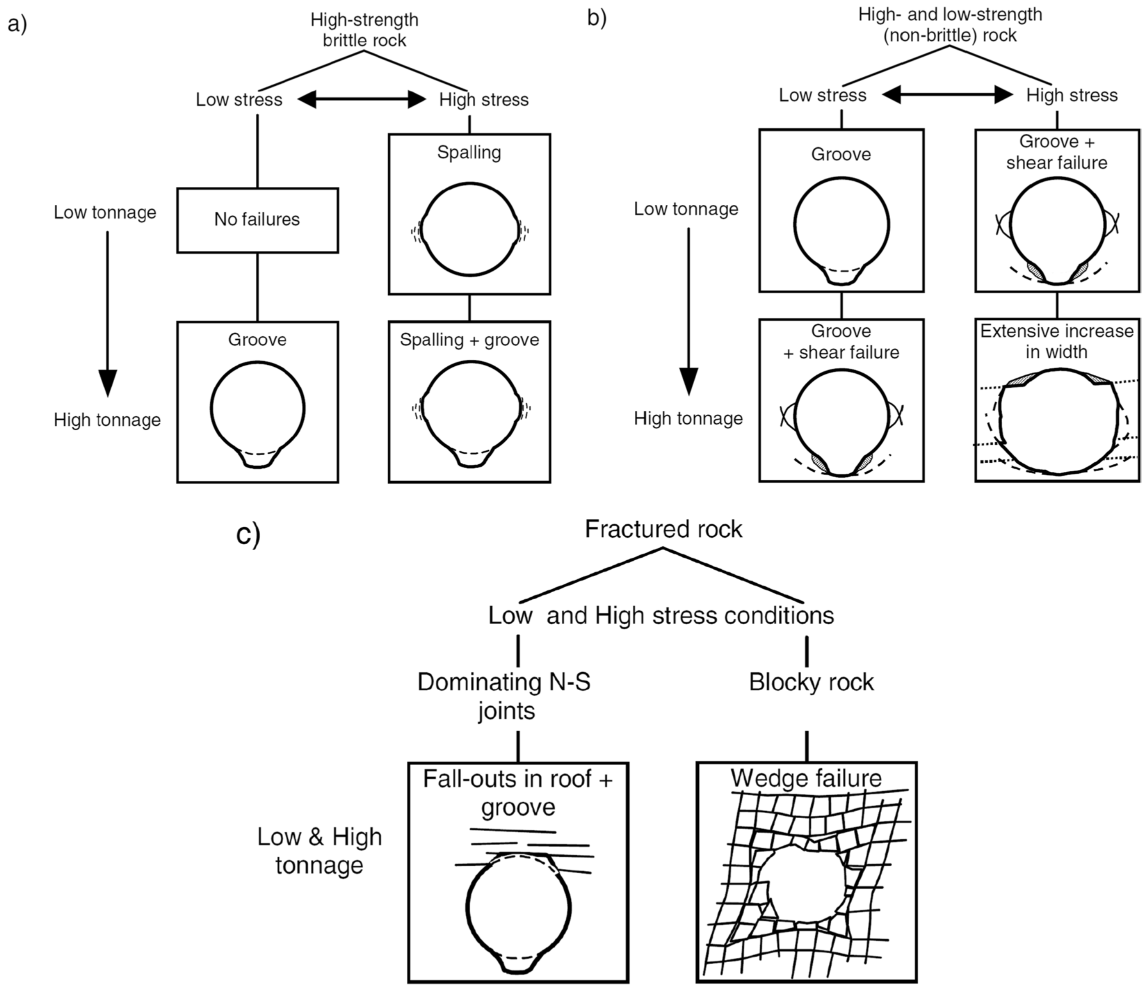


Fig. 2 Failure modes categorized based on governing factors (**a**—high-strength, brittle rock conditions, **b**—non-brittle rock conditions, **c**—fractured rock conditions) [adopted from Sjöberg et al. (2003) with permission from the authors and publisher]

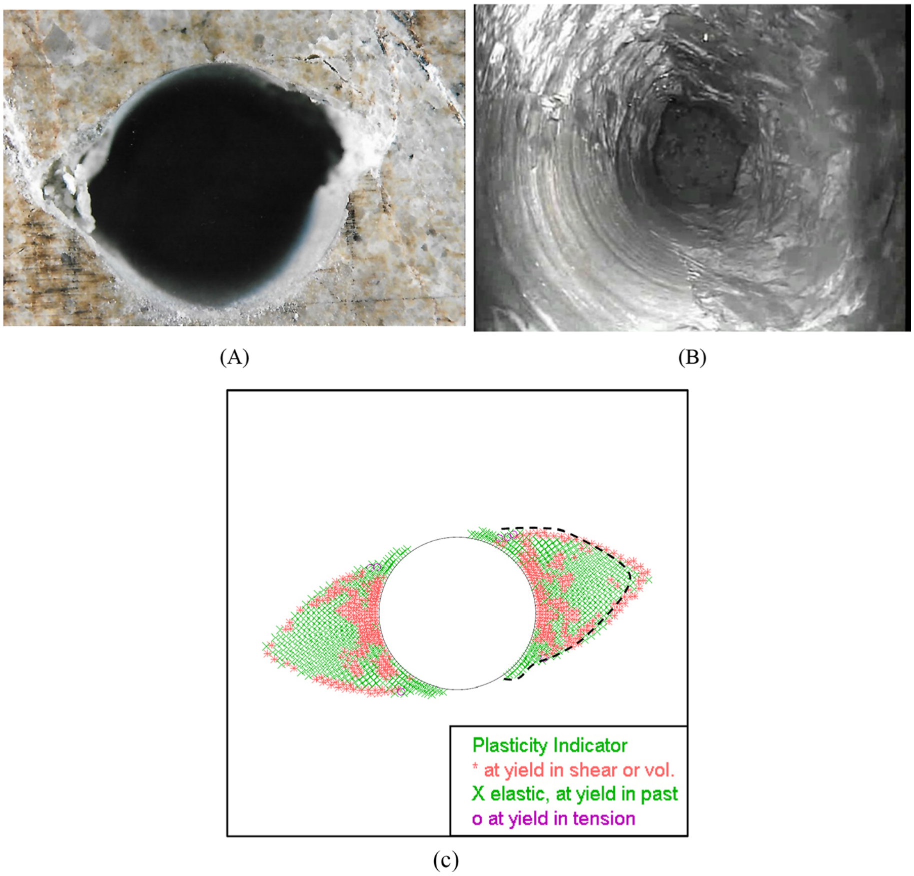
Fig. 3 Examples of structural failure [**A** photo taken by Dr. Ewan Sellers, and **B** Hadjigeorgiou and Stacey (2011)]

(A) (B)

- Finger raises (Esmaeili and Hadjigeorgiou 2009, 2011; Hadjigeorgiou and Mercier-Langevin 2008a). Materials flowing from finger raises to the ore pass could result in high stress-induced zones and localised damage to the ore pass walls.
- Stress-induced failure, breakout, also known as “dog-earing” (Kaiser et al. 2000; Sjöberg et al. 2015; Stacey 1981; Zoback et al. 1985). Principal stresses can vary in orientation for various reasons, such as destressing. Maree (2011) reported on the research conducted by Gay (1992) and suggested that ore pass systems should ideally align with or closely parallel the major principal stress direction to reduce or eliminate the impact of principal stresses on the ore pass system. In some cases, σ_2 and σ_3 act horizontally on the sides of the ore pass within an ore pass system. These two principal stresses, σ_2 and σ_3, are not always equal in magnitude and exert their influence on the same plane but in perpendicular directions. This could result in a specific form of failure commonly referred to as dog-earing. Figure 4 shows examples of dog-earing formation in experimental tests and a mining raise. Stacey and Erasmus (2005) also stated that in situations characterised by high-stress conditions, the most favourable orientation for an ore pass, regarding the principal stresses, is one that closely aligns with the maximum principal stress, running sub-parallel to it. If other relevant factors permit, this orientation should be prioritised whenever it is feasible and appropriate.

Stacey et al. (2005) investigated the ore passes’ instabilities in deep-level mines, in South Africa, where they observed that failures typically originate from stress-induced fractures occurring along the pass walls. This can progress to a stage where the geological structure of the rock mass takes over, making large, joint-defined blocks and slabs unstable. Thus, having information about rock discontinuities and applying statistical and probabilistic analyses can help to conduct risk assessments related to the stability of ore passes (Baecher and Christian 2005; Christian 2004; Einstein and Baecher 1982, 1983; Stacey and Bartlett 1990).

The numerical investigation conducted by Sjöberg et al. (2015), also aimed at comprehending the mechanisms behind ore pass failures occurring at significant depths within the LKAB mining operations, yielded valuable insights into the main mechanisms of stress-induced failure in ore passes. Their study highlighted the necessity of applying a brittle material model, specifically the cohesion-weakening friction-strengthening (CWFS) model (Hajiabdolmajid and Kaiser 2003; Hajiabdolmajid et al. 2003), to



(A) (B)

(c)

Fig. 4 Example of dog-earing in **A** an experimental test, and **B** a mining raise, and **C** FLAC prediction of the dog-earing formation through CWFS model [from **A** the photo gallery of Dr. Ewan Sellers, **B** Edelbro et al. (2019), and **C** Sjöberg et al. (2015) with the permission of the authors] accurately simulate the initiation and propagation of stress-induced failures in such ore passes. Similarly, the studies by Stacey (1981) and Stacey and Harte (1989) proposed the application of the "extension strain criterion" for the modelling of spalling in the raises and ore passes. These findings underscore the critical role of selecting an appropriate material model to capture the complex behaviour of rock masses around the ore passes under high mining and in-situ stresses.

Predicting the lifetime of ore passes is also an important factor for the design and yet is a very challenging task for mining and geotechnical engineers because ore passes are affected by consistent dynamic loads and can undergo significant wear and deterioration in the long term (Hadjigeorgiou and Mercier-Langevin 2008b; Hadjigeorgiou and Stacey 2011). Consideration must be given to dynamic mining-induced stresses, which can result in different forms of instabilities (see Fig. 5) including rock bursts and severe squeezing (Ortlepp and Stacey 1994; Potvin et al. 2019). Proper support measures should be applied to minimise the risks of abrasion and deterioration in the long term.

According to the literature, the most widely used approach for investigating the stability of the raise-bored shafts and ore passes, in mining, has been based on the methodology proposed by McCracken and Stacey (1989). This method uses the Tunnelling Quality Index, Q-system, proposed by Barton et al. (1974) and modifies the method by applying a few adjustment factors. These include "wall adjustment", F_w (see Table 3), "discontinuities orientation adjustment", F_{jo} (see Table 5), and "weathering and deterioration adjustment", F_d (see Table 6).

Table 3 Wall adjustment factor (Barton et al. 1974)

Description	Q-value	Wall adjustment factor, F_w
Very good and good quality rocks	$Q > 10$	5
Intermediate quality rocks	$0.1 < Q < 10$	2.5
Very poor quality rocks	$Q < 0.1$	1

$$Q_r = F_w \times F_{jo} \times F_d \times Q \tag{1}$$

where Q is Barton's rock quality index and is defined as (Barton et al. 1974):

$$Q = \frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_W}{SRF} \tag{2}$$

where RQD is the rock quality designation (Deere 1964), J_n is the joint set number, J_r is the joint roughness number, J_a is the joint alteration number, and J_w denotes the joint water reduction factor. In addition, parameter SRF shows the stress reduction factor. The rock mass quality Q can, therefore, be considered a function of three parameters which are crude measures of, (1): block size (RQD/J_n), (2): inter-block shear strength (J_r/J_a), and (3): active stress (J_w/SRF) (Barton et al. 1974).

It is, however, noted that McCracken and Stacey (1989) considered a more conservative approach to define the wall adjustment factor.

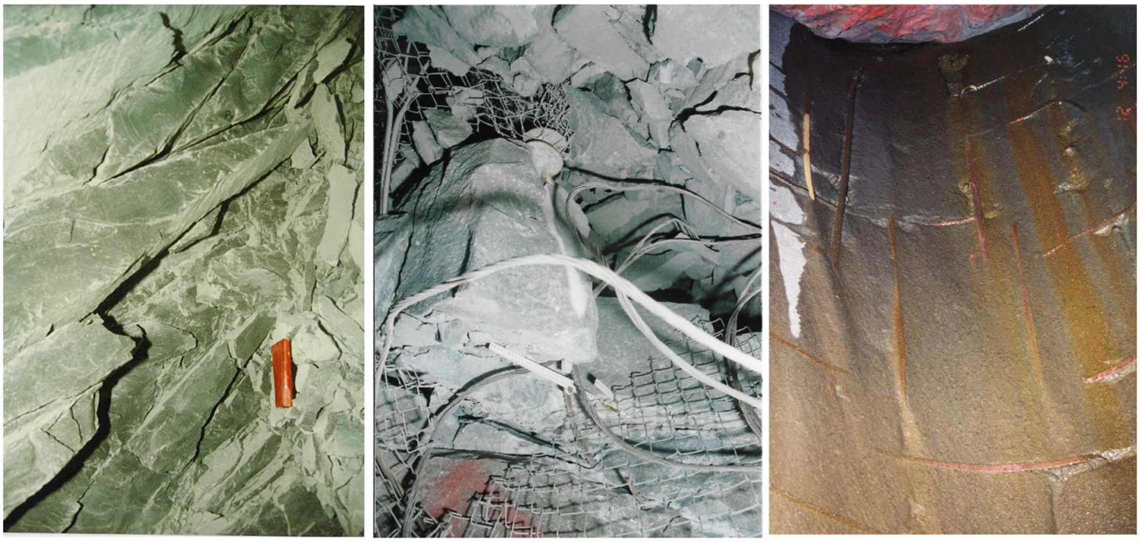

(A) (B) (C)

Fig. 5 Examples of **A** stress-induced fractures (photo taken by Dr. Ewan Sellers), **B** rock burst (photo taken by Dr. Ewan Sellers), and **C** using abrasion-resistant shotcrete for stabilising a vertical ore pass (7 years in operation) [adopted from Hadjigeorgiou and Stacey (2013) with permission of the authors and publisher]

Table 4 Estimating the stress reduction factor (Barton 2007; Grimstad and Barton 1993)

Description of rock strength and stress level	σ_c/σ_1	σ_θ/σ_c	*SRF*
Low-stress, near-surface, open joints	> 200	< 0.01	2.5
Medium stress, favourable stress condition	200 to 100	0.01 to 0.03	1.0
High-stress, very tight structure. Usually favourable to stability, may be unfavourable for wall stability	10 to 5	0.30 to 0.40	0.5 to 2.0
Moderate slabbing after > 1 h in massive rock	5 to 3	0.50 to 0.65	5 to 50
Slabbing and rock burst after a few minutes in massive rock	3 to 2	0.65 to 1.0	50 to 200
Heavy rock burst (strain burst) and immediate dynamic deformations in a massive rock	< 2	> 1	200 to 400

Table 5 Adjustment factor for joint orientations, F_{jo} (McCracken and Stacey 1989)

Number of major joint sets	Flat-dipping (0°–30°) major joint sets Face	Steep-dipping (60°–90°) major joint sets Wall
1	0.85	0.85
2	0.75	0.75
3	0.60	0.60

Table 6 Adjustment factor, F_d, for the weathering and deterioration of rocks (McCracken and Stacey 1989)

Description	F_d
Slight weathering	0.90
Moderate weathering	0.75
Severe weathering	0.50

$$\begin{array}{ll} \text{If } Q > 1.0 & \text{then } F_w = 2.5 \\ \text{If } Q \leq 1.0 & \text{then } F_w = 1.0 \end{array} \tag{3}$$

Perhaps the most challenging parameter in the Q-system to determine is the *SRF*. Barton (2007) reported on the work performed by Peck (2000) which showed that the value of the *SRF* can be estimated as:

$$SRF = 34\left(\frac{\sigma_1}{\sigma_C}\right)^{1.2} \tag{4}$$

Peck (2000) also proposed the following equation as the best fit for estimating the *SRF* in a heavily anisotropic stress field condition:

$$SRF = 31\left(\frac{\sigma_1}{\sigma_3}\right)^{0.3}\left(\frac{\sigma_1}{\sigma_C}\right)^{1.2} \tag{5}$$

where σ_1 and σ_3 are the major and minor principal stresses and σ_c is the uniaxial compressive strength of the rocks.

Barton (2007) also combined the information presented by Grimstad and Barton (1993) and Barton (2002) and developed a guideline for the estimation of the *SRF* (see Table 4).

The other adjustment factors needed for determining the value of Q_r, can also be extracted from the information presented in Tables 5 and 6.

Peck and Lee (2007) also investigated the applicability of Barton's tunnelling quality index, Q, and the modified version, Q_r, proposed by McCracken and Stacey (1989) for the stability analysis of shafts and vertical excavations (e.g., ore passes) in Australian metal mines. They determined that the stability and support assessments that are conducted merely based on Q or Q_r may not always be sufficient. In other words, for a detailed analysis, designers need to account for other rock mass parameters, the regulatory environment, and risk issues, as well.

To produce raise stability design charts, Penney et al. (2018) amended the AMC's benchmarking data (Peck et al. (2011), which was originally developed based on Australian experiences, to incorporate international cases of raise boring stability diagrams (see Fig. 6). Stability diagrams prove to be highly valuable for conducting rapid and initial stability assessments of raises during pre-feasibility and feasibility studies. These charts, however, only consider diameter and not ore pass length.

In tandem with the above-mentioned research on ore pass design performed in the United States, Canadian and South African scholars and engineers have also made substantial contributions to this domain. Notably, scholars like Hadjigeorgiou and coworkers have dedicated considerable efforts to explore the main issues associated with ore passes in hard rock mines in Canada, the mechanisms of ore flow within ore passes, and the methods for the restoration of clogged ore passes (Hadjigeorgiou and Lessard 2004, 2010; Hadjigeorgiou et al. 2005; Lessard and Hadjigeorgiou 2003a). This was followed by the work of Esmaeili and his team where they not only numerically investigated the flow mechanisms but brought into focus several other critical factors such as the integrity of the ore passes, themselves, the design of fingers, and the impact-induced damage to the ore pass walls due to the tipping of rock particles (Esmaeili 2010; Esmaeili and Hadjigeorgiou 2009, 2011, 2012, 2014,

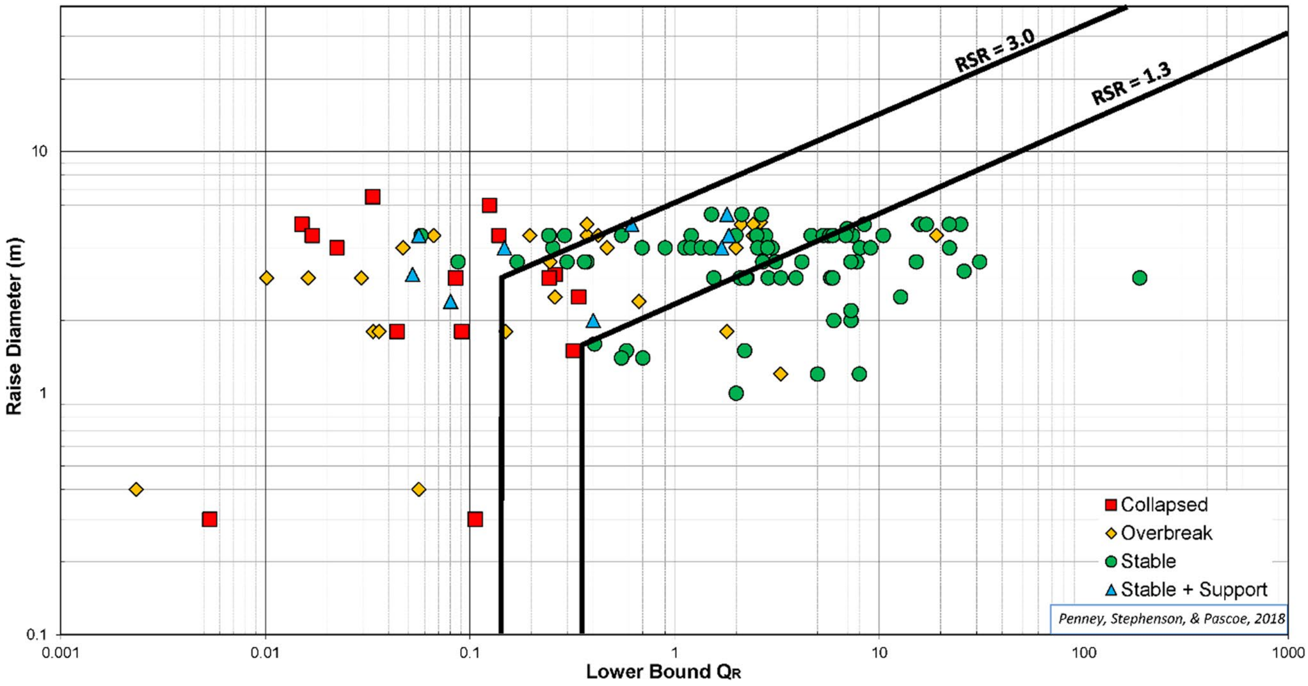


Fig. 6 A revised version of the raise stability charts [adopted from Penney et al. (2018) with the permission of the authors]

2015; Esmaeili et al. 2010). For over three decades, Stacey, and co-workers have also made significant contributions to the scientific and engineering principles associated with ore pass design in deep and ultra-deep level South African Gold mines (Hadjigeorgiou and Stacey 2011; Joughin and Stacey 2005; McCracken and Stacey 1989; Stacey and Bartlett 1990; Stacey and Erasmus 2005; Stacey and Harte 1989; Stacey et al. 2005).

Ore pass integrity can be seriously compromised because of stress and structural failures (Sjöberg et al. 2015, 2003; Stacey and Bartlett 1990), as well as by repeated blasting that is used to clear hang-ups (Hadjigeorgiou and Lessard 2010; Szwedzicki 2007). The impact from free-falling material (Larson et al. 1998; Remennikov et al. 2014; Van Heerden et al. 2005), and abrasive wear caused by material flow (Hadjigeorgiou and Lessard 2010; Hadjigeorgiou and Stacey 2011; Sjöberg et al. 2003) are the other important issues affecting the functionality of the ore passes. The frequency of ore pass blockages also increases considerably in ore passes in which structural degradation is occurring (Esmaeili 2010; Sjöberg et al. 2003; Szwedzicki 2007). Table 7 furnishes a summary of notable research studies related to various aspects of ore pass design.

Ore pass inclination

One of the key important factors in the design of ore passes, especially long and ultra-long ore passes, and the flow of the materials is the inclination of the ore passes. Kvapil (1998) mentioned that vertical ore passes are needed for the transport of some specific ores otherwise the risks of hang-ups significantly increase, depending on the charactristics and particle size distribution of the ore. This is consistent with the observations of Brady et al. (1969) at the CSA mine in Cobar, NSW, Australia, where they suggested that all passes must be raised at an inclination greater than 70° to minimise the frequent hang-ups occurring in copper-zinc ore. Kvapil (1998) defined four basic types of materials (classes I through IV) which represent different flowability and mobility as a function of the inclination of chute and ore passes. These include Type-I showing coarse material with large spherical pieces of the same size and form, Type-II representing coarse material with pieces of the same size but different form, Type-III indicating coarse material consisting of large pieces, chippings, and sand, and eventually Type-IV demonstrating a coarse mixture of materials consisting of large pieces, chippings, sand, and earthy-clayey constituents. The highest ore pass inclination is required for the materials in class IV while, in contrast, granular materials with uniform spherical shapes and sizes (Class I) represent the highest flowability (see Fig. 7). Hadjigeorgiou and Lessard (2007), and Turcotte (2004) also performed numerical modelling to analyse the effects of the ore pass inclination on the flow of the rock materials. An example of the design charts developed based on numerical modelling of inclined ore passes is shown in Fig. 7.

Table 7 Summary of previous research on ore pass design

Issue	Type of problem	Cause	Method of analysis	References
Ore pass integrity issues	Structural failure	Due to the impact of rock structures	Continuum and discontinuum numerical modellings (e.g., UDEC, FLAC, and PFC), and discrete fracture network (DFN)	Esmaeili (2010), Esmaeili and Hadjigeorgiou (2015), Hadjigeorgiou et al. (2008), Sjöberg et al. (2003, 2015), Stacey and Bartlett (1990)
	Stress-induced failure	In-situ stresses, and dynamic mining-induced stresses	Field inspections, and 2D and 3D numerical modellings	Esmaeili (2010), Hadjigeorgiou et al. (2008), Maree (2011), Sjöberg et al. (2003, 2015), Sredniawa et al. (2023), Stacey and Harte (1989), Vieira and Durrheim (2005)
	Blast-induced failure	Blasting that is used to clear hang-ups	Field investigation and LiDAR scanning data	Emesent (2021), Hadjigeorgiou and Lessard (2010), Li and Qin (2016), Sredniawa et al. (2023), Szwedzicki (2007)
	Impact-induced damage to walls, supports, and liners	Free-falling of rock material	Laboratory and small-scale testings, continuum, and discontinuum numerical modellings	Aziznejad et al. (2018), Esmaeili and Hadjigeorgiou (2012), Mutton et al. (2013), Remennikov et al. (2014), Van Heerden et al. (2005)
	Wear, degradation, and progressive scaling	Abrasive flow of heavy and dense rock fragments	Experimental tests, field inspections, LiDAR scanning, and numerical modelling	Esmaeili (2010), Esmaeili and Hadjigeorgiou (2011, 2012), Sjöberg et al. (2003, 2015), Sredniawa et al. (2023), Van Heerden (2004a)
Finger design issues		Mis-design of size, number, inclination, and intersection location with the main passes controlling the dynamic impact damage to the ore passes' walls	Numerical modelling through particle flow code	Esmaeili and Hadjigeorgiou (2009, 2011)
Dog-leg design issues		Mis-design of the location of the dog-leg, the inclination, and the length impacting the flow of the materials as well as the dynamic loads experienced by the gates	Experimental analysis and numerical modelling through particle flow codes	Goodwill et al. (1999), Iverson (2002), Iverson and Jung (2005), Nazeri (2001)

Table 7 (continued)

Issue	Type of problem	Cause	Method of analysis	References
Frequency of ore pass blockages and flow dynamic problems	Cohesive hang-ups	The combination of water and fine clay minerals, liberated by blasting, results in the formation of a cohesive, adhesive mixture. Apart from the water, the intense fragmentation and the mineralogy of the ore body are also key factors	Experimental and physical tests, analytical and numerical modellings	Beus et al. (2001), Brady et al. (1969), Hambley (1987), Hambley et al. (1983), Hambley and Singh (1983), Iverson and Jung (2005), Pariseau (1966), Vo et al. (2016)
	Interlocking hang-ups	Forming because of the arching effect when large fragments become wedged and locked together, leading to the development of blockages	Experimental and physical tests, analytical and numerical modellings	Castro et al. (2016), Hadjigeorgiou and Lessard (2007), Iverson et al. (2003), Pariseau (1966, 1969a), Sato and Tang (2018), Szwedzicki (2007), Turcotte (2004)
	Preferential flow in a complex ore pass system	Poor ore pass design (inclination, size, length), and fragmentation effects	Discrete element numerical modelling	Gresham and Turichshev (2016)
Excessive gate loads	Static loads	Due to the gravitational forces exerted by the accumulated muck within ore passes	Experimental and physical small-scale and pilot-scale tests, field inspections and monitoring, analytical and numerical modellings	Beus et al. (1999, 2001), Blight and Haak (1994), Scott et al. (2000), Stewart et al. (1998)
	Dynamic loads	Free-falling and dumping muck into ore passes, collapses of rock wedges and slabs from walls	Experimental and physical small-scale and pilot-scale tests, field inspections and monitoring, analytical and numerical modellings	Beus et al. (1999), Blight and Haak (1994), Iverson et al. (2003), Scott et al. (2000), Stewart et al. (1998)
Boulders and oversize fragments		Poor blast designs, misfires, overbreaks, and misclassification of rocks for blastability assessment	Field inspections, numerical and analytical modellings	Bunker et al. (2015), Kumar (1997), Manzoor et al. (2023a, b), Yi et al. (2017)
Mudrush		The presence of excessive underground water, substantial precipitation, suboptimal drainage systems, and inadequate management of water infiltration in excavation sites. Also, excessive fragmentation resulting in fine particles that can mix with water and generate mud	Experimental studies and field inspections and observations, as well as numerical modelling	Butcher et al. (2005), Castro et al. (2023a), Jakubec et al. (2016), Sánchez et al. (2019a), Vallejos et al. (2017)
Airblast/back blast		Variability and inconsistency in feeding ore into ore passes, extended pass lengths causing pronounced piston effects, and inadequate design of pass system and ventilation	Field inspections and theoretical and CFD numerical modellings	Calizaya and Duckworth (2007), Casten et al. (1999), McPherson and Pearson (1997)

Table 7 (continued)

Issue	Type of problem	Cause	Method of analysis	References
Dust propagation		Arises when there are inadequacies in the design of interconnected ore pass systems, deficiencies in ventilation planning, and when there is a chance of cohesive hang-ups to suppress the dust by spraying water. Also, the mineralogy of the ore and intense fragmentation resulting in ultra-fine particles are critical	Lab-scale experiments, field inspection and monitoring, and numerical modelling such as CFD	Nelson and Rutter (2018), Wang et al. (2019, 2020)

Static gate loading

Numerous efforts have been devoted to investigating the static loads which are defined as the averaged vertical stresses acting on the bottom gate of the ore pass. When designing ore passes, and specifically long ore passes, geotechnical engineers must confirm the structural integrity of the gate and ensure that the gate can withstand these static loads without deforming and failure. Jassen's equation (1895) has been among the main approaches that have widely been used in silo designs and has, therefore, been adopted for the assessment of static loads in ore passes (Beus et al. 1997, 1998; Castro et al. 2014). Jassen (1895) proposed the following equation for the averaged vertical stress over the cross-sectional area of a silo for cohesionless grains:

$$\sigma_N = \sigma_{Nmax}\left[1 - \exp\left(-\gamma z/\sigma_{Nmax}\right)\right] \tag{6}$$

where σ_N (Pa) is the vertical pressure on the chute gate of the silo or ore pass, R (m) is the hydraulic radius (cross-sectional area over perimeter), γ (N/m^3) is the unit weight of rock in the ore pass, and z (m) is the height of ore above the chute gate (Bagster 1971; Beus et al. 1997). In addition, σ_{Nmax} (Pa) shows the maximum vertical pressure and is defined as:

$$\sigma_{Nmax} = \gamma R/(K\tan\delta) \tag{7}$$

where K denotes the stress ratio between lateral and vertical pressure, and δ (°) is the wall friction angle (Beus et al. 1998).

Blight and Haak (1994) amended Janssen's equation by considering the inclination of ore passes by introducing an inclination angle β.

$$\sigma_N = \sigma_{Nmax}\left[1 - \exp\left(-\gamma z/\sigma_{Nmax}\right)\right] \tag{8}$$

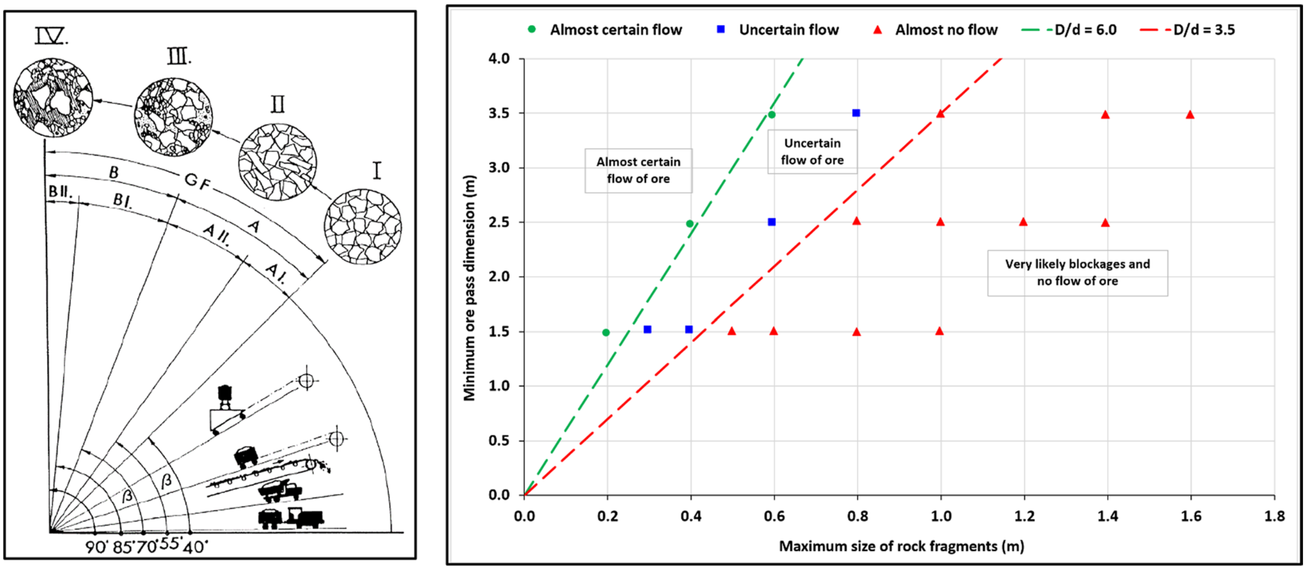
$$\sigma_{Nmax} = \gamma R\ \mathrm{Sin}\ \beta/(K\ \tan\ \delta) \tag{9}$$

It is noted that Janssen's equation was derived for cohesionless grains and, therefore, it does not consider the cohesion of fines, and this may be a limit in analysing the stresses generated by the ore in the ore passes when the proportion of the fine and the cohesion effects are considerable. To address this issue, Beus et al. (2001) developed an equation for averaged vertical stresses with cohesion effect included:

$$\sigma_N = \left(\frac{C_2}{C_1}\right)\left\{1 - \exp\left[-zC_1\right]\right\} \tag{10}$$

where *z(m)* is the depth of muck in the ore pass, and parameter c also denotes the fine cohesion (Pa). Parameters C_1, and C_2 can also be computed as:

$$C_1 = Mtan\varphi/(A/P) \tag{11}$$



(A) (B)

Fig. 7 **A** Different classes of material and their mobility as a function of ore pass inclination (Kvapil 1998), and **B** example of numerical modelling results for muck flow in ore passes with a 65° inclination (data collected from Turcotte 2004)

$$C_2 = \gamma - cM/(A/P) \tag{12}$$

where A (m^2) shows the cross-sectional area of the pass, P (m) is the perimeter of the pass, γ indicates the specific weight of the muck, and φ (°) is the friction angle of the materials. In addition, parameter M is defined as:

$$M = 1/\left[1 + 2(tan\varphi)^2\right] \tag{13}$$

Scott et al. (2000) also reported on the experimental tests performed by NIOSH to investigate the static and dynamic loads on gates in ore passes. They compared the static results against the classical bin-load theories (Janssen 1895). Scott et al. (2000) stated that some variation from classical bin-load theory was observed and they suggested some modifications of the theory that can be employed to improve the predictions of the analytical models.

Dynamic gate loads

For the engineering design of long and ultra-long ore pass systems, it is essential to account for the dynamic loads that arise from the abrupt release of ore during material muck tipping and sudden dumping. Gate design must account for the dynamic loads to prevent premature failure or malfunction during operation. The properties of the material (e.g., density and stiffness) are needed for the calculation of the mass and velocities, and for analysing the impact forces and energy upon collision (Jung and Iverson 2004). Continuous monitoring and maintenance are essential to ensure the long-term reliability and safety of the ore passes' systems. Due to its importance load, the dynamic impact loading responses of rock materials, in ore passes, have become of interest to some researchers (Aziznejad 2015; Beus et al. 1999; Blight and Haak 1994; Iverson et al. 2003; Larson et al. 1998; Nazeri 2001; Stewart et al. 1998). For example, Beus and Ruff (1997) used mock-up tests and PFC2D/3D numerical modelling to argue that, when the ore pass is used as a storage facility, dynamic loads are important only during the first few dumps (called the cushioning effect). However, when the ore pass contains muck with moisture, compaction due to the impact of rock particles and the dynamic forces, increases the chance of hang-ups and the muck needs to be emptied as fast as possible to avoid cohesive hang-ups (Brady et al. 1969; Nazeri 2001).

Iverson et al. (2003) also used PFC2D to study the effect of doglegs, inclined ore passes, and rock fragment impacts on chute gates of ore passes, and the grizzly used to screen coarse rock. The simulation results by Iverson et al. (2003), as illustrated in Fig. 8, predicted that inclined ore passes reduced the impact forces compared to vertical ore passes. Doglegs in ore passes, also, further decreased the dynamic impacts. High frictional coefficients between particles and ore pass walls lead to lower impact loads on ore pass walls, which correlated with what Nazeri (2001) found when he studied the static and dynamic loadings on the ore pass bottom gate. Nazeri (2001) indicated that static load on the gate reduced significantly with increasing friction forces, but this effect is less pronounced for dynamic loading. Furthermore, it was identified that with the ore size distribution included, there would be more interactions

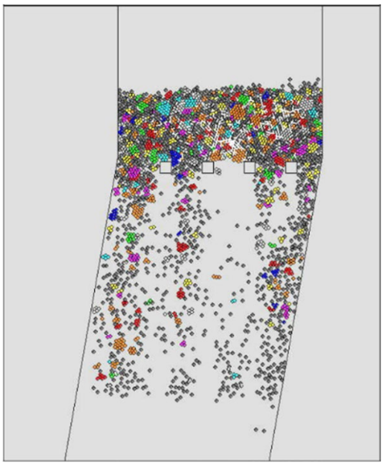


Fig. 8 PFC2D simulation of an ore pass with a dog leg and a grizzly (Iverson et al. 2003)

between ore particles and walls, which would lower the static loads (Nazeri and Mustoe 2002; Nazeri et al. 2002). The particles in the numerical models were assumed to be rigid, while in reality there will be some degradation on the ore pass walls and ore particles will fracture during impacts, which results in damping of the dynamic loads (Beus et al. 1998; Jung and Iverson 2004). These numerical predictions, therefore, overestimate the impact forces leading to difficulties in achieving realistic results from modelling dynamic loading in ore passes.

The dynamic loads in ore passes and gates were also investigated by Stewart et al. (1998), Scott et al. (2000), and Beus et al. (1999). A simplified method to quantify the impact at the top of the muck in the ore pass is to consider additional stress, σ_0. Therefore, the dynamic equilibrium in a vertical ore pass can be estimated as:

$$\sigma_d = \left(\frac{C_2}{C_1}\right)\left\{1 - \exp\left[-z_0 C_1\right]\right\} = \sigma_0 \exp\left(-z_0 C_1\right) \tag{14}$$

where z_0 (m) is the muck depth at the time of impact (Beus et al. 2001).

Furthermore, an analytical solution for the dynamic stresses could be estimated based on the theory of elasticity (Beus and Iverson 2000). Based on this approach the dynamic stress, σ_d, formed in a structural element (e.g., ore pass gates) due to the impact of falling rock fragments from a height, h, is greater than the static stress, σ_{st}, loads, and depends on the static deformation, δ_{st}, produced by the same body applied as a static load. This can be estimated as (Beus et al. 1999):

$$\sigma_d/\sigma_{st} = 1 + \left(1 + 2h/\delta_{st}\right)^{\frac{1}{2}} \tag{15}$$

It is assumed that the energy losses of material falling in an ore pass could be substantial. Therefore, the dynamic stress on the chute gate in an empty ore pass can be approximated by a case of sudden loading ($h = 0$), which leads to a dynamic stress higher by a factor of 2 over static stress.

However, if h is considerably large compared to the deflection and the energy loss of the impact is not considerable, the dynamic stress can be estimated as (Beus et al. 2001):

$$\sigma_d/\sigma_{st} = \sqrt{2h/\delta_{st}} \tag{16}$$

Beus et al. (1999) also amended the above-mentioned relationships for predicting the ratio of dynamic loads over static ones by adopting the concept of softening the chute and control gate assembly and supporting structures with an overall stiffness of k_a. This damping of the load is applied by introducing a spring with a stiffness, k_s. The ratio of the dynamic loads over static loads after accounting for the damping is computed as:

$$\sigma_d/\sigma_{st} = 1 + \left(1 + 2h/k\delta_{st}\right)^{\frac{1}{2}} \tag{17}$$

where k is defined as:

$$k = 1 + k_a/k_s \tag{18}$$

Esmaeili and co-workers also dedicated significant effort to numerically investigating the effects of critical parameters such as rock mass characteristics, foliation, and dynamic impact loads on the stability of ore passes (Esmaeili 2010; Esmaeili and Hadjigeorgiou 2012, 2014). They also investigated the effects of finger geometry and configuration on the dynamic impact loads and the performance of ore passes (Esmaeili and Hadjigeorgiou 2009, 2011).

Construction method

According to the literature, the development of ore passes typically uses one of two methods. The first method involves mechanical development, often utilising a raise borer. The second method requires drill and blast techniques, which can include Alimak, conventional raising, and drop raising approaches (Hadjigeorgiou et al. 2005; Lessard and Hadjigeorgiou 2003b). We will provide concise explanations of these methods in this section.

Drill and blast excavation

In ore pass (and shaft) excavation, and at the early stages of mining, there is initially no access to the bottom of the excavation. At its core, the process of shaft sinking involves planning based on the needs of the project and the processing of the geological and geotechnical characteristics of the shaft/ore pass country rocks, and firm precision. The construction involves drilling and precise blasting, material removal known as mucking, and systematic, supporting of the shaft excavation. Precision drilling is fundamental to the process of shaft sinking. Advanced drilling rigs drill the blast holes and the contour holes. Controlled blasting plays a key role in shaft sinking. Explosive charges are strategically placed within the holes and detonated with specific timing to fragment, generate free surfaces, and move the hard rock. Controlled blasting techniques such as smooth blasting and pre-splitting are often employed to protect the walls from blast-induced damage (Van Eeckhout 1987). Implementing precision blasting techniques can also helps to minimise the vibration and shock waves and is crucial for preserving the structural integrity of both the shaft and its surrounding rock masses (Jimeno et al. 1995). Post-blast, the process of removing broken rock materials from the shaft occurs which is known as mucking. Mechanical mucking systems or specific buckets transport the debris to the surface, ensuring a continuous flow of excavation operations. Proper mucking design and execution are essential for maintaining shaft stability and minimising downtime (Jenny 1996). The main advantage of drill and blasting for shaft sinking is its flexibility for dealing with complex geological and geotechnical conditions (e.g., fault shear zones) and the ability to excavate ore passes with different cross-section shapes. But, in medium-strength rocks, the progress of the excavation by drill and blasting technique could be less than mechanised boring (Vogt 2016).

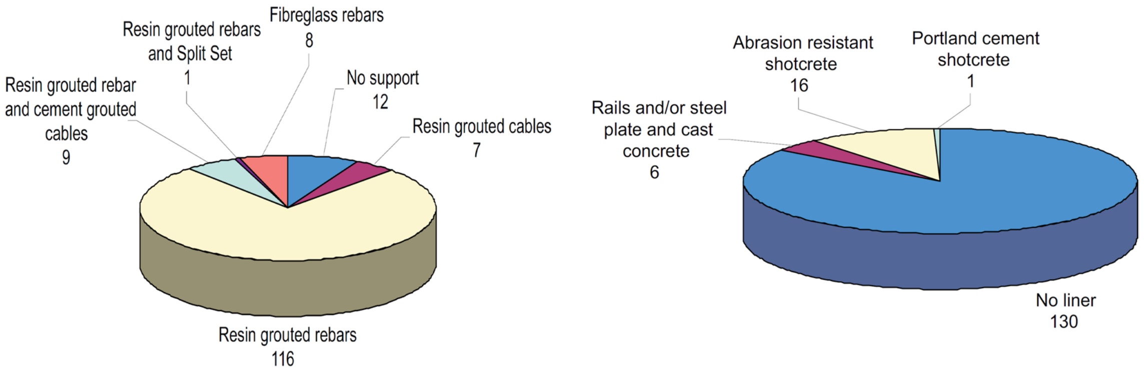
Supports and liner

The other key step is the comprehensive support of the pass. As excavation advances, the exposed walls need to be reinforced to prevent instability and collapses. The role of ground support in the construction of rock passes serves a dual purpose: first, to guarantee the raises' stability during excavation, and second, to prevent structural failures throughout the passes' operational lifespan. However, the site observations conducted by Lessard and Hadjigeorgiou (2003b) indicated that ground support frequently proves insufficient in preventing structural failures, particularly in the context of ore passes in polymetallic mines, even after the pass has been put into operation.

Engineers often use different ground support techniques and liners, including rock bolting, shotcrete, application, steel sets, and meshing for this purpose. These measures ensure that the shaft/ore pass retains its structural integrity and remains stable for the designed lifetime. Engineers need to carefully evaluate the subsurface conditions, adopting proper ground support measures (Hoek et al. 1995; Unrug 1984).

Lessard and Hadjigeorgiou (2003b) investigated the main supports used in the ore passes in Quebec, Canada. As depicted in Fig. 9A, various reinforcement systems have been used for the stabilisation of ore passes. Notably, resin-grouted rebar stands out as the dominant preferred support choice. A chronological examination of the development timelines of ore passes' sections revealed the growing popularity of resin-grouted short cable bolts. In instances where cement-grouted cables were used, they were consistently applied alongside resin-grouted rebar. Fibreglass rebars, on the other hand, were only used in one single operation, till the time of the research, and only for specific sections. This support type was not pursued further due to installation challenges, coupled with significant deterioration observed in the sections where they were used, occurring after a mere 60,000 tons of material were transported. The research also showed that the ore passes lacking reinforcement were excavated either through raise boring or drop raises.

The field investigation by Lessard and Hadjigeorgiou (2003b) also revealed an increased tendency in the application of liners to mitigate wall degradation in ore passes in Quebec. Among the seven mines visited by these scholars,



(A) (B)

Fig. 9 **A** Ground support types, and **B** liner variations used in ore passes, as determined from the analysis of 153 ore pass sections (Lessard and Hadjigeorgiou 2003b) five had deployed liners in specific sections. The types of liners chosen are shown in Fig. 9B, with abrasion-resistant shotcrete being the most used option. Typically, liners were installed as a proactive measure. However, in two instances, liners were put in place after indications of wall degradation became evident during the ore pass excavation. In these cases, the liners also served to protect the workers during the excavation process.

Raise boring

The drill and blast method offers the advantage of versatility, making it suitable for various geological conditions and project scales. However, the technique is time-consuming, labour-intensive, and poses safety risks due to the use of explosives charges. In contrast, mechanised raise boring offers exceptional efficiency and safety by utilising specific equipment. For example, Nash (1985) investigated the application of raise boring for the construction of shafts in civil engineering and mining. He mentioned that the application of raise boring has resulted in several achievements against conventional shaft sinking such as: improved safety; increased productivity; minimised excavation-induced damage and minimised disturbance of the rock unit from its equilibrium state compared to drilling and blasting methods; the semi-automated nature and smaller excavation crew size; and reduced cost of shaft construction (Nash 1985).

Raise boring is particularly advantageous for large-diameter shafts and deep excavations but often requires much higher initial capital investment. Raise boring is a sophisticated drilling technique widely used in mining and civil engineering projects where the vertical or inclined pass is developed from a lower level to an upper level by excavating and cutting upwards. Raise boring offers several advantages, including enhanced safety, precision, and efficiency. It allows for controlled and precise shaft/ore pass development, minimising the damage to the walls and the risk of rock failure and ground collapses. Moreover, it is a relatively versatile process and adaptable to various geological conditions, making it a preferred choice for constructing ore passes, ventilation shafts, and escape routes in underground mining (Robbins 1973; Shaterpour-Mamaghani and Bilgin 2016; Wilson and Graham 1972). The raise boring operation starts with the drilling of the pilot hole from the top levels. This hole is then reammed by a cutter from the lower level to achieve the desired dimension. Figure 10 presents an actual instance showcasing the application of raise boring in excavating a shaft measuring 5 m in diameter and spanning a length of 742 m. McCracken and Stacey (1989) stated that raise boring could be a risky operation due to lack of access to the excavation face to reinforce the rock mass if needed, and to support the raise behind the face. Nonetheless, the choice between these methods should be based on project-specific factors, including geological conditions, budget constraints, and project timelines. Penney et al. (2018) stated that before initiating the raise boring process, it is helpful to detect and evaluate areas that could pose potential issues. This enables informed risk-driven choices regarding construction methods or exploring alternative solutions. Taking proactive measures to address a known weak zone is more favourable than applying engineered solutions to an area prone to significant instability or failure.

To the best of the authors' knowledge, the only practical, systematic framework for mining decision-makers to select an appropriate excavation method for a specifically given ore pass length is based on a comparative analysis of various excavation techniques within short South African mine ore passes conducted by Sachse and Westgate (2005). Table 8 shows a consolidated version of their comparison of various factors such as safety, time for site preparation, the overall time of excavation, risk of achieving not a usable and acceptable excavation, cost of complete rock pass, and cost per meter of the pass. Although this study was limited to ore passes with lengths up to only 90 m, it implies that only raise boring is suitable for long and ultra-long ore passes.

Raise boring, despite its many advantages, comes with certain challenges and limitations. One key challenge is the need for precise planning and expertise due to the irreversible nature of the drilling process; errors can be costly. Additionally, it may struggle in extremely hard or abrasive rock formations, requiring specific equipment and longer drilling times with significant consumption of disc cutters. Furthermore, raise boring can be limited by the height and diameter of the raise, affecting the size of equipment that can be used. Accessibility to the drilling and cutting face and the potential for hole deviation are also concerns. Lastly, it may not be suitable for all geological conditions (large fault zones) or specific project requirements, necessitating careful consideration of alternatives in certain scenarios.

According to Lessard and Hadjigeorgiou (2003b), in the Quebec region, in Canada, ore passes were constructed by several different methods: 63% through Alimak raising, 29% via conventional raising, 5% utilising drop raising, and 3% through raise boring. The predominance of Alimak raises can be attributed to several factors, including the method's reasonable safety record, the need for only one access point (as opposed to raise boring, which requires both top and bottom access), and the local mining community tradition and expertise. In Ontario, however, ore passes were primarily developed using different proportions: 39% through Alimak raising, 30% via raise boring, and the remainder through alternative raising methods. The motivation behind the increased use of raise boring in Ontario is to minimise ground disturbance during excavation (Hadjigeorgiou et al. 2005). However, a closer chronological analysis of ore pass development trends in Ontario's mining industry conducted

Fig. 10 The process of raise boring a 5-m diameter shaft with 742 m length (Photos courtesy of Phillip Viljoen, used with permission)

Table 8 An example of a risk assessment method for the selection of ore pass excavation method (Adopted from Sachse and Westgate 2005)

Length in meters	Handheld	Raise climber	Conventional drop raising	Invert drop raising	Blind boring	Raise boring
15		Time and cost	Time		Cost	Cost
30	Safety					
45		Cost			Cost	
60			Unknown			Cost
75		Time		Unknown		
90					Unknown	

by Hadjigeorgiou et al. (2005) showed a shift away from raise boring in favour of a more widespread adoption of Alimak technology. According to the data collected by these scholars approximately 70% of recently constructed ore pass sections were accomplished using Alimak methods, while only 15% relied on raise boring techniques. This significant surge in Alimak-based ore pass construction can be attributed to its inherent capability to seamlessly incorporate ground support installation throughout the excavation process (Hadjigeorgiou et al. 2005).

Ferreira (2005) also provided a summary of the main methods used for the excavation of shafts and passes in South African and Southern African mines (see Table 9). Ferreira (2005) provides a standard way to measure the capacities of different excavation methods and the capabilities of different raise bore machines readily accessible in the market. As can be seen, raise boring is increasingly emerging as a cost-effective method for excavating shafts and raises of varying sizes, offering significant advantages, particularly in terms of extended lengths.

Table 9 Comparison of inclined excavations (Ferreira 2005)

Type		Meters							
		<30	30 to 45	45 to 60	60 to 90	90 to 200	200 400	400 to 700	>700
Conventional	Handheld	🟩							
	Drop raising	🟩	🟩						
	Alimak		🟩	🟩	🟩	🟩			
Blind boring	52R		🟩	🟩					
	53R	🟩	🟩	🟩	🟩	🟩			
	33/34R	🟩		🟩					
	Other	🟩	🟩						
	65R	🟩	🟩	🟩	🟩	🟩			
Raise boring	43R	🟩	🟩						
	53R	🟩	🟩	🟩	🟩	🟩			
	6 Series - RBM6			🟩	🟩	🟩			
	7 Series - RBM7			🟩	🟩	🟩			
	8 Series			🟩	🟩	🟩	🟩		
	9 Series					🟩	🟩	🟩	
	10 Series					🟩	🟩	🟩	
	12 Series					🟩	🟩	🟩	🟩
	HG330					🟩	🟩	🟩	🟩
	HG380					🟩	🟩	🟩	🟩

Figure 11, shows some of the Herrenknecht raise boring products containing several different types of machines with power ratings between 300 and 800 kW and thrust forces between 458 *tonne* and 2243 *tonne* which covers a very wide range of applications. It is also noted that drilling deep raises and shafts with large diameters needs powerful rigs with high torque and high thrust forces. This has been addressed by developing Raise Boring Rig RBR900VF with a torque of 900 *kNm* and thrust of 2243 *tonnes* which has been developed by Herrenknecht in cooperation with Australian mining contractor Macmahon. According to Künstle and Frey (2014), the RBR900VF is among the most powerful Raise Boring Rigs currently on the market.

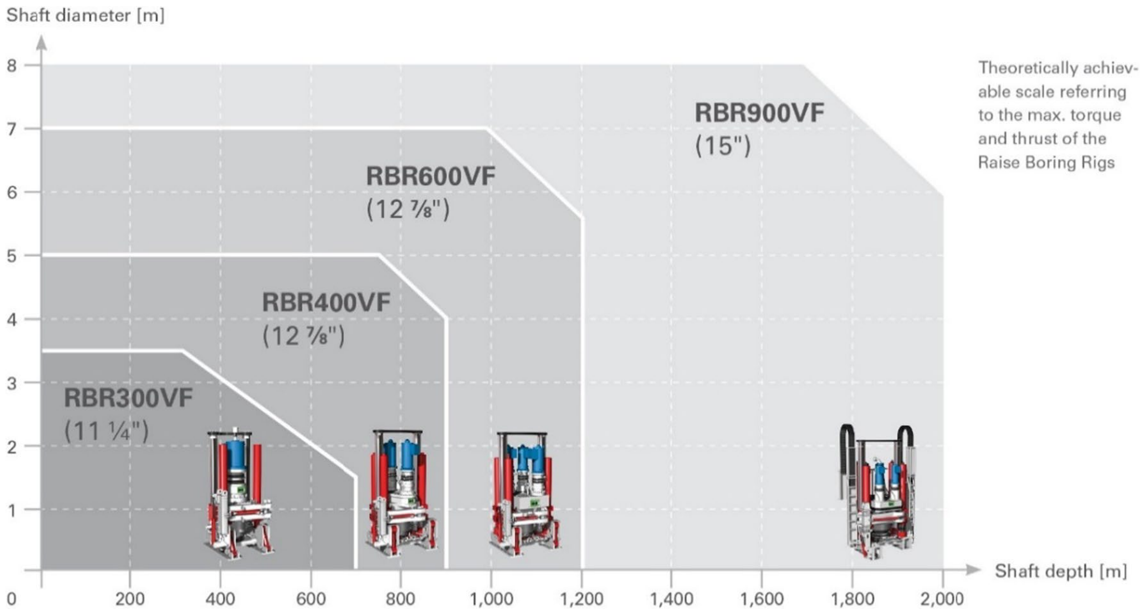


Fig. 11 Example of Herrenknecht Raise Boring Rigs capabilities (Künstle and Frey 2014)

The utilisation of modern mechanical excavators for the implementation of ultra-long and long ore passes presents both opportunities and challenges from an economic perspective. While these machines offer advantages such as increased productivity, reduced labour requirements, and enhanced safety, it is essential to weigh these benefits against the associated costs. Factors contributing to the high costs include initial capital investment, equipment maintenance, operator training, and operational downtime for maintenance and repairs.

Furthermore, the economic feasibility of using modern mechanical excavators in long ore passes may vary depending on the specific geological and operational conditions of the mine. For instance, in mines with favourable ground conditions and ample space for maneuverability, the use of these excavators may be more economically viable compared to mines with challenging ground conditions or constrained access. Additionally, the practicality of using modern mechanical excavators in ultra-long and long ore passes must consider factors such as pass dimensions, access constraints, and operational requirements. While these excavators offer high performance and precision in shaft sinking and development, their suitability for pass construction and maintenance needs to be evaluated on a case-by-case basis. The study conducted by Sachse and Westgate (2005) took into account several crucial factors, including safety considerations, site preparation and readiness for operation, excavation speed, overall expenses, and cost per meter. Their aim was to determine the most effective and optimised excavation method for ore passes of varying lengths (from 15 to 90 m). Their analysis revealed that as the length of the ore passes increases, mechanised excavation methods become increasingly cost-effective. Additionally, mechanised excavation through boring offers notable advantages in terms of speed and safety, further reinforcing its viability for longer ore passes' excavations. The study conducted by Ferreira (2005) also highlighted that when the length of ore passes exceeds 200 m, the most cost-effective, efficient, safe, and viable method for excavation is raise boring using appropriate machinery.

Future options

Traditionally, shaft sinking, and conventional raising were done by drill and blast operation. However, some modern mechanical excavators can be applied for shaft sinking such as the Herrenknecht shaft borer machines (Neye et al. 2015). An example of the application of these machines is the excavation of the blind shaft at the BHP Jansen Project by a Vertical Shaft Sinking Machine (VSM) (Rennkamp et al. 2021). The possibility for application in long and ultra-long ore passes at an early stage in the mine would be a constraint unless equipment suitable for the excavation of large-scale shafts is used (Rennkamp et al. 2021). Examples include Herrenknecht Shaft Boring Cutterhead (SBC), Shaft Boring Roadheader (SBR), Shaft Boring Extension Machine (SBE), Vertical Shaft Sinking Machine (VSM) (Herrenknecht 2022, 2023). Though, to the authors' best knowledge, these machines have not been used for the excavation of ore passes and the machines are very costly. On the contrary, to raise boring, the mining industry currently possesses a paucity of comprehensive information and operational experience concerning the deployment of such machinery. Existing literature has also highlighted the potential occurrence of shaft alignment deviations when employing these machine types in heterogeneous rock masses, with the subsequent adjustments presenting a potentially costly, time-intensive, and complex process (Kilkenny et al. 2023). It is also noteworthy that ore pass design diverges from that of shafts, primarily due to the elevated wear experienced by ore passes because of abrasive ore flow and the dynamic impact loads imposed by particles. Additionally, ore passes frequently experience multiple blast loads aimed at dislodging material blockages (Dunn and Menzies 2005; Gardner and Fernandes 2006; Hart 2006). Consequently, the design of ore passes can be significantly more challenging in comparison to shafts.

The economic and practical challenges of using modern excavators in ultra-long and long ore passes compared to traditional methods primarily revolve around efficiency, capital and operational costs, and safety. Modern excavators may offer higher initial capital investment and maintenance costs, potentially impacting the project's economic viability. However, under favourable geological and geotechnical conditions, the excavation rate using these methods surpasses that of conventional excavation methods, outweighing and justifying the higher capital costs. Additionally, the complexity of operating and maintaining modern excavators in long ore passes requires specialised training and skilled personnel, which could pose practical challenges. The suitability of modern excavators for navigating long ore passes, especially in terms of maneuverability and material handling capacity, must also be carefully evaluated to ensure optimal performance. Safety considerations, such as the risk of equipment breakdowns or accidents in confined spaces, also warrant thorough assessment when adopting modern excavators for the implementation of ultra-long and long ore passes.

Operation

As surface orebodies become scarcer, the need for deeper underground mining becomes more prominent, with deep mining such as cave mining becoming a common mass mining method of future deposits. Long and ultra-long ore passes, which play a major role in transporting materials to deeper deposits underground, especially for sub-level caving, have the potential to act as the bottleneck in the overall

Mine to Mill (M2M) or Cave to Mill (C2M) procedure. The integrity of long ore passes can be seriously compromised because of stress and structural failures, repeated blasting to clear hang-ups, the impact of free-falling rock fragments, and abrasive wear caused by material flow. Reports from mining operations indicate that ore pass systems frequently encounter several different types of problems, including the degradation of the structural integrity of the ore pass, and hang-up of materials. Beus et al. (1997) produced a fault tree diagram (See Fig. 12) showing the main mechanisms of failure.

The investigations conducted by Beus and co-workers provided valuable insights into an essential facet of ore passes in underground mining. Their research has yielded a crucial finding: the average length of the ore passes under their scrutiny was approximately 46 m (Beus et al. 2001). While this finding is significant, it warrants thoughtful consideration of its broader implications.

It is essential to acknowledge that the challenges documented in Beus's research, while noteworthy, may not well cover and reflect the entire spectrum of issues that can potentially arise in the planning, construction, and operation of long and ultra-long ore passes, particularly those with a length exceeding 300 to 1000 m. This means that their findings can serve as a starting point for a more comprehensive analysis of the complex and dynamic nature of long ore pass configurations. Our investigation will, therefore, extend beyond the boundaries of these initial observations by Beus and co-workers.

A rigorous investigation is required to explore and understand the multifaceted challenges that can be encountered in the design, and optimisation of long ore passes at substantial depths. These in-depth studies can help to develop a holistic understanding of the unique complexities associated with long ore passes and ore pass systems and to formulate robust solutions that are applicable for the design and optimisation of such passes with varying lengths and in complex geological and geotechnical conditions. It is expected that the outcomes ultimately assist in enhancing the safety and efficiency of ore transportation for sustainable deep-underground mining.

Fig. 12 A partial fault-tree diagram showing the main mechanisms of failure in ore passes (Adopted and modified from Beus et al. 1997)

Flow dynamics

The United States Bureau of Mines (USBM) (Hambley 1987; Hambley et al. 1983; Hambley and Singh 1983) and subsequently, the National Institute for Occupational Safety & Health (NIOSH), (Beus et al. 1999, 1997, 1998, 2001; Beus and Ruff 1997; Iverson et al. 2003; Iverson 2002; Iverson and Jung 2005; Jung and Iverson 2004; Larson et al. 1998; Scott et al. 2000; Stewart et al. 1998) have made substantial and enduring contributions to the broad examination of critical aspects pertaining to the process of ore passes for both surface and underground mining operations. Over several decades, a range of investigative approaches, including field inspections, small-scale and pilot-scale tests, as well as numerical modelling, carefully examined the flow behaviour of rock materials and identified that the primary issues are static and dynamic loads exerted on walls, chutes, and gates with an overarching objective of refining and optimising the design of ore passes. The U.S. Mine Safety and Health Administration (MSHA) studies on injury and fatality data in underground mining, reported between 1975 to 1995, showed that nearly 75% of the issues were either directly or indirectly related to accidents resulting from pulling or freeing ore pass chutes, and structural failures of control gates and ore pass walls (Beus et al. 1998, 2001; Larson et al. 1998; Scott et al. 2000; Stewart et al. 1998).

In parallel with this research effort, Pariseau's research into the intricacies of material flow within ore passes produced systematic designs of ore passes with the primary goal of ensuring a consistent and highly efficient flow of materials (Pariseau 1966, 1969a, b; Pariseau and Pfleider 1968). Later, in the early 2000s, scholars at the Colorado School of Mines, utilising the Discrete Element Method (DEM), studied the dynamics of material flow to analyse the effects of the ore pass geometries (e.g., inclination and dog-legs), particle sizes, and fragment shapes on the flow (Nazeri 2001; Nazeri and Mustoe 2002; Nazeri et al. 2002, 2001).

Generally, speaking there are two main types of problems related to the flow of ore in ore passes which are known as hang-ups. These two types of interruption, as illustrated in Fig. 13, are: interlocking arches due to large boulders, and cohesive arches due to fine material with the presence of moisture (Esmaeili 2010; Hambley 1987; Iverson and Jung 2005; Vo et al. 2016). Interlocking hang-ups were the dominant problem in ore passes of ten Quebec underground mines (Hadjigeorgiou et al. 2005).

The consistent flow of fragmented rocks in ore pass systems is also an essential factor affecting the economic performance of underground mining operations. The interaction between the flow of the rock materials, and the rock mass surrounding ore passes is a complex problem because the roughness of the walls and the changes in the shape and dimension of the ore passes can affect the flow of the materials and cause turbulences in the flow (Sredniawa et al. 2022). Convergence of the ore pass walls due to squeezing or collapse of the blocks can also affect the flow of the materials and cause blockages (Beus et al. 2001; Szwedzicki 2007). A cycle of degradation occurs as the flow of ore and the impact loads due to the fall of rock particles damage the walls and the liner, which in turn, jeopardises the stability of the ore passes (Beus et al. 2001; Esmaeili 2010) (see Fig. 14).

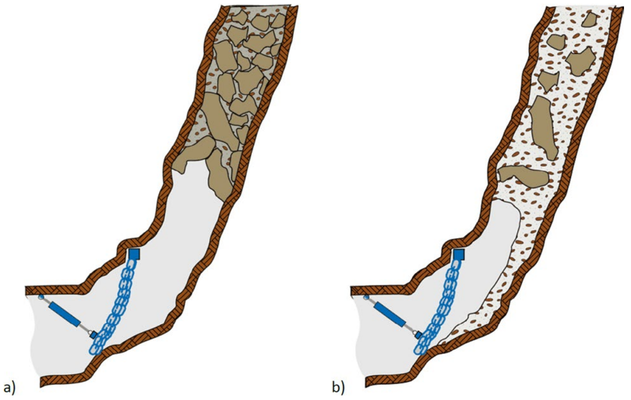
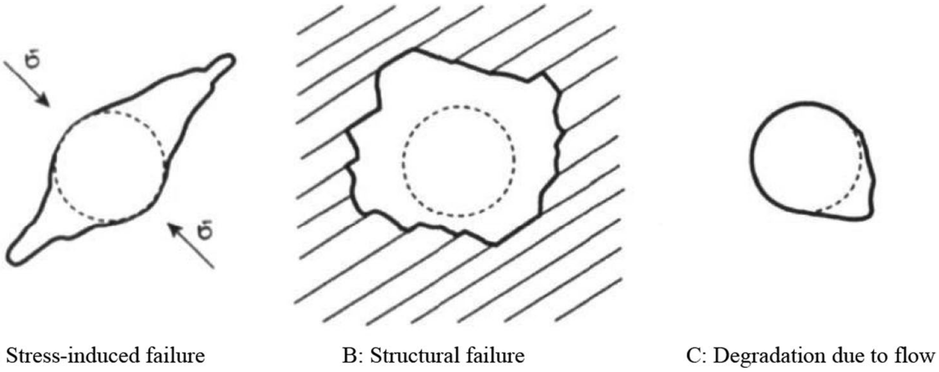


Fig. 13 Two types of hang-ups: **a** interlocking arches; **b** cohesive arches (Hadjigeorgiou and Stacey 2013)

Cohesive hang-ups

Under wet or moist conditions, hang-ups occur very frequently and often persist for extended durations, leading to disruptions in the flow of mineral material (Torres et al. 1981). The presence of moisture in a range of 4–8% is enough to significantly enhance cohesive forces within the material, resulting in prolonged blockages and hindrances to the smooth transport of minerals through the ore pass system. However, when the water content rises above 8%, the viscosity of the muck reduces, it behaves like a semi-fluid material, and the potential of hang-ups drops. However, this presents another serious risk-type to the personnel at the points of flow control which cannot withstand the high hydrostatic pressures.

Brady et al. (1969) investigation of design and operational aspects of ore passes at the CSA mine in Cobar, New South Wales, Australia, indicated that hang-ups, while relatively uncommon when dealing with copper ore, posed significant challenges when handling copper-zinc ore, primarily due to its higher sulfur content. The study underscored the critical importance of maintaining continuous ore flow within the ore passes and emphasised the need to extract ore at least once during each work shift to mitigate hang-up occurrences effectively. In addition, to address the specific issue of hang-ups associated with



A: Stress-induced failure B: Structural failure C: Degradation due to flow

Fig. 14 Schematic view of the main modes of failure in ore passes (adopted from Esmaeili (2010) with permission from the author)

copper-zinc ore, the researchers proposed a targeted strategy for optimising future ore pass designs. This strategy involved essential design modifications, such as increasing the inclination angle of newly designed ore passes beyond 70 degrees and transitioning to a circular cross-sectional shape. These purposeful adjustments demonstrated significant success in improving the flow characteristics of copper-zinc ore and substantially reducing the incidence of hang-ups.

Cohesive hang-ups in ore passes refer to the phenomenon where lumps of material become stuck or retained together within the passageway of an ore pass system. This occurs due to the cohesive forces acting between individual particles, such as adhesion and interlocking, preventing the material from freely flowing down the pass. Cohesive hang-ups pose a significant challenge in mining and materials handling as they can disrupt the continuous flow of material from the ore body to the collection point. To mitigate this issue, engineers employ various strategies such as adjusting drill and blast patterns to liberate less fines and to control the ore dilution as in many cases fines are separated from the waste either in the footwall or hanging wall (Iverson 2003; Iverson and Jung 2005; Vo et al. 2016).

Hambley et al. (1983) and Hambley (1987) also suggested the following relationship for computing the minimum dimension of an ore pass to prevent cohesive arching:

$$D > 2\frac{c}{\rho}\left(1 + \frac{1}{r}\right)(1 + \sin\varphi) \quad (19)$$

where D is the ore pass dimension, c is the cohesion of the fines, ρ is the fine density, r is the length-to-width ratio of the opening, and ϕ is the friction angle of the fines (Hambley 1987).

Bunker et al. (2015) also investigated the design of ore passes for the SLC operation at Ernest Henry Mining (EHM) which is situated 38 km northeast of Cloncurry in the Eastern Fold Belt of the Mount Isa Inlier of Northwest Queensland. They adopted Hambley's equation (Eq. 19) and used a Monte Carlo parametric analysis to estimate the minimum ore pass diameter to account for the uncertainties in predicting the cohesion and friction angle of the muck containing fine clay materials. Their investigation resulted in a minimum ore pass diameter of 4.2 m which was calculated based on the average of the Monte Carlo simulation results (see Fig. 15).

Interlocking hang-ups

This type of hang-up occurs due to the formation of arching of larger rock fragments (Hadjigeorgiou and Lessard 2007; Hambley 1983; Silva Filho et al. 2010; Szwedzicki 2007) or because of the abrupt changes in ore pass geometry (Hambley 1987; Iverson et al. 2003; Sato and Tang 2018, 2020). Interlocking hang-ups depend not only on the shapes and sizes of maximum particles but also on the ore size distribution after blasting (Firouzabadi et al. 2023; Meiring 2021). Several empirical approaches to the material flow in ore passes have been developed to account for the interlocking hang-ups. These empirical rules often consider the ratio between minimum ore pass dimension (D) and largest rock size (d) and the main existing models are summarised in Table 10 and are shown in Fig. 16.

The information summarised in Table 10 indicates that there are no universal rules in determining the appropriate dimension for an ore pass to ensure the free flow of muck materials occurs. Therefore, the analysis of granular flow may be limited to selecting the largest ratio (i.e., $D/d > 10$) to make sure no hang-ups occur. This lack of consistency in the guidelines for the design of ore passes was first reported by Pariseau over 55 years ago (Pariseau 1966; Pariseau and Pfleider 1968) and is still a common issue in the ore pass design for the underground mining industry.

Numerous researchers have also tried to use numerical simulations, such as the discrete element method (DEM) and finite element method (FEM), to investigate the material flow, the risk of interlocking hang-ups as well as the role of secondary fragmentation (Beus et al. 1997; Gresham and Turichshev 2016; Hadjigeorgiou and Lessard 2010; Nazeri

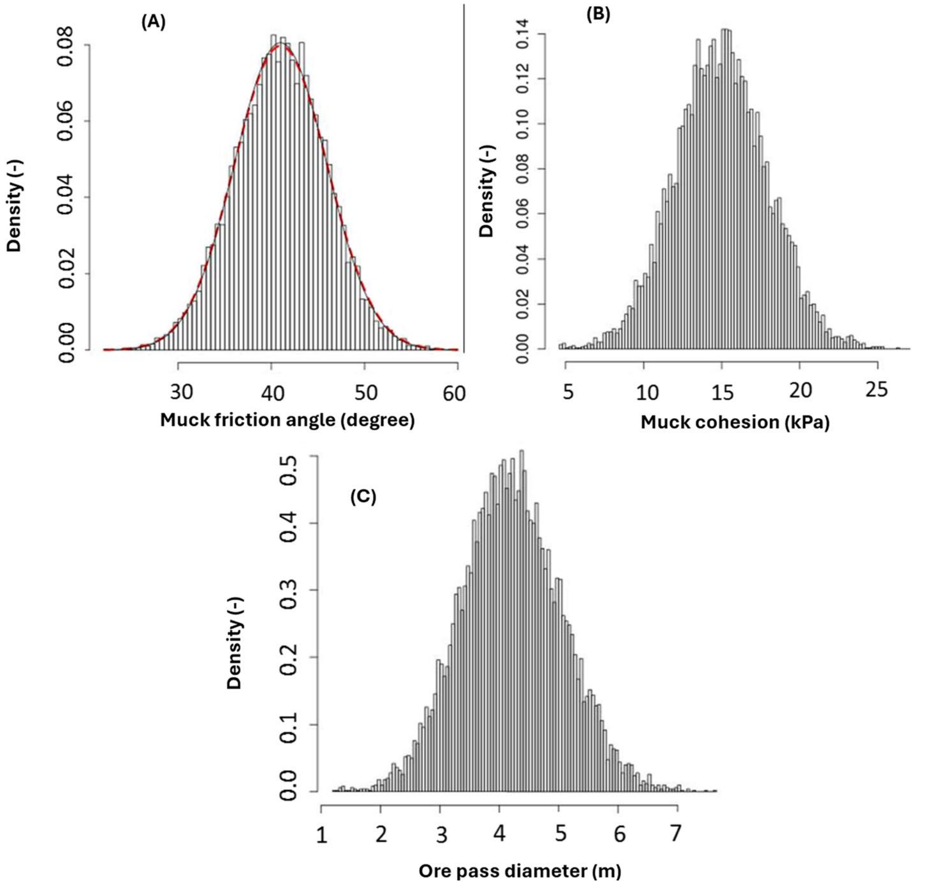


Fig. 15 Predicting the minimum ore pass length based on Monte Carlo simulation, **A** distribution of the muck friction angle, **B** distribution of the muck cohesion, **C** distribution of the predicted minimum ore pass diameter (Adopted and modified from Bunker et al. (2015) with permission from the authors and publisher)

Parameter	**1st quartile size**	**Median**	**Mean**	**3rd quartile size**
Unit	(m)	(m)	(m)	(m)
Value	3.6	4.2	4.2	4.8

Table 10 Guidelines to ensure free flow in ore passes (Hadjigeorgiou and Lessard 2007; Hambley 1983)

References	Free flow
Peele (1961)	(D/d) > 3
Aytaman (1960)	(D/d) > 4.21
Kvapil (1965)	(D/d) > 4.74
Hambley (1983)	(D/d) > 5
Joughin and Stacey (2004)	(D/d) > 6
Pariseau (1983)	3.6 < (D/d) < 4.5
Goodwill et al. (1999)	(D/d) > 10

2001; Sato and Tang 2018, 2020; Tang et al. 2013). Tang et al. (2013) used numerical modelling based on an integration of the energy tracking method (ETM) and the finite element method (FEM) to analyse the role of fragmentation on productivity and the efficiency of draw point extraction. The outcomes of this analysis showed that fragmentation is a key element in the development of issues such as arching and ore-pass hang-ups.

Similarly, Lessard and Hadjigeorgiou (2003a), Hadjigeorgiou and Lessard (2007), and Turcotte (2004) implemented the DEM to investigate the effects of ore pass geometry, rock fragment shape, and size distribution on material flow in ore passes and the risks of clogging. They also used the outcomes of the numerical modelling to develop some guidelines that can be used to minimise the risks of interlocking hang-ups in an ore pass. These analyses have, however, been done for ore passes with a limited length of 30 m and may not apply to long ore passes with a length of up to 1000 m. An example of the design charts for vertical ore passes is shown in Fig. 17.

Recent innovations aimed at addressing hang-ups in ore passes have focused on improving ore pass and chute design (Esmaeili 2010; Sjöberg et al. 2015; Sun et al. 2024), quantifying the flow dynamic of ore in ore passes and fingers by using discrete element method (DEM) (Esmaeili and Hadjigeorgiou 2011; Gresham and Turichshev 2016; Hadjigeorgiou and Lessard 2007; Sato and Tang 2018, 2020), using Discrete Fracture Network (DFN) for investigating the potential of block failure from ore passes' walls and

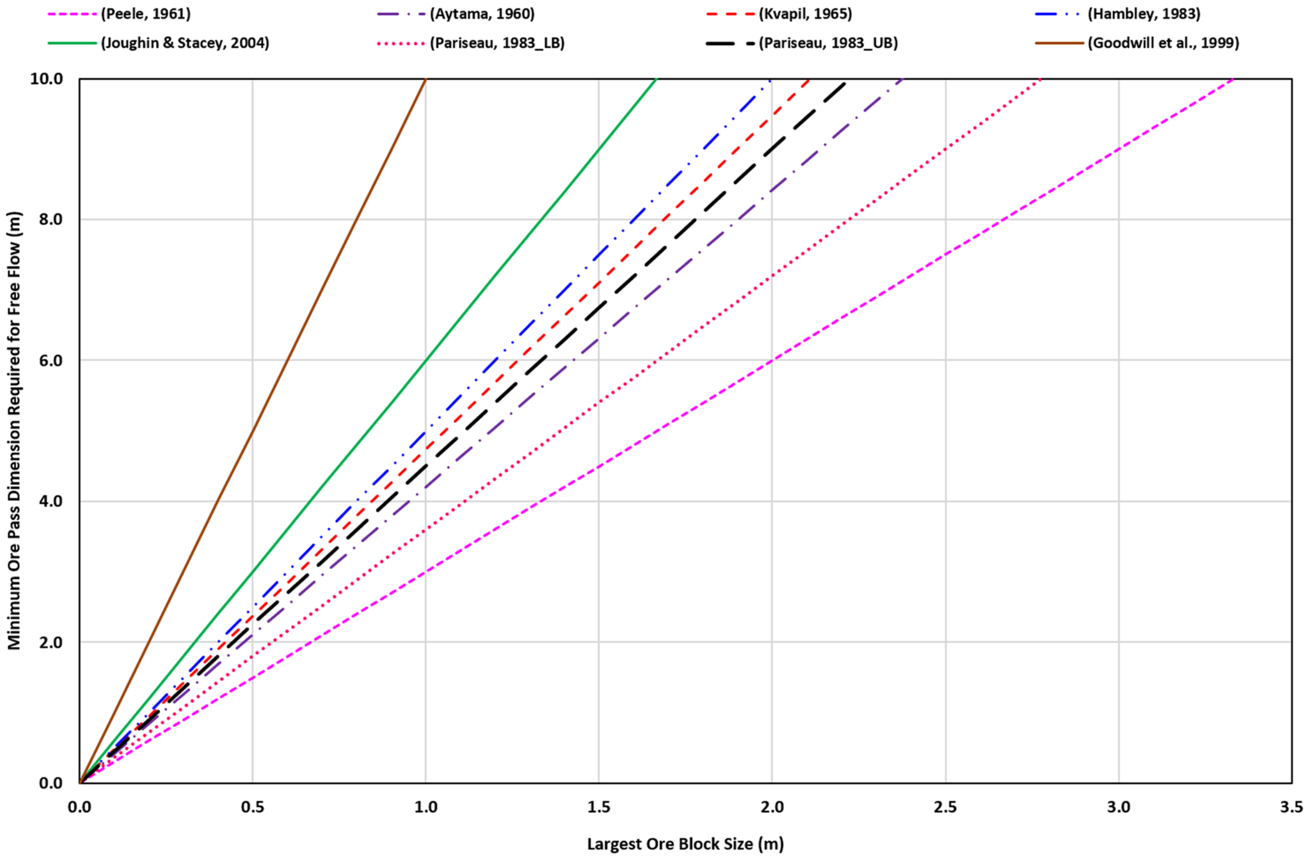


Fig. 16 Guidelines to ensure free flows from past literature (adopted and modified from Hadjigeorgiou and Lessard 2007)

chocking (Esmaeili and Hadjigeorgiou 2015; Esmaieli et al. 2013), implementing advanced monitoring systems such as Hovermap and drone (Emesent 2021; Flyability 2024a, b) for the detection of hang-ups, and employing new vibrating restoration machines for the release of hang ups in ore passes (Meiring 2021).

Conducting detailed experiments can also provide engineers with valuable insights into the behaviour of granular materials in ore passes and draw points (Goodwill et al. 1999; Ma et al. 2023). For example, Sánchez et al. (2019b) investigated the impact of moisture content and fine material on draw-zone characteristics and hang-up frequency through a series of laboratory experiments on a physical model at a scale of 1:75. The results of their study indicated that the dimensions, diameter, and height of the draw-zone are influenced by three main variables, including moisture content, particle sizes, and accumulated extraction mass. In tests involving moisture, the diameter increased up to a maximum value before stabilising. The ratio of the flow zone width to drawpoint width falls within the range of 2.7–3.0 times, consistent with prevailing block cave design guidelines. In addition, when moisture content exceeds 6%, "non-flow" conditions emerged due to the formation of a cohesive arch, inhibiting material flow.

Furthermore, advancements in ore pass geometry (e.g., size, shape, inclination, fingers, dog-leg) and lining materials design have contributed to reducing the risk of wall deterioration, and decreasing the frictional resistance and material adhesion, minimising the likelihood of hang-ups occurring. For instance, the incorporation of smooth, wear-resistant liners and streamlined chute profiles can promote smoother material flow in passes and reduce the risk of hang-ups (Van Heerden 2004b; Van Heerden et al. 2005). In practical applications, the effectiveness of these solutions varies depending on factors such as ore characteristics, operating conditions, and maintenance practices. Improvements in chute design and material handling techniques have also demonstrated positive outcomes in mitigating hang-up occurrences and improving ore pass system efficiency. However, the practical effectiveness of these solutions ultimately depends on their successful implementation and ongoing maintenance within specific mining operations. Recent innovations targeting hang-ups in ore passes offer promising opportunities to enhance system performance and safety. However, further research and field testing are still needed to assess their long-term effectiveness and applicability across diverse mining environments.

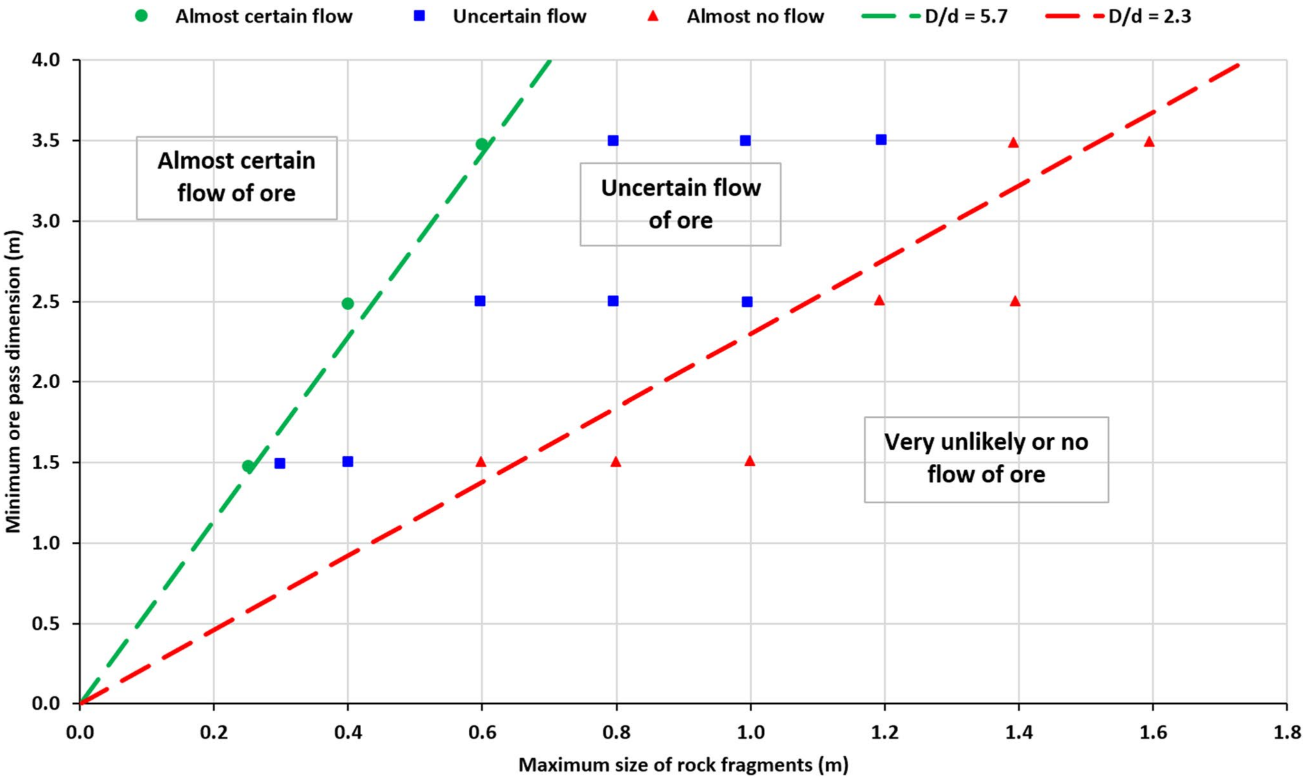


Fig. 17 An example of a design chart for a vertical ore pass developed based on the results of DEM modelling (data collected from Turcotte 2004)

Ore fragmentation

Since the objective of the ore pass is to transport ore by gravity, ore fragmentation is a key element in the assessment of their behaviour. Blasting with high powder factors can result in the liberation of fines from the ore, or can cause significant overbreak of the waste rock from the hanging wall or the footwall which can generate large boulders. Both fines and large boulders could result in issues in ore passes (Iverson and Jung 2005; Kumar 1997; Szwedzicki 2007). The productivity and efficiency of material loading from draw points are also profoundly influenced by the state of rock fragmentation in the Sub-Level Cave (SLC) environment. The presence of oversized rock fragments poses a notable risk, capable of disrupting the loading process and leading to unplanned halts, thereby causing significant downtime for Load-Haul-Dump (LHD) machines. Moreover, these oversized fragments have the potential to interlock, forming obstructive arches that may block ore passes. Furthermore, even in cases where blockages do not occur, these fragments can inflict damage on the ore pass walls, thereby escalating maintenance costs. Additionally, they have the propensity to become lodged in chutes, creating disruptions in material transportation at the haulage level. Hence, it is imperative to address rock fragmentation issues in the mine systematically to ensure smooth and uninterrupted ore pass operations (Firouzabadi et al. 2023; Manzoor et al. 2023a, b).

The particle size distribution of the rock fragment not only depends on the rock mass strength, and structures but also the confinement generated by the re-distribution of the in-situ stresses due to the mining (Liu 2006). Apart from the rock mass characteristics, the explosive type the pattern of blasting, and the existence of free surfaces also impact the outcomes of rock fragmentation underground (Liu 2006; Onederra and Chitombo 2007). The in-situ block size distribution of the rock mass is also a key component controlling the size of the large boulders (Sellers and Salmi 2020). Blast design for underground mining is a fairly mature science (Cunningham 1980a, b) and there exist methods that can be applied to predict the outcomes of blasting for improving rock fragmentation and minimising the risks of overbreaks (Jackson and Sellers 2017; Liu 2006; Onederra and Chitombo 2007). This can help to reduce the risk of choking ore passes with large boulders and minimising the risks of cohesive hang-ups due to excessive fine materials.

To systematically address ore fragmentation issues in the design of ultra-long and long ore passes, the mining industry can implement a multifaceted approach integrating advanced technologies and best practices. Firstly, improving rock mass characterisation through techniques like LiDAR for better classification of rocks and analysing natural discontinuities enables a more reliable understanding of the geological structure and fragmentation behaviour (Azhari 2022; Manzoor et al. 2023b). Techniques such as measurement while drilling can help to more efficently characterise the rocks for charging, blasting, and supporting the ground (Ghosh et al. 2018; van Eldert et al. 2019).

Utilising data analytics, machine learning and artificial intelligence for clustering rocks based on their blastability can also enhance blast pattern design by tailoring explosive properties to specific rock characteristics (Jackson and Sellers 2017; Salmi et al. 2023). The application of powerful computers and advanced numerical modeling techniques, such as the hybrid FEM-DEM method, can also enable the simulation and optimisation of the blasting process, in real scale, to achieve the desired fragmentation targets (An et al. 2021; Liu et al. 2021).

Quality control and assessment measures, including monitoring blast patterns with modern technologies like seismographs from Blast Log (Birch et al. 2023), enable the understanding of blast quality and any potential deviations from the plan and misfires (Liu 2012). Other advanced techniques such as image processing can assist in rock fragmentation characterisation, ensuring desired fragmentation outcomes (Thurley et al. 2015). Implementing rigorous quality control measures, including real-time monitoring of blast parameters and fragmentation analysis, facilitates immediate adjustments to blasting practices for improved fragmentation consistency.

Another effective factor for dealing with potential hang-ups in long ore passes is implementing proper blast design techniques for rock fragmentation in stopes to minimise overbreaks and employing screening techniques to remove oversizes, further optimising fragmentation for the gravity feed into long ore passes (Manzoor et al. 2023a). Additionally, leveraging novel blasting technologies such as wireless remote detonators (Hawkins 2021; Melbourne et al. 2020) enhances fragmentation control, contributing to efficient material loading by LHD's and transportation in long ore passes. Detonators with precise timing capabilities, enables better control over fragmentation outcomes by optimising blast energy distribution. Utilising innovative blasting agents tailored to the specific rock mass properties also enhances fragmentation efficiency, minimising energy wastage and overbreaks. Furthermore, integrating automated ore handling systems with real-time fragmentation sensors allows for dynamic material sorting and optimisation of loading practices, reducing the transportation of oversized fragments through ore passes. By integrating these strategies, the mining industry can mitigate ore fragmentation challenges, optimising production efficiency of long ore passes and reducing operational costs of material transportation.

In an interesting case study of cave mining, Ngidi and Pretorius (2010) investigated The impact of ore fragmentation on caving performance in an underground copper mine operated by the Palabora Mining Company in Limpopo, South Africa. It was observed that Sector 4 of the mine exhibited significantly coarser fragmentation compared to other areas within the cave operation. At the time, this sector was characterised by the presence of younger drawpoints and higher draw columns. On average, the production crews address approximately 70 hang-ups per day, resulting from the flow of oversized fragments in drawpoints and arching. Sector 4, of the mine which possess the coarser fragmentation, experiences the highest number of hang-ups treated per period, contributing approximately 40% to the total hang-ups addressed daily. Meanwhile, Sector 1 contributes around 30%, with indications of declining hang-up occurrences, suggestive of drawpoint maturity in this area (see Fig. 18).

Hang-ups at the site were managed through various methods, including drilling and blasting or deploying concussion bags to dislodge oversize rocks obstructing drawpoints. The secondary breaking units utilised a fleet of four medium reach rigs for drilling or placing concussion bags. Water cannons were used to release hang-ups, with up to 12,000 L of water pumped at high pressure to dislodge loose fines between oversize blocks. According to Ngidi and Pretorius (2010) more than 40% of hang-ups were resolved through this process, while the remaining require drilling and blasting. Hang-ups located at higher levels were stabilised and treated with concussion bags until safe drilling with medium reach rigs becomes feasible. Oversize rocks resulting from the caving process were, also, addressed by either blasting or physical breaking using mobile or fixed rock breakers. Rocks larger than 2m3 were broken using robust rigs and non-explosive technology. Mobile rock breakers, further augment secondary breakage activities. The Load Haul and Dump (LHD) units were also equipped with hydraulic hammers, with four units operational, they fragmented over 300 oversize rocks per day.

Discussion

This research highlights a significant scarcity of publicly available information concerning the design, construction, operation, and maintenance of long and ultra-long ore passes, typically ranging from 300 to 1000 m in length, in the mining industry. Addressing these ultra-long and long ore passes poses unique challenges, including potential damage due to elevated stress levels, wear, increased impact loads, hang-ups, and risks associated with crossing weak rock formations, intersecting faults, and brecciated and shear zones. The complexities also extend to ore flow mechanisms, encompassing issues like preferential flow,

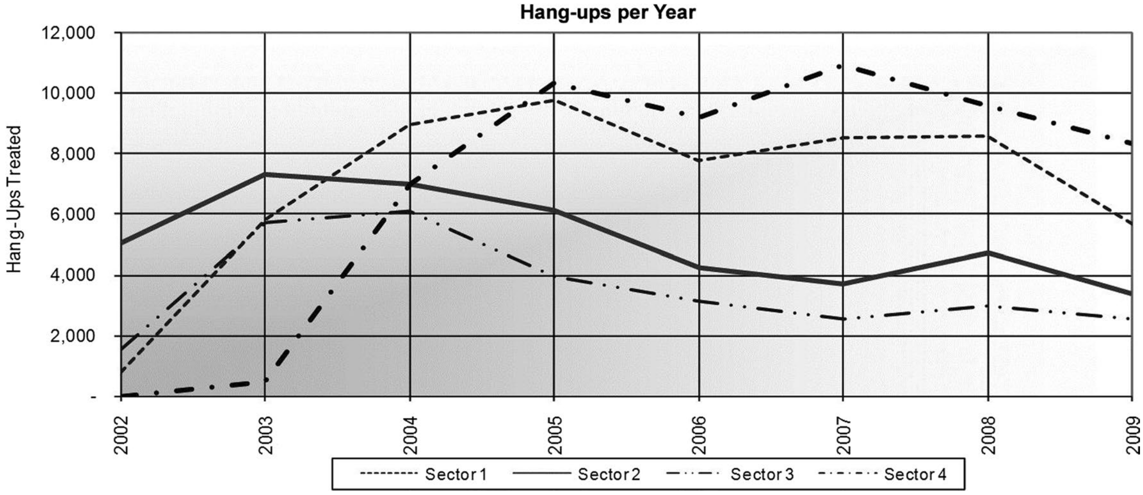


Fig. 18 Hang-ups treated per different sectors in the Palabora caving operation (Ngidi and Pretorius 2010)

severe turbulence, air-blasts, and back blasts, which are less common in shorter passages, underscoring the lack of comprehensive design information for long and ultra-long ore passes.

It is also important to note that there are several reasons contributing to the scarcity of data related to the design, implementation, operation, and maintenance of ultra-long and long ore passes. Firstly, these types of ore passes are employed in deep mines or in mines situated in areas with particular surface topography, such as mountainous regions. In such settings, ore from high ground can be efficiently transferred to the processing plant located at the mountain's base. In some instances, ore can also be transported from an underground mine to an open pit at a lower elevation or vice versa. Examples of these type of ore passes have been utilised in the Grasberg cave mining operation, in Indonesia (Parhusip et al. 2021), and in Andina (Río Blanco) mine, in Chile (Ascencio 1985). In addition, the specialised nature of ore pass design and operation means that expertise in this area may be limited to a few professionals or organisations. Additionally, companies may consider details related to the common issues in ore passes proprietary information, leading to a lack of publicly available data. Furthermore, the complexity and variability of mining operations mean that there is no one-size-fits-all solution for long ore pass design and optimisation, making it challenging to create standardised guidelines or resources. The potential consequences for the mining industry include increased risk of inefficiency, safety hazards, and operational disruptions. The challenge for mining operations is, however, that loss of an ore pass creates additional congestion underground that increases the productivity loss over and above the direct tonnage of the ore pass (Skawina et al. 2018; Sredniawa et al. 2023). Without access to comprehensive information and best practices, mining companies also struggle to optimise their long ore pass systems, leading to reduced productivity and higher operating costs. Moreover, inadequate understanding of ultra-long and long ore passes' design, optimisation and maintenance could result in safety incidents or equipment failures, posing significant risks to personnel and operations. Addressing the scarcity of information on long ore passes is, therefore, a crucial task to improve efficiency, safety, and sustainability in deep mass mining operations.

In certain instances, research on the design and stability assessment of long ore passes has referenced both shafts and ore passes, given that they both constitute vertical or sub-vertical infrastructure in underground mining. Yet they serve distinct purposes and may exhibit notable differences in their design, excavation, operation, and maintenance. Understanding these distinctions could be useful for optimising the design, and operation of these excavations. Shafts typically provide vertical access to underground workings for personnel, materials, and equipment, necessitating robust construction to withstand high loads and ensure safety during the lifetime of the shaft. In contrast, ore passes facilitate the transfer of ore and waste materials between different levels of the mine, often requiring inclined or vertical chutes for gravity-driven transport. While shafts undergo extensive engineering for structural integrity and hoisting systems, ore passes are designed with considerations for material flow dynamics and fragmentation control. Operational differences also arise in their usage, with shafts primarily serving transportation via cages and skips and without any interaction with the walls or ventilation functions (Visser 2009), whereas ore passes focus on material handling and ore flow management with significant interaction between the ore fragments and the pass walls. Maintenance practices may also diverge, with shafts requiring regular inspection and servicing of hoisting equipment and support systems, while ore passes often necessitate periodic clearing of blockages and monitoring for wear and degradation of walls and linings and structural elements.

Hang-ups, wherein material becomes lodged within ore passes, can lead to operational disruptions, reduced throughput, increased operatonal costs, and increased maintenance requirements (Gómez et al. 2022). Removing hang-ups can be a challenging task for the mining crew and may involve numerous safety hazards (Hadjigeorgiou and Lessard 2010; Szwedzicki 2007). By explicitly linking hang-ups to these consequences, mining operators can better understand the importance of implementing preventive measures, such as chute design and optimisation; fragmentation design; and regular clearing procedures, to maintain the uninterrupted flow of materials and maximise production efficiency (Bunker et al. 2015; Lessard and Hadjigeorgiou 2003a). It is also noted that the occurrence of hang-up events is subject to various factors. For example, the recent study by Sun et al. (2024) indicated that as the ratio of drawpoint size (or ore pass dimention) to average particle size increases, the frequency of hang-up events tends to decrease. Conversely, higher particle friction coefficient and overburden stress (equivalent to the muck height in ore passes) contribute to an increased risk of hang-up events. However, among these factors, the ratio of drawpoint size to average particle size exerts the most significant influence on the occurrence of hang-up events, followed by the particle friction coefficient. Overburden stress, however, comparatively, has the least impact on the occurrence of hang-up events (Sun et al. 2024).

Arching phenomena, where material forms stable bridges over the outlet of ore passes, can also limit the material flow and increase the risk of structural overloading and pass blockages. Emphasising the potential safety hazards and production constraints associated with arching events highlights the importance of monitoring and addressing flow obstructions promptly to mitigate adverse impacts on the ultra-long and long ore passes system performance (Manzoor et al. 2023a). In a recent study, Hekmatnejad et al. (2021) applied a hybrid methodology to investigate the uncertainty surrounding block geometry, focusing on the variability in blockiness and hang-up frequency at El Teniente mine in Chile. Their hybrid approach integrates geostatistical simulation, probabilistic discrete fracture network modeling, and geometric and topological characterisation of fracture networks, along with supervised Poisson regression models. Their study offers insights into systematically characterising fractured rock masses in cave mining settings, aiding in mine design, production rate assessment, and hang-up risk evaluation by a better understanding of the fragmentation. Flow dynamics, encompassing phenomena like hang-ups and arching, sudden releases of blockages and air blasts, mud-rush, preferential flow and can considerably influence the efficiency and safety of ore passes systems (Gresham and Turichshev 2016; Sato and Tang 2020). Hang-ups, disrupt material flow, leading to production delays, increased maintenance, and potential safety hazards. Arching phenomena also create stable bridges (Sun et al. 2024), limiting the material flow and potentially causing structural overloading, when suddenly released, compromising both efficiency and safety.

Additionally, high water content can alter material adhesion and cohesion, increasing cohesive resistance and the risk of pass blockages or failures, further impacting ore passes' system efficiency and safety (Iverson and Jung 2005; Vo et al. 2016). Water can also accumulate in ore passes and results in mud-rush and mud-flow (Butcher et al. 2005; Castro et al. 2023a; Vallejos et al. 2017). The effects of water content on material flow dynamics can significantly influence the operational efficiency and structural integrity of ore pass systems (Castro et al. 2023b; Torres et al. 1981). By identifying the correlation between water content and flow behaviour, mining operators can implement moisture control measures and material conditioning techniques to optimise flow rates and minimise the risk of long ore passes' blockages and potential structural failures. Understanding and addressing the flow dynamics challenges are, therefore, critical for optimising ore pass system performance and ensuring a safe and reliable operation of material transportation via long ore passes.

To counter the lack of data, our study has proposed engaging recognised experts in a structured expert elicitation method. This approach aimed to identify critical risk factors essential for geotechnical design and optimisation of long and ultra-long ore passes. Concurrently, CSIRO has initiated laboratory-scale experiments probing ore flow dynamics, examining the role of particle characteristics, and exploring factors such as ore pass inclination and particle size distribution to comprehend preferential flow behaviour. Advanced numerical modelling, notably the discrete element method (DEM), has also been used to facilitate parametric studies to develop guidelines for the design of these extended ore passes. Such modelling takes into account the particle interactions on the formation of hang-ups and quantitatively demonstrates the effects of particle impacts on passes' walls by considering the variations in the shape, and size of particles as well as the inclination and shape of the passes, themselves. Investigations will also encompass complexities like dog-legs length and inclination, finger shapes and inclination, and passes' shapes and inclinations to comprehend flow patterns and to compute the loads on the passes' walls and gates. Such information can significantly help to optimise the design of ultra-long ore passes and to forecast the risks.

Finally, insights from this extensive review of ore pass literature in challenging grounds—specifically based on South

African, Chilean, Canadian, and Sweden experience—will be fused with expert survey outcomes. This integrated information will feed into the Rock Engineering System approach, identifying influential factors, cascading effects and control measures to mitigate potential risks in the design and operation of long and ultra-long ore passes.

Conclusions

The utilisation of long and ultra-long ore passes presents itself as a promising solution for mining operations aiming to limit the extent and scale of development required in underground mass mining operations (e.g., sublevel caving), along with the machinery needed for the transport of ore and waste from the stopes to the surface. Strategic adoption of long ore passes can potentially contribute significantly to the reduction of energy consumption and the mitigation of emissions associated with the complex processes of material handling, in underground mining. As the lengths of ore passes increase, the likelihood that they pass through weak geological formations or intersect fault shear zones and large discontinuities also increases. The magnitude of dynamic and static loads affecting the ore pass walls and the gates can also increase with the length of the ore passes. There is, however, very limited information available about the design, implementation, operation, and maintenance of such long ore passes.

The principal aim of this paper was, therefore, to present a thorough gap analysis concerning the methodologies applied in the design of ore passes, with a specific focus on ore passes over 300 m in length. Additionally, the objective was to perform a comprehensive desktop study to pinpoint the key risk factors that necessitate careful consideration in the design of these passes. By investigating the key aspects, our study aimed to contribute to a holistic understanding of long ore passes, facilitating informed decision-making and the development of resilient engineering solutions in the field.

This study also detailed a careful examination of multiple dimensions related to ore passes and their optimisation. It also compiled modes and mechanisms of failure, and controlling factors and identified the key factors in the ore passes' stability assessment. We also investigated several other related critical factors such as ore pass inclination, hang-ups, and static and dynamic gate loads. Ensuring the structural integrity and reliability of these ore passes is paramount in the design phase, so ore pass integrity, finger design, dog-leg design, gate loading, boulders and oversize, mud rush, airblast, back blast, and dust propagation must be considered differently than for shorter ore passes.

The complexity of ore passes construction increases with length and the intricacies of construction methodologies, which encompass conventional drill and blast operations, support and lining strategies, as well as raise boring methods have been presented with discussion on future opportunities. Operational considerations such as flow dynamics within the passes, the challenges posed by cohesive hang-ups, interlocking hang-ups, and the effects of ore fragmentation are shown essential to be identified in the earliest stages for the long-term, and efficient functioning of long ore passes and deserve in-depth examinations.

The achievement of safe and efficient deep mass mining, specifically sublevel caving, hinges upon the seamless and effective management of material transfer within ore and waste passes, as the operation of these passes is bound by specific operational limitations. To address the array of challenges that may arise during material transport in underground mining, it is also necessary to implement a resilient engineering design approach. This involves the development of long ore pass systems that exhibit not only robustness but also adaptability when confronted with unforeseen obstacles. The concept of resilient engineering emphasises the importance of this proactive approach in mitigating unforeseen issues in material conveyance in underground mining, thereby enhancing the overall operational performance. By systematically infusing these insights, from past experiences, into the design process, engineers can cultivate ore passes' systems that are not only more robust but also finely prepared to adapt to unforeseen complications. These unforeseen issues may encompass, among others, hang-ups, mudrush, and different forms of instabilities, which are prevalent in the domain of ore pass operations in high-depth and weak rocks. The outcome is an elevated level of resilience, where the engineered systems are better prepared to navigate such challenges, fostering enhanced productivity, durability, and flexibility across the spectrum of mining geomechanics. The results of this gap analysis have also been instrumental in identifying crucial areas for future research aimed at enabling energy-efficient mines, especially focusing on material transportation in deep mass mining. To add to ongoing work to understand the behaviour of typical ore passes, a move to long and ultra long ore passes would require research into resilient engineering design, considering Rock Engineering System and probabilistic approaches to account for the increased probability of encountering poor rock or high stresses. These can include enhanced Bayesian approaches that account for the additional failure probability with length given the greater ability to collate knowledge from short ore pass experiences. Considerations of energy optimised mine design approaches with value trade-offs or real options that incorporate environmental, social and governance risks alongside net present value, NPV, are needed to enable mining by reduction of footprints and improved social engagement. Additionally, researchers should enable efficient construction methods, novel support technologies, blockage removal at a long distance from access, long range sensor systems, such as fibre optics, for flow management and robust operating procedures to increase productivity by eliminating congestion.

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