



Expert Elicitation for the Resilient Design and Optimisation of Ultra-long Ore Passes for Deep Mass Mining

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Abstract

Extension of ore pass length has become increasingly critical for optimising energy-efficient underground mining operations. Long and ultra-long ore passes, spanning from 300 to 700 m, can significantly improve the functionality and viability of underground mass mining operations though suboptimal performance has an extremely adverse impact on production. The public domain lacks substantial information regarding the primary engineering, geological, and geotechnical risks and challenges associated with the design, implementation, operation, and maintenance of such long ore passes. Therefore, the aggregation of past experiences and the insights of experts assume paramount significance. An innovative methodology is introduced to address this evident data deficiency and to establish comprehensive guidelines for the resilient design of such lengthy ore passes — combining gap analysis with expert elicitation techniques. This equips design engineers with the necessary tools to formulate and adapt strategies for assessing the numerous challenges and uncertainties that invariably accompany their projects. Expert elicitation techniques are summarised, and a gap analysis is conducted with subject matter experts, from various countries, collating their extensive ore pass design experience, to create a comprehensive list of effective parameters and key risks that must be considered. Quantitative analysis of the survey results enabled the identification and ranking of the numerous factors affecting the design, operation, and maintenance of long and ultra-long ore passes and highlights the complex technical challenges (substantial damage from rock particle impact, increased dynamic mining stresses leading to failure, air-blasts and back blasts, dust, preferential flow, turbulent and dynamic material flow) that are uncommon in shorter ore passes. Additionally, increasing length heightens the probability of intersecting weak rock or discontinuities, leading to a higher risk of structural failure and instabilities. Faulting, folding, and large-scale structures are also critical geological factors to be considered in the design of such structures. The key geotechnical factor is also the rock type surrounding the pass. Experts highlighted the lack of clear guidelines for decision-making, resilient design, and construction so this work suggests future investigations to determine the complex interaction between the effective parameters, using approaches like the rock engineering system, discovery of cascading hazards, and optimal controls.

Keywords Long ore passes · Sublevel caving · Underground mining · Expert elicitation · Risk assessment · Survey data · Resilient design

1 Introduction

In mining engineering, it is a well-acknowledged fact that all surface mining operations inherently possess a finite lifespan, primarily dictated by the concept of economic depth [1, 2]. As mining ventures delve deeper below the Earth's surface, the increasing expenditures associated with ore transport and waste removal via substantial diesel or electric trucks become economically prohibitive [3, 4]. To effectively extend the operational lifetime of existing surface mines or to access deeper ore reserves, the industry typically transitions to underground mining methodologies. This

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strategic shift not only facilitates the exploration of deeper and intact resources but also tactically navigates the financial limitations that restrict continued surface extraction [1, 5].

Ore passes, whether they are vertical or inclined, form the fundamental infrastructure underpinning most underground mining methods. These passes are of essential importance, serving as key channels for the conveyance of ore. In sub-level cave mining, particularly, ore passes play a dominant role in the transfer of both ore and waste materials, facilitating their movement from distinct sublevels to the primary haulage level situated below [6–9]. For example, Fig. 1 schematically illustrates the application of long ore passes (approximately 350 m in length) at the LKAB Kiirunavaara mine, in Sweden [10]. It is also notable that, often, to optimise ore recovery, these ore passes are excavated through waste rock formations, which may exhibit distinct characteristics when compared to the more extensively investigated and characterised ore body rock masses [6, 7, 11, 12].

As the global shift towards energy efficiency gains momentum and the plans to eliminate diesel emissions become more pronounced, the application of gravity-driven systems for ore transport through rock passes is expected to emerge as a favoured solution within the mining industry. This trend is likely to drive the adoption of long ore passes, enabling the hauling and transport of materials over more substantial distances [3, 4, 13, 14].

In deep underground mining, particularly in sublevel caving, it is essential to examine the crucial role of ore passes. Unfortunately, the complexities of long and ultra-long ore

passes' conceptualisation, design, construction, operational procedures, and maintenance protocols have not received the necessary level of attention, even though they involve numerous distinctive technical challenges [11, 15–18]. Amongst these, a main issue appears to be the susceptibility of ore passes to different forms of failure and deterioration (e.g. structurally controlled failure, stress-included failure, blast-induced damages, impact-induced failure and wear due to the abrasive ore flow) [17, 19–22] or obstructions that may emerge during the transport of ore and are known as different forms of hang-ups and mud-rush [10, 20, 22–26] (see Fig. 2). These types of issues can lead to profound influences on the operational throughput and efficiency of the ore passes. For example, instances of hang-ups or blockages within ore passes can lead to their breakdown, thereby initiating bottlenecks in the overall production continuum [27–31]. The interruption and malfunctioning of ore passes directly translate to a reduction in mine production, underscoring their essential role in upholding operational efficiency and throughput. Consequently, the importance of encountering these challenges cannot be overstated, as it is fundamental to preserving the uninterrupted flow of ore and sustaining optimal operational productivity [3, 20, 23, 27, 32].

According to the theory of constraint postulated by Goldratt and Cox [33], ore passes, specifically long ore passes, can transfer to the operational bottlenecks of underground mining. This indicates that the malfunctioning of an ore passes holds the inherent potential to induce substantial

Fig. 1 A simplified representation of long ore passes (approximately 350 m in length) at the Kiirunavaara mine [10]

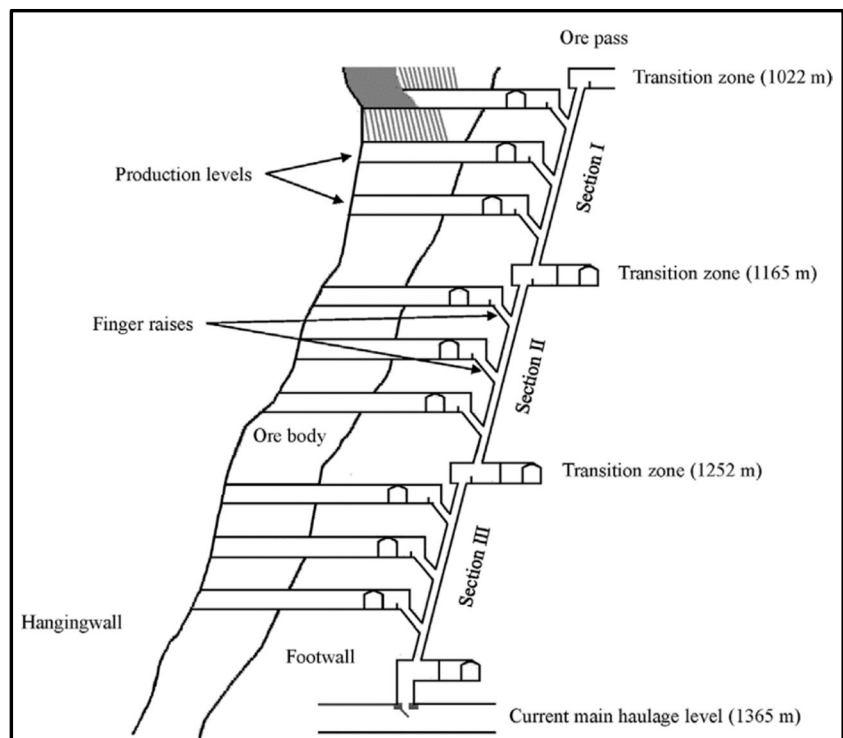


Fig. 2 Examples of **A** hang-up and **B** wear and damage in ore passes (adopted from Flyability (<https://www.flyability.com/ore-pass>) with permission)



disruptions in mining productivity [10, 31, 34]. Geotechnical engineers have the difficult and complex task of ensuring the uninterrupted functionality and optimisation of these passageways throughout the life of the mining operation, thereby enhancing the efficiency and productivity in the mining value chain.

As of now, there is a noticeable scarcity of information regarding the degradation trends and maximum throughput capacities for ore passes exceeding 300 m in length. A comprehensive industry benchmarking analysis of ore passes in various deep and ultradeep mines in South Africa has highlighted that, typically, these passages are under 200 m in length, with only one exception (with a length of around 280 m) that approached the 300-m threshold [35]. The same benchmark study of ore passes in hard rock mines in Quebec, Canada, undertaken by Lessard, Hadjigeorgiou [36] and Hadjigeorgiou et al. [37], covering a dataset of 153 cases, disclosed that the passes ranged from 10 to 273 m in length, with a mean value of 87 m. Notably, only two of these passes extended beyond 250 m in length. Subsequently, their research was extended to encompass 98 sections of ore passes at the Brunswick mine. Within this study, they reported on an unsupported raise bore ore pass with a 3-m diameter, which consisted of two long sections. The first section had a length of approximately 325 m and a dip of 65°, while the second section measured 226 m in length with an inclination of 72° [17]. The insights gained from Canadian and South African mining experiences provide very useful information regarding the design and operational aspects of ore pass systems. These experiences highlight a progressive establishment of clear objectives for the design and management of these systems within mining operations. However, there is a lack of carefully devised strategies to effectively attain these objectives [12, 15, 21, 22, 36, 37].

In this study, upon recognising a gap in strategies for designing and optimising ore passes exceeding 300 m in length, we relied on expert opinions and engineering judgment to identify the key factors influencing the stability and functionality of such passes. Considering the aforementioned data limitation, the work was initiated by investigating prior instances of ultra-long ore pass operations that have been documented in the literature [38]. This previous work

also attempted to extract and compile the fundamental factors that are critical for the effective optimisation of long and ultra-long ore passes, by delving into the prominent challenges involved in their design, implementation, operation, and maintenance. Numerous pieces of literature on ore pass design and operation were carefully investigated and processed for this purpose. We also identified key indicators that signify when the use of long ore passes should be avoided. A comprehensive gap analysis was also conducted by examining the body of work related to ore pass design by experts hailing from Canada [15, 17, 23, 37, 39–41], South Africa [18, 22, 26, 30, 31, 35, 42–47], Sweden [10, 11, 16, 32], Australia [8, 48–51], Chile [24, 52, 53], and the USA [25, 54–59]. The analyses aimed to reveal critical issues and opportunities associated with the application of long and ultra-long ore passes, leveraging insights distilled from prior research to facilitate the resilient design of these rock structures. It is also noted that a summary of the gap analysis and desktop study has been previously presented elsewhere [60] and due to space limitations, it will not be reiterated here.

This paper, therefore, serves as a complementary extension to the above gap analysis work by Phan, Salmi [60]. Given the limited availability of information regarding long ore passes, this paper's primary objective is to pinpoint areas necessitating additional research efforts. These activities are essential to facilitate the successful design and optimisation of extended ore passes within complex geological and geotechnical conditions. We conducted a rigorous technical survey involving several well-known subject matter experts (SMEs) and harnessed the methodological rigor of "Expert Elicitation" as illustrated by Baecher [61]. This systematic approach was implemented to carefully identify and evaluate the primary influential factors as well as the key risks associated with the design, implementation, operation, and maintenance of long ore passes. The method's precision ensures the generation of robust and substantiated insights, aligning with the highest standards used for resilient design in geotechnical engineering applications. Collating and disseminating the collective expertise of twenty-five esteemed international specialists represents a key effort, furnishing invaluable insights essential to achieving a robust design of long ore passes. This collaborative work serves as the

bedrock upon which future initiatives can be built, by utilising the rock engineering system methodology as proposed by Hudson [62]. Through this latter approach, we not only evaluate the multifaceted impacts of the key effective factors on various risk types but also uncover the cascading consequences that succeed from any perturbations in ore pass systems (e.g. changes in fragmentation, ingress of water, changes in mining stresses), further enhancing our understanding and preparedness for the geotechnical design of long ore passes for deep mass mining.

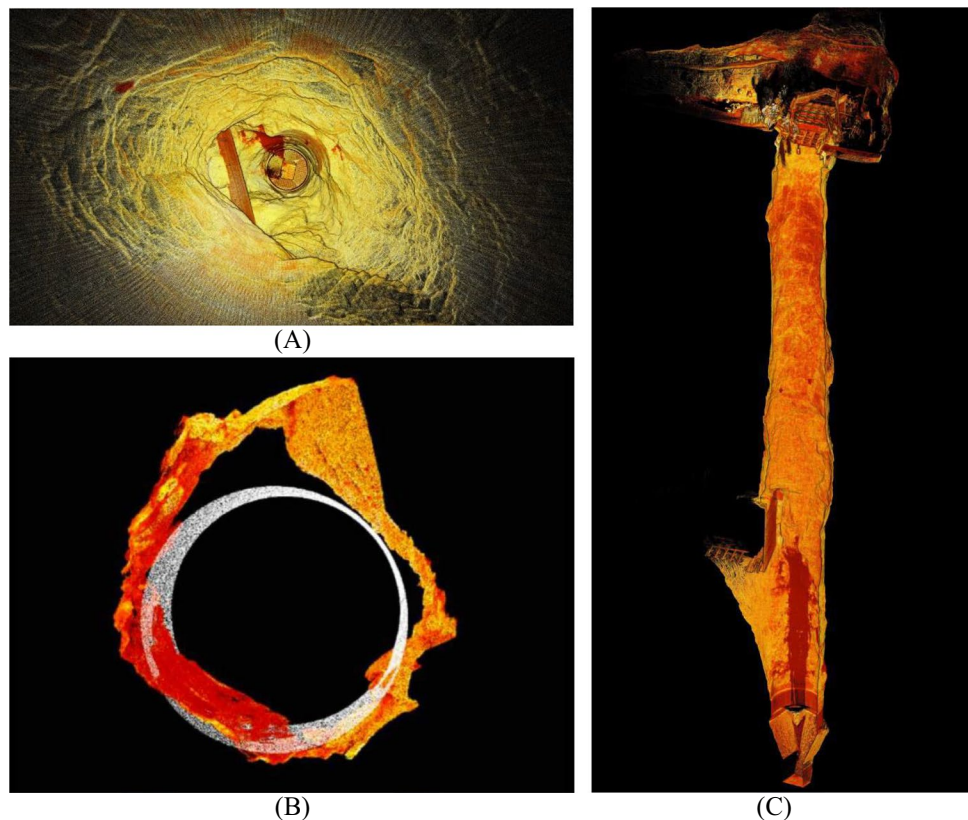
1.1 Previous Deployments of Long Ore Pass Systems

In both surface and underground mining operations, the mining industry has been using ore pass systems with diverse lengths, in very rare cases ranging from over 300 m to occasionally reaching nearly 500 m, and in certain cases, extending to approximately 650 m. These types of very long passages serve as conduits for the transport of both ore and waste materials [10, 17, 53, 55, 63–66]. Unfortunately, the public domain suffers from a dearth of comprehensive, systematically compiled, and organised information about these ore pass systems, including their functionality and performance. More precisely, there exists a scarcity of data addressing the risks and challenges, specifically, associated

with the various stages of design, construction, operation, and maintenance of these substantial rock structures.

In a preceding technical report [38], we compiled information related to a selection of long ore passes surpassing the 300-m mark. Our research highlighted that the design of such extended ore passes presents distinctive challenges. These encompass concerns such as airblast and back blast phenomena [64, 67, 68], the pronounced impact-induced degradation and deterioration [10, 16, 32, 39, 69], hang-up issues arising from the feeding of muck containing wet fine materials [52, 53], sophisticated inspection requirements [63, 66], a significant likelihood of intersecting fault shear zones and large geological structures, and increased susceptibility to collapses and structural failures [12, 17, 22, 30, 31, 39, 47, 70, 71]; escalated risks of stress-induced failures such as dog-earing, spalling, and burst [11, 16, 18, 46, 72, 73], greater risk for dust propagation [74, 75], challenges in monitoring muck levels within ore passes [65, 76], and complex flow dynamics giving rise to preferential flow patterns in long passes' systems [55]; and amplified abrasive effects due to the movement of dense rock materials [10, 16, 39, 69, 77]. For example, in Fig. 3, we present various instances of long ore pass (350 m in length) and shaft failures observed using Emesent Hovermap technology within a South African diamond mine [66]. These images depict the substantial widening of the pass, attributed to factors such as scaling due

Fig. 3 Examples of long ore passes, and shaft failures collected using Emesent Hovermap technology: **A** stress-induced damage and breakout (dog-earing) and abrasive ore flow, and **B** and **C** significant raise and pass widening and scaling due to dynamic mining-induced stresses, the abrasive nature of the ore flow, and impact loads of falling rock fragments (adopted from [66, 78, 79] with permission)



to the abrasive nature of the ore, the impact loads from rock fragments, dynamic mining stresses, and damage resulting from controlled blasts aimed at dislodging hang-ups. As we have extensively detailed these challenges, associated with long ore passes, in the previous part of this study, we shall refrain from reiterating the specifics herein.

1.2 Expert Elicitation

The literature review discussed in the previous section showed that several factors play critical roles in the stability and operation of long ore passes. The study also revealed considerable gaps in documented information available in the public domain about the design, implementation, and maintenance of long ore passes. To overcome this lack of recent data availability, a technical survey was conducted by the research team. The survey provides a novel way of rapidly identifying the critical risk factors, determining the areas that need further attention, and identifying research required for the successful and resilient design and application of such complex mining structures.

Often the problems in rock mechanics fall in the data-limited category as a geotechnical engineer seldom knows enough about the rock mass behaviour, environmental controls, intact rock properties, and discontinuities (Starfield & Cundall, 1988). Geotechnical engineers are often faced with situations in which the design of a method to resolve a rock engineering problem cannot be done through information from a textbook, a written rule, or even advanced analytical and numerical modelling. Such non-conforming situations may be resolved through a process known as executing an “Engineering Judgment”. Einstein [80] mentioned observations and scientific interpretation by Terzaghi, a pioneer in geoenvironment and the father of modern soil mechanics, formed the main pillars of Terzaghi’s connection with geology. Judgment and geology became aligned as a unique pair, as Terzaghi observed the limitations imposed by nature on the application of theoretical approaches. Einstein [80] also reported several quotes from Terzaghi highlighting the importance of engineering judgment in geoenvironment, for example, “In our field, theoretical reasoning alone does not suffice to solve the problems which we are called upon to tackle. As a matter of fact, it can even be misleading unless every drop of it is diluted by a pint of intelligently digested experience”.

Figure 4 shows the classification of the modelling problems originally introduced by Holling and Walters [81] that was adopted by Starfield and Cundall (1988) for discussing the problems in rock mechanics and rock engineering. Figure 4 relates one axis to the quality and/or quantity of the available data and the other measures the understanding of the problem to be investigated. The quadrant between the axes is divided into four regions. In region (1), there

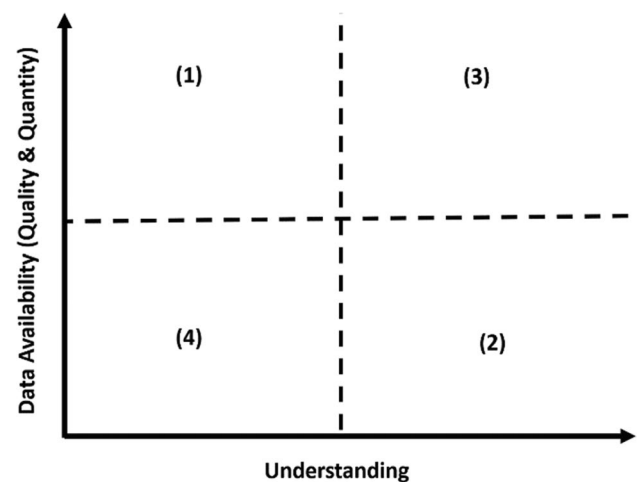


Fig. 4 Holling’s different classes of technical problems

exists good data, but the problem lacks a good understanding, implying statistical analysis could be a good tool to tackle these problems. In region (3), good data availability, and good general understanding, is where models can be developed, verified, and implemented. In regions (2) and (4), the problems suffer from data limitation where relevant data are unavailable or cannot easily be obtained. These are the areas where engineering judgment and expert elicitation techniques can help to provide some insights [61, 82, 83]. Long ore pass design is expected to be in region (4): very limited information is available about successful or failed cases of long ore passes and the high complexity of the coupled mechanisms involved.

To incorporate such uncertainties into risk assessment of problems situated in region 4 of Fig. 4, the application of quantified expert opinions becomes imperative. In risk assessment, the quantification of expert opinion in the form of judgmental probabilities is known as “expert elicitation” [61]. Judgmental probability serves as a formal method for expressing expert opinions in numeric terms and integrating them with existing models. It is important to note that uncertainties captured through judgmental probability are assigned numerical values that are influenced by the expertise, knowledge, and perspective of the individual involved. Such an approach is deemed appropriate since the primary objective of risk assessment is to systematically support and enhance engineering judgment, rather than replacing it [61, 80]. The experiences from the past (also known as lessons learned) can assist in ensuring that systems can be resilient and withstand or recover from various stresses and disturbances. Kutsch et al. [84] defined resilience in engineering projects as the art of *noticing, interpreting, preparing, containing, and recovering*. In resilient engineering design, the roles of SMEs, and engineering judgment and opinion, are crucial. They are directly linked

to “noticing”, “interpreting”, and even “preparing” from Kutsch’s definition.

Therefore, to address the uncertainties associated with the design of long ore passes, the research team decided to perform a technical survey of expert experiences. From technical publications and discussions with experts in the field, the team identified several SMEs from the mining industry, geotechnical consulting companies, and from universities and research organisations. Individuals with ore pass design experiences related to Australia, the United States of America, Canada, Asia (e.g. Kazakhstan, Indonesia), Chile, Sweden, and Africa (e.g. South Africa and Ghana) were invited to participate in the survey. The role of the SMEs is to support the reliability assessments within the design process [82, 85]. Owing to privacy and ethics issues, the names of, and information related to, the participants will remain confidential.

1.3 Search Methodology

In pursuit of pertinent literature and engagement with subject matter experts, we executed a meticulous research initiative. Beyond a rudimentary query on “Google Scholar (<https://scholar.google.com.au/>)”, our investigation encompassed an exhaustive exploration of publication repositories affiliated with prominent research organisations, esteemed universities, and authoritative agencies dedicated to the realms of mining geomechanics and mine design. The list of these distinguished repositories is presented in the [Appendix](#) of this paper. Our quest for knowledge was also executed through meticulous keyword-based searches, encompassing terms such as “Ore pass”, “Orepass”, “Ore drive”, “Oredrive”, “Rock pass”, “Rockpass”, “Waste pass”, and “Wastepass”.

This endeavour was undertaken to assemble a comprehensive foundation of literature and expertise, ensuring the highest degree of rigor and relevance in our pursuit of advancements in ore pass design. This process of investigation yielded the initial identification of a roster comprising 22 SMEs, a number that was subsequently augmented to encompass a total of 40 SMEs through consultations with field-specific specialists. Subsequently, invitations for survey participation were extended to this comprehensive cohort of 40 SMEs, garnering enthusiastic responses from 25 experts who actively engaged in the survey.

The researchers posed 39 questions related to the effective operational and design, geological, and geotechnical parameters. These questions are listed in the appendix (Supplementary Data). It is also noted that the principles suggested by Kitchenham and Pfleeger for building the questionnaire and the collection, processing, and interpretation of the survey data were used to ensure that we have minimised the biases involved in the survey [86–91]. A few of the principles considered in this study include,

but were not limited, to using clear and neutral language to ensure that the survey questions are clear, unbiased, and written in neutral language; performing a pilot testing of the survey with a small group to identify and rectify any potential issues with the wording of the questions or survey design; balancing response scales to prevent acquiescence bias (tendency to agree with statements) or extreme response bias (tendency to choose extreme responses) and including both positive and negative statements to gauge a more accurate sentiment; ensuring the respondent anonymity so, the participant may provide their answers, freely, when they know their responses cannot be traced back to them; keeping the survey reasonably short to reduce respondent fatigue, which can lead to careless or biased responses; including demographic questions, when appropriate, to avoid influencing responses to other questions based on demographics; conducting pre-tests and post-tests to evaluate whether the survey instrument introduced any bias or influenced respondents’ opinions; aiming at transparency by clearly communicating the purpose of the survey, who is conducting it, and how the data will be used to build respondent trust and reduce response bias; and continuously monitor and analyse responses during data collection to detect any potential sources of bias and address them promptly.

The survey for the research project was approved by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) Social and Interdisciplinary Science Human Research Ethics Committee (ethics clearance 066/21) as well as CSIRO Privacy (Privacy Threshold Assessment (PTA) Approval — granted on 07-03-22) to ensure that the research study does not involve any ethics or privacy issues before the distribution to the participants.

The anonymous survey was conducted from March 21, 2022, and following the CSIRO ethical and privacy regulations, it remained accessible for a duration of nearly 2 weeks, concluding on April 7, 2022. Microsoft Forms was used to perform the survey and around 40 individuals with significant (over a decade to several decades) experiences, in mining and geotechnical engineering, from several different disciplines: research, engineering consulting, and operations were invited to attend the survey. The research team aimed to achieve about $n = 30$ separate responses so that, based on the central limit theorem of statistics, the distribution of the sample mean, $\bar{x}_n$, is approximated to a normal distribution. However, in most cases, the normal approximation can be valid for sample sizes greater than five experts [92].

The expert rated the parameters in each question as being 1, not very critical; 2, critical; and 3, very critical in their experience. No definitions of criticality were provided, and the experts were free to make their own judgments. The data was analysed by taking averages of all the data, as well as their variations to investigate any potential biases.

2 Results of Expert Elicitation

2.1 Demographics

Subject matter experts are specialised individuals, such as mining and geotechnical engineers, who provide deep knowledge and expertise in specific aspects (here underground mining and long ore pass design). They play a key role in identifying vulnerabilities of long and ultra-long ore passes and suggesting strategies based on their specific knowledge to mitigate and control any exposed risk. Expert opinions come from experienced professionals who offer recommendations informed by their extensive practical and theoretical understanding of engineering principles [82, 93]. These opinions help in complex decision-making, especially in situations where established guidelines are lacking, such as the subject of this study which is the design,

implementation, operation, and maintenance of long ore passes [94].

At the same time, this means that there are a limited set of such experts in the field, and who have the time to contribute to such a study. Pleasingly, twenty-five experts provided their time (about half an hour per survey), slightly below the desired 30, but well above the lower bound of 5 required by [92]. Most of the participants indicated that their experiences are related to ore pass design either in Australia or South Africa, accounting for 60% of the participants' experiences as shown in Fig. 5. Mining and geotechnical engineers self-identifying as being from industry accounted for 60%, consulting engineers 20%, and universities and research organisations 20% of the disciplines as can be seen in Fig. 6. Thus, the range of experts, providing experience from many different areas around the world, different geologies and geotechnical conditions, and mining methods and different

Fig. 5 Locations of the related experiences of the participants (in %)

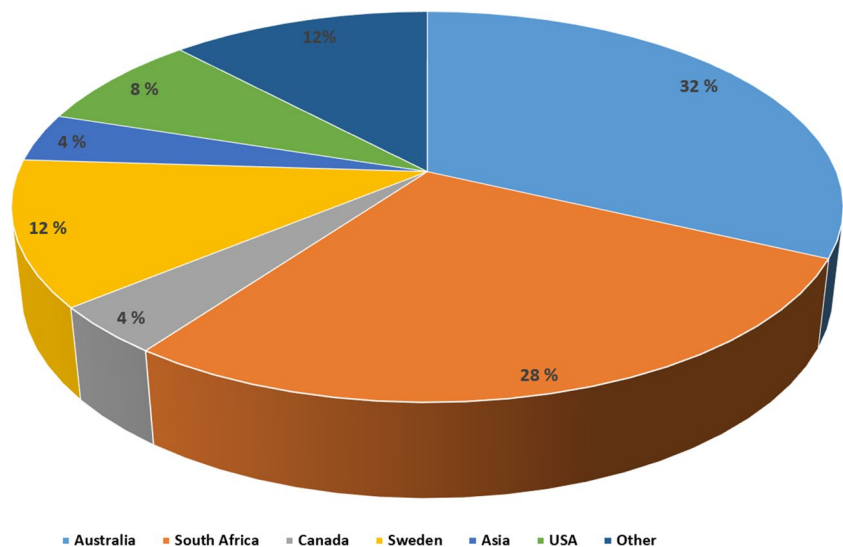
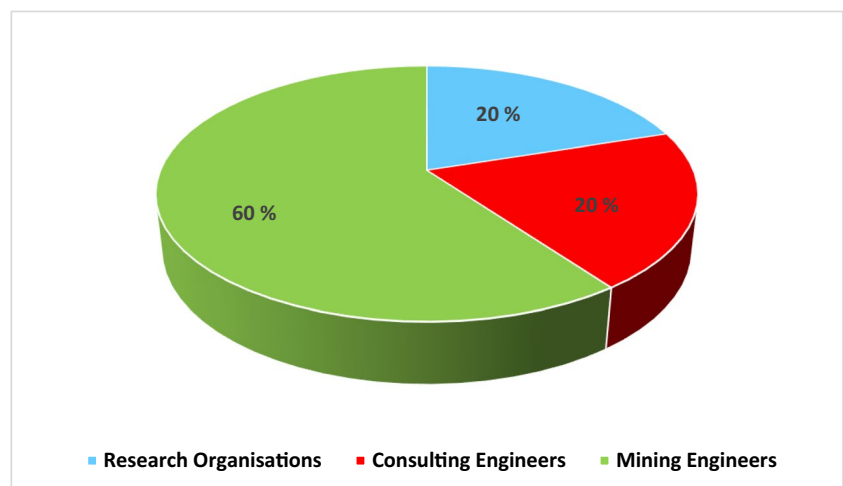


Fig. 6 Field of work of the participants



disciplines, is considered sufficient to ensure minimal bias as per [86, 87].

Several interesting results can be determined from the data that was gathered from the survey. From the analyses, the results showed that the country and location of the experience do not appear to have a significant effect on how they selected their answers. This assessment is based on the analysis of the respondents with related experiences in Australia and South Africa because these two groups account for 60% of the respondents.

It is also noted that throughout the remainder of the study, for simplicity, participants from the universities and research institutes are referred to as “Research Organisations”, those from the mining industry are referred to as “Mining Engineers”, and respondents from consulting firms are referred to as “Consulting Engineers”.

2.2 Average Ratings

The initial analysis was focused on the average ratings for the effective operational and design, geological, and geotechnical parameters for different groups. The average ratings related to the operational and design parameters are shown in Fig. 7. Priorities for design and operational parameters

(see Fig. 7) showed that the most important parameters were the “length, induced stresses due to other adjacent mining activities, orientation, cross-section shape, dimension of the ore passes”, and then “blast fragmentation”. Since the goal of this research study is to investigate the feasibility of implementing long ore passes, it was interesting to observe that the experts have independently identified length as the most critical design and operational factor in the design of ore passes.

Figure 8 also shows the average ratings related to different geological parameters. The “Faulting, folding and large-scale structure” was identified as the most critical geological factor that can affect the design of ore passes. “Underground water regime and the excavation condition (e.g., dry, humid, and wet)”, and the “Mineralogy of the orebody, clay content, and water sensitivity, and swelling potential” are the other critical geological factors (see Fig. 8).

The average ratings related to the effective geotechnical factors are also shown in Fig. 9. From the results, the most important geotechnical factor was found to be the “Types of the rock mass around the ore passes”. The “Joints dips and dip direction” and the “Strength of the intact rocks” were also identified as the other very critical factors to be included in the design of long ore passes (see Fig. 9). This once again

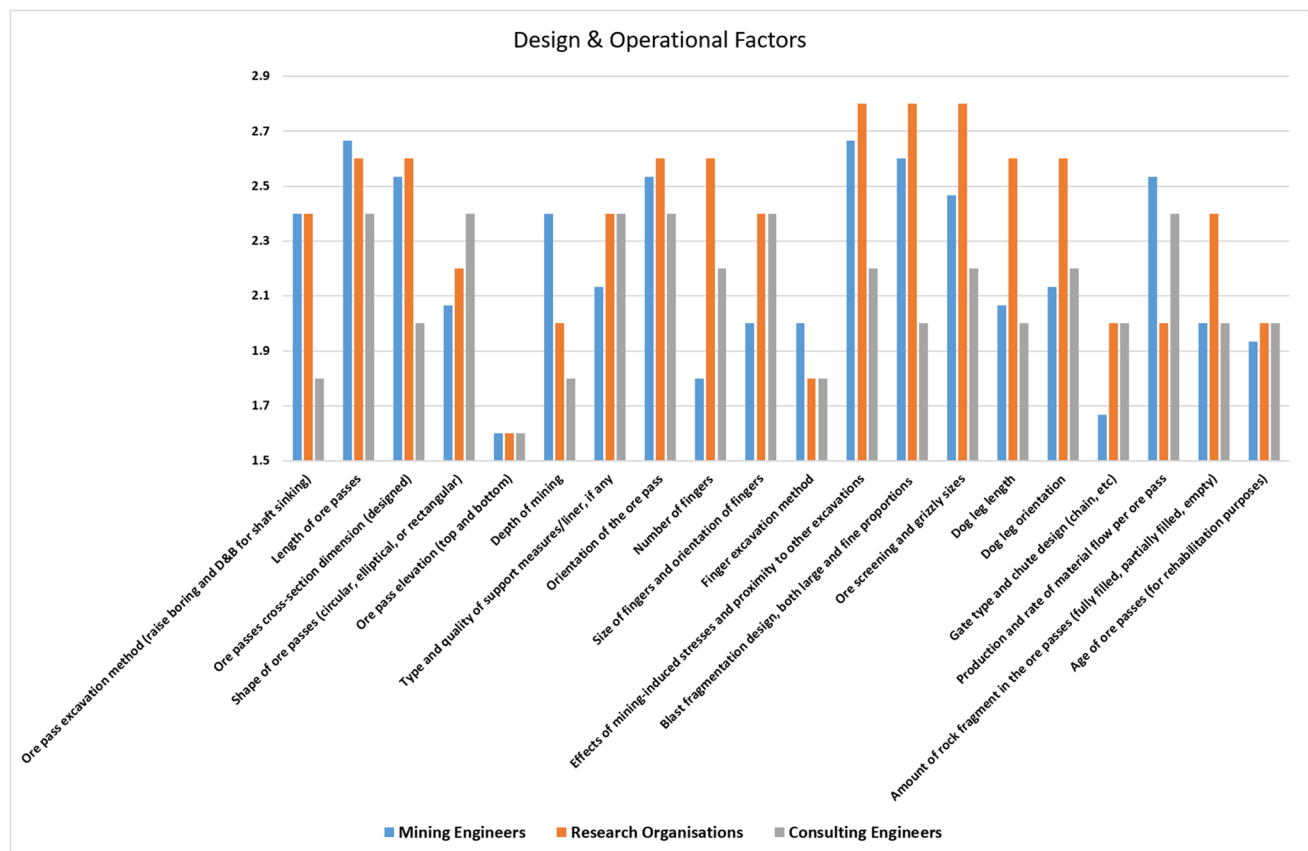


Fig. 7 Comparing the average ratings related to the design and operational factors (1, not very critical; 2, critical; and 3, very critical)

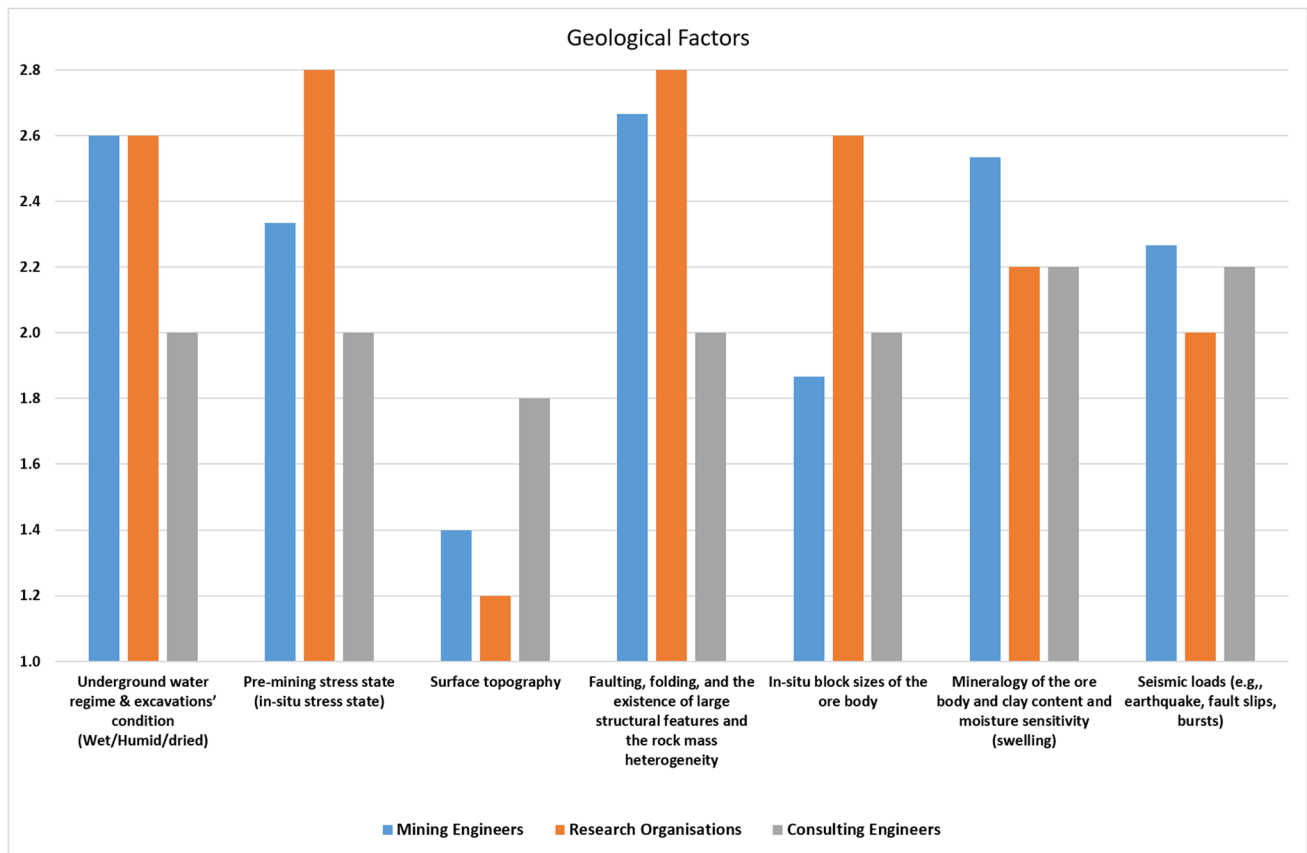


Fig. 8 Comparing the average ratings related to the geological factors

is well aligned with the prior research which stated that the types of rock mass and its mechanical behaviour are very important for the design of long ore passes [11, 16, 39, 71]. It is also noted that the rock mass behaviour is controlled by both discontinuities and intact rock properties, and a decent characterisation of these factors is essential for the design of long ore passes for long-term operations [47, 95, 96].

It is notable that the crucial factors depicted in Fig. 7, Fig. 8, and Fig. 9 were discerned through an extensive literature review focused on ore pass design and optimisation. Additional information regarding the literature review can be found elsewhere [60, 97] and will not be reiterated here. Subsequently, these factors underwent review and refinement by a team of three SMEs before being incorporated into the survey. To ensure thoroughness, participants were prompted to identify any additional critical factors that may have been overlooked.

It is also noted that the review performed by Hadjigeorgiou and Stacey [15] revealed that several of the ore pass issues are common in active mines in Canada and South Africa. The problems may, however, have varying degrees of severity. The reason for some issues is that the design procedure has not been comprehensive enough to account for

the effects of all critical factors governing the stability and functionality of the ore passes. Some of the main factors that must be considered in the design of ore passes include the geological and geotechnical characteristics of rock masses (e.g. the rock structures, and the rock mass strength); the in situ stress state, and the dynamic mining-induced stress field; the condition of underground water; the fragmentation of the ore materials and consequently the sizes of rock particles; the wear and deterioration of the liner and the rocks due to the abrasive flow of the ores; and the impact of the dynamic and static loads that are applied by the gravity flow of the ore materials [8, 39, 56, 98]. These well confirm the outcomes of the survey.

The results of the survey also showed that there is a consensus from the experts that the main cause of concern with the use of long ore passes is that “Damage that can be caused to the walls”. This is consistent with the findings of other scholars in this field [10, 16, 17]. The second most important concern was with the “formation of hang-ups in the ore pass” with “cohesive hang-ups” being given slightly higher importance compared to “interlocking hang-ups”. The full order based on the average value assigned can be seen in Fig. 10. Note that the definitions of the ratings are 1, not very

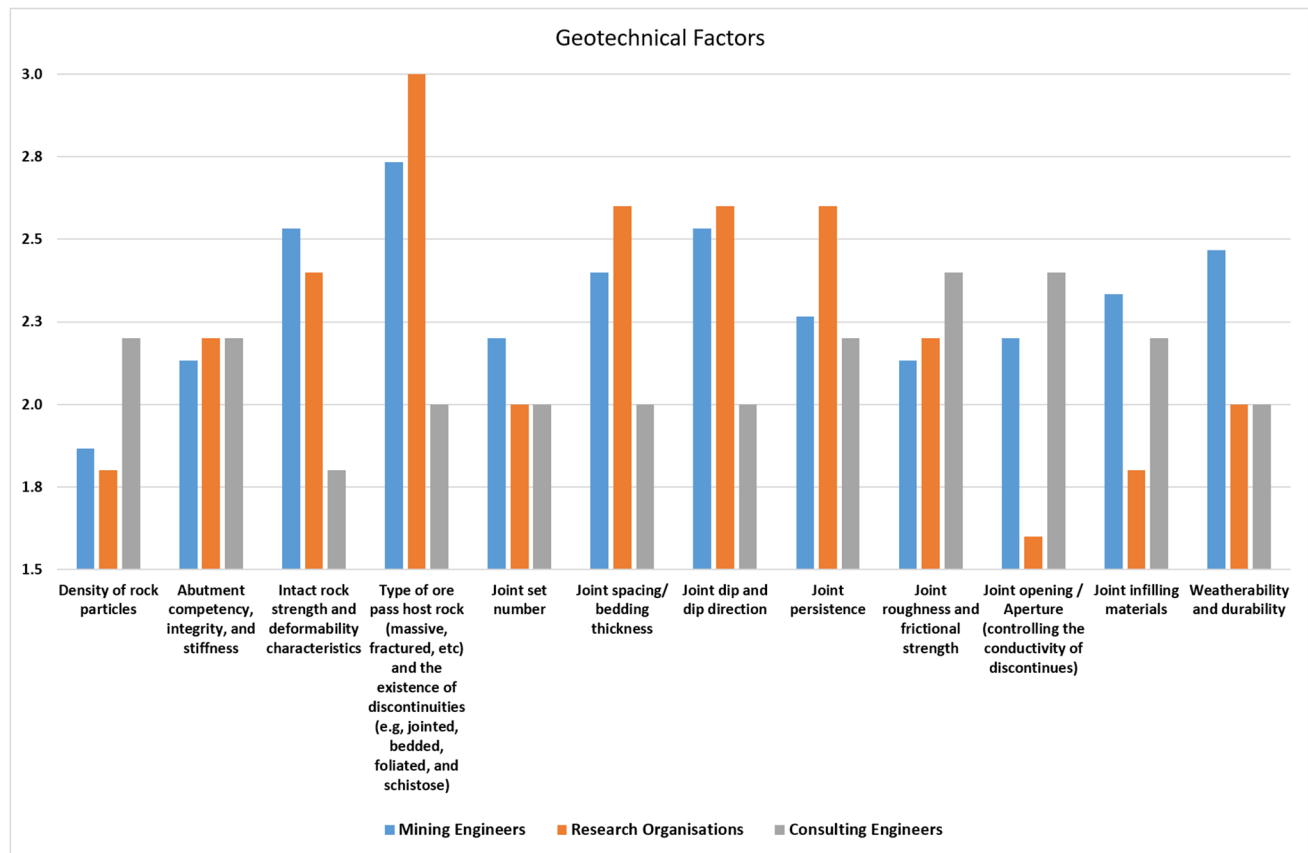


Fig. 9 Comparing the average ratings related to the geotechnical factors

critical; 2, critical; and 3, very critical. The breakdown of these average ratings per occupation has also been shown in Fig. 11. As can be seen, the average ratings are almost consistent across all different disciplines. The ratings related to responses by researchers are relatively larger than the other two groups, but this is not consistent for all 9 parameters. The average rating that consulting engineers have considered for the effects of the “deterioration of liner” is considerably higher than the counterpart rating considered by researchers and mining experts.

To further investigate the gaps in the existing methods for the design, implementation, and maintenance of ore passes, the participants were also asked to identify the areas of future research related to the design of long ore passes (see Fig. 13). This is to investigate the requirements to be able to meet the different steps of the wheels of design proposed by Stacey [99] (see Fig. 12), based on a combination of rock mechanics design [100] and strategic thinking [101], to strategically tackle the geotechnical problems associated with the design of long ore passes.

Furthermore, as depicted in Fig. 13, the average ratings across various potential areas earmarked for future research consistently fall within the range of 2 (indicating critical

importance) to 3 (signifying very critical significance). Notably, the preeminent research avenue identified by respondents as a warranting pursuit in future endeavours pertains to “A method to link the location of the ore passes to the geological and geotechnical information from the early-stage feasibility studies”. Two additional focal points emerged with equal prominence, both averaging the same criticality ratings. These encompass “identifying continuous monitoring technologies to survey the ore passes for the evaluation, hazard assessment, and rehabilitation” and “developing a comprehensive database of ore passes that can be used as a decision support tool for the design of long ore passes in different geological and geotechnical condition”. Interestingly enough, these research priorities align cohesively with various phases within the design framework developed by Stacey [99] (see Fig. 12).

Figure 14, in turn, provides a granular breakdown of these average ratings, highlighting the perceived criticality of these research areas, as assessed by a diverse cohort comprising researchers, consulting engineers, and mining professionals within the industry.

A specific question was also designed and incorporated into the survey to identify the main barriers and

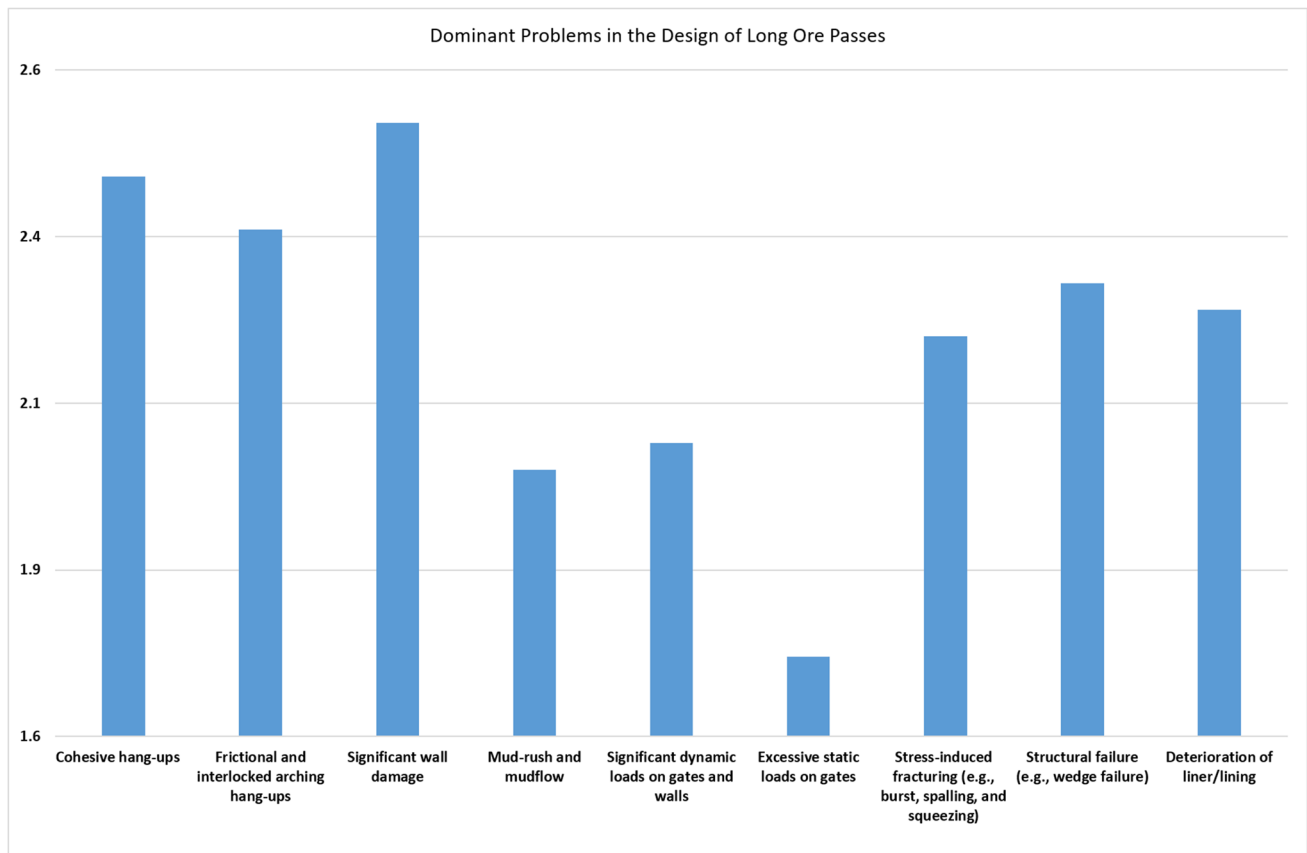


Fig. 10 Ratings for the dominant problems in the design of long ore passes

uncertainties related to the design of long ore passes. This question, which is linked to the wheel of design, targeted the problems and unknowns related to the design of long ore passes.

The participants were asked, *recalling the wheel of engineering design and with regard to the design of long ore passes (with a length above 300 m to 500 m and even to 1000 m), what do you think are the main barriers and uncertainties that shall be addressed in this research?*

The following options were provided. However, the participants were allowed to select multiple answers if they wished, and they could also add their own ideas in the space provided.

1. Data availability (geological and geotechnical) and challenges in uncertainty minimisation (stage 3 in the wheel of design) to make informed decisions about the “optimum design (step 8 in the wheel of design) of long ore passes”
2. Lack of guidelines and documented case examples of previous long ore passes’ designs and the operational aspects (e.g., keeping them fully filled, partially filled, or empty) (to help in performing steps 4&5 modelling and analysis in the wheel of design)
3. Lack of reported information related to the common geotechnical issues associated with long ore passes (to help in performing steps 5 & 6 in the wheel of design)
4. Lack of reported information related to the common operational issues associated with long ore passes (e.g., the likelihood of damage due to static and dynamic loads) (to help in performing steps 5 & 6 in the wheel of design)
5. Technical challenges associated with the inspection and surveying of the ore passes (to help in performing steps 6&7 in the wheel of design)

As can be seen in Fig. 15, seventeen experts have selected option 2 “Lack of guidelines and documented case examples of previous long ore pass designs and the operational aspects (e.g., keeping them fully filled, partially filled, or empty) (to help in performing step 4&5 modelling and analysis in the wheel of design)” as the main barrier associated with the design of long ore passes.

In addition, the first option “Data availability (geological and geotechnical) and challenges in uncertainty minimisation (stage 3 in the wheel of design) to make informed decisions about the (optimum design (step 8 in the wheel of design) of long ore passes)” was also

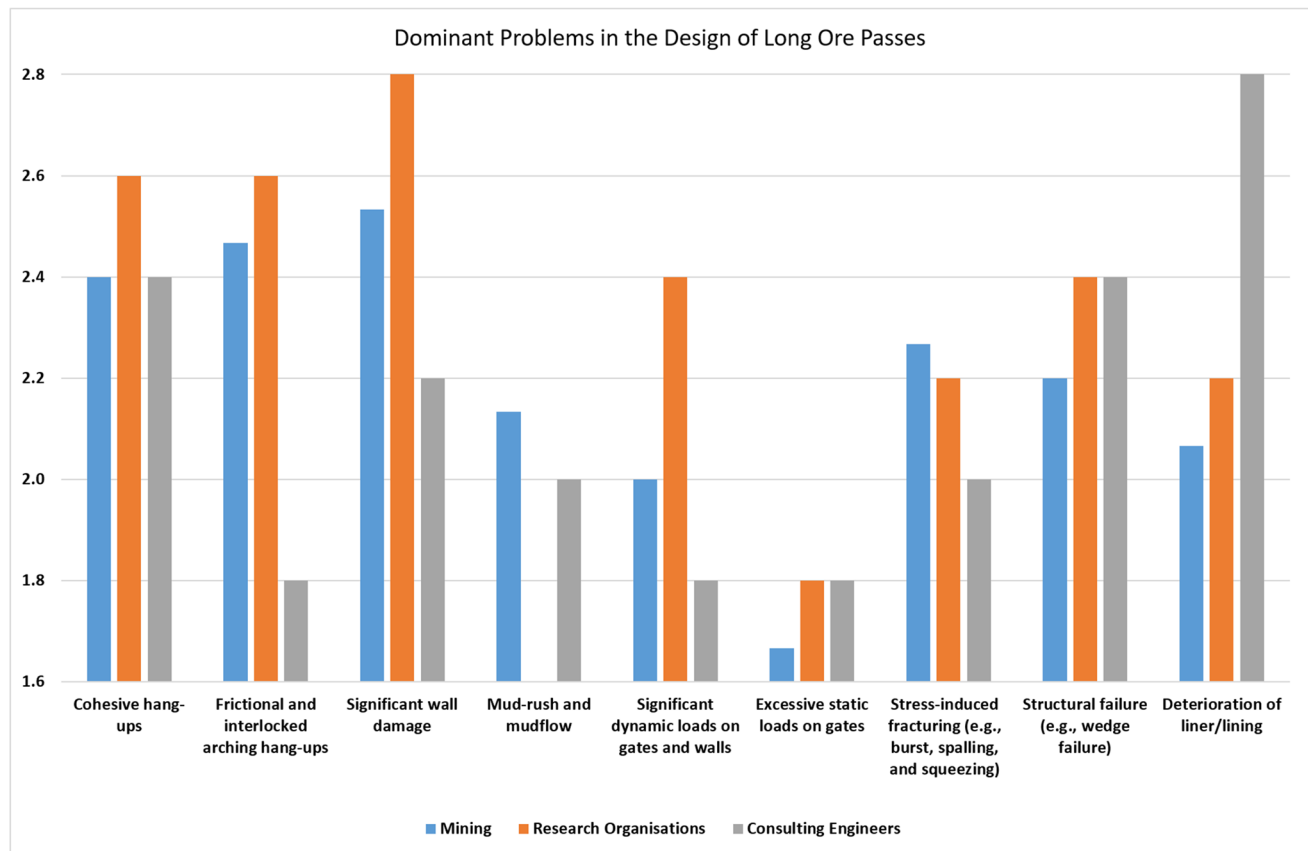


Fig. 11 Average ratings for the dominant problems in the design of long ore passes — separated per discipline

selected by 16 participants as the other critical barrier. The third critical issue was also identified as option 4, “Lack of reported information related to the common operational issues associated with long ore passes (e.g., the likelihood of damage due to static and dynamic loads) (to help in performing steps 5 & 6 in the wheel of design)”.

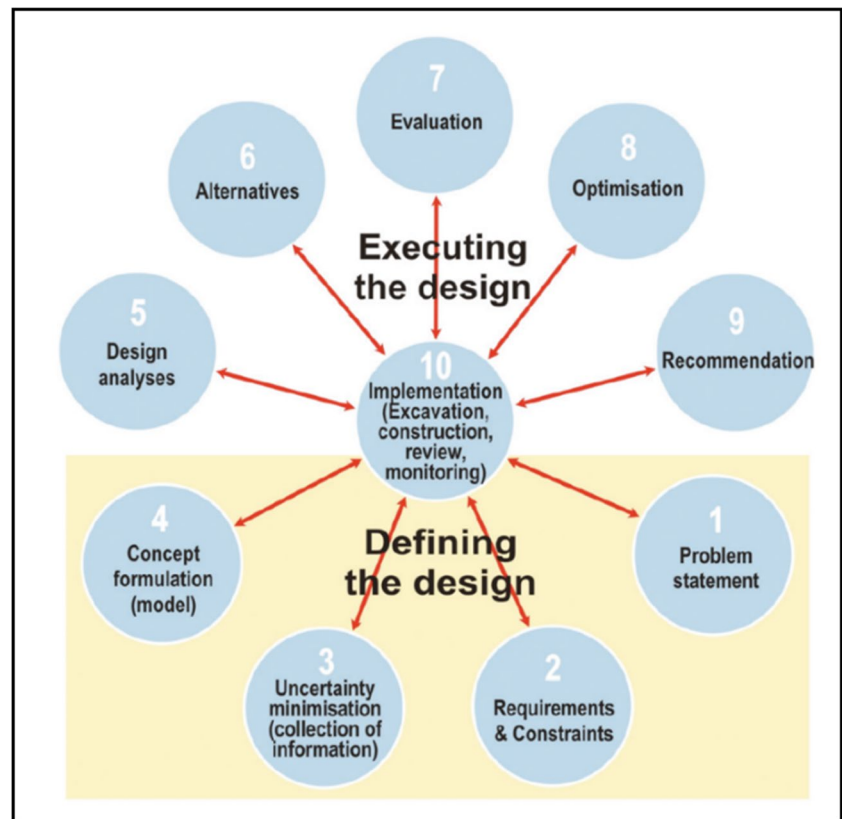
When participants were asked to identify additional barriers and uncertainties related to the design of long ore passes using the wheel of design, two critical issues emerged:

- 1- The necessity of incorporating a design that enables access to the entire length of the ore passes for subsequent firing and releasing of hang-ups, if any occur in the operation phase.
- 2- The importance of ensuring continuous material withdrawal from the passes to maintain flow and minimise the risk of blockages. This underscores the need for integrating geotechnical design with operational aspects and mine planning and scheduling.

2.3 Response Variations

For a better interpretation of the collected survey data, it might be useful to recall the “wisdom of the crowd” theory used in the economic and social sciences. The theory developed based on the work by Sir Francis Galton, an English polymath, in the Victorian era [102, 103], in the early 1900s. It indicates that the result of a specific process, where independent judgments are statistically combined (e.g. using their mean or the median), can lead to a final judgment with better accuracy. In other words, a diverse collection of independently deciding individuals is likely to make certain types of decisions and predictions better than individuals or even sometimes better than experts [104]. The approach has been used in engineering [105] and project management [106]. Bearing in mind this thesis, a mean or median of all results from different groups combined may result in much more accurate estimations for the different parameters. It is also noted that the ratings used in the previous section show the averages computed from all ratings assigned by all participants (e.g. see Fig. 7, Fig. 8, and Fig. 9), and for

Fig. 12 The wheel of design proposed by Stacey (2009) (with the permission of the author)



different fields of work (mining industry, research organisations, and consulting firms). There are some variations in the responses, and considering these variations is also essential to ensure that the results of the technical survey are applicable.

The variation related to the assigned ratings for parameters in the class of “design and operational factors” can be seen in Fig. 16: most of the ratings vary in a narrow area, and this confirms the quality of the results of the surveying data. It is also noted that apart from a few factors such as “gate type and design”, “ore pass elevation”, and “the age of ore pass”, the rest of the factors in this category have been classified as either critical (rating of 2) or very critical (rating of 3). The “elevation of the ore passes” was also identified as the least important factor in the design of ore passes and hence research will be focused elsewhere. Interestingly enough, “the finger excavation method” and “number of fingers” have also been assigned a diverse rating from 1 (non-critical) to 3 (very critical) with an average of around 2 (critical).

The variation in the ratings related to the “Geological factors” is also shown in Fig. 17. As can be seen, apart from the “surface topography”, the rest of the “geological factors” are critical (with a rating of 2) to very critical (with a rating of 3) (see Fig. 17). In addition, the rating related to the “in-situ block size distribution” has a wider range compared to

the other parameters but has an average of around 2 (critical). According to the literature, the top sizes of the particle size distribution (PSD) generated by blasting, which are also known as boulders, are governed by the “in-situ block size distribution” [107]. In situ, block size should, therefore, be key in any future design. Several research studies, funded by LKAB, have also underscored the significance of factoring in boulders and oversized fragments when evaluating the performance of long ore pass systems [27, 28, 108].

Furthermore, the variation in the ratings related to the “Geotechnical factors” is shown in Fig. 18. According to the survey data, apart from “Rock density” which has a wide rating ranging from 1 (not critical) to 3 (very critical) with an average of around 2 (critical), the other geotechnical parameters have a rating with a narrow range varying in between 2 and 3. This shows the importance of these factors and simultaneously validates the quality of the surveying data. Regarding the influence of rock density, the research investigations conducted by Van Heerden demonstrated that the density of rock particles within metalliferous mines is a key parameter governing the extent of impact damage inflicted upon the walls, supports, and liners of ore passes as a result of the tipping of rock fragments [69, 77, 109]. This parameter may, therefore, be included in any future research as well.

Figure 19 also shows the variation related to the ratings regarding the importance of the dominant issues in the

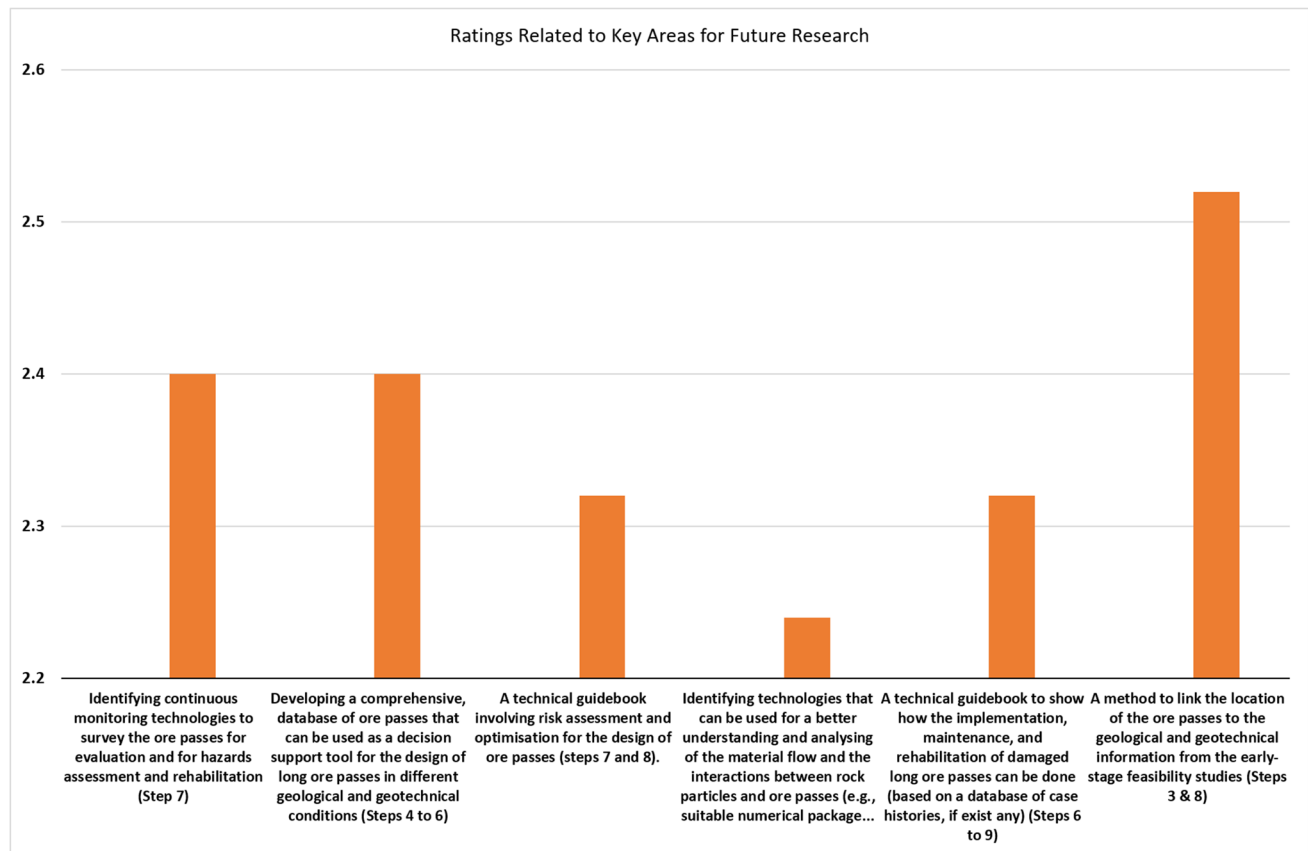


Fig. 13 Average ratings for critical areas to perform further research related to the design, implementation, and maintenance of long ore passes

design of long ore passes. As can be seen, a significant variation is seen in three of these factors “Significant dynamic loads on gates and walls”, “Stress-induced fracturing (e.g., rock burst, spalling and squeezing)”, and “Mud-rush and mudflow”. Apart from the “excessive static loads” with a narrow rating between 1 and 2, the rest of the parameters have been identified as important with narrower ratings in the order of 2 (critical) to 3 (very critical). This finding is well consistent with the key issues identified in the relevant literature [16, 17, 22, 39, 98].

When the participants were asked if the current methods of designing, constructing, and operating ore passes of 300 m+ are mature enough or if further research is needed, the respondents were unable to agree on a dominant answer. Of the respondents, 14 said that the current technologies were insufficient in dealing with the issue and 11 responded that existing protocols and procedures were sufficient for the design of long ore passes. The lack of agreement is related to a clear difference of view between the different fields. Both the research industry and consulting had 60% of respondents selected that the current protocols and procedures were sufficient. It must be borne in mind that this was a small sample size of 5 participants. The opposite was true for the respondents from the mining industry where 33% of respondents

agreed that current technologies and methodologies for the successful design and implementation of ore passes are sufficient. This was a larger sample size of 15 respondents which would reduce the chances of bias.

2.4 Additional Factors

The results of this survey can be useful for risk assessment to reduce the uncertainties in the engineering design, to determine the parameters that have first-order effects in the design of long ore passes, and to identify any other influential factor that has likely been overlooked by the design team. The subject matter experts were, therefore, asked to include any item that had been ignored in the initial analyses. A few of the participants provided some suggestions related to the other factors that should be considered as “the design and operational factors” and rated their criticality between 1 (least important) and 3 (most important). A list of these factors is seen in Table 1.

To ensure that the research team has not ignored any important factor related to the design of long ore passes, the experts were also asked to include any parameters that they think have been overlooked and have not been included in the initial investigations. They provided a list

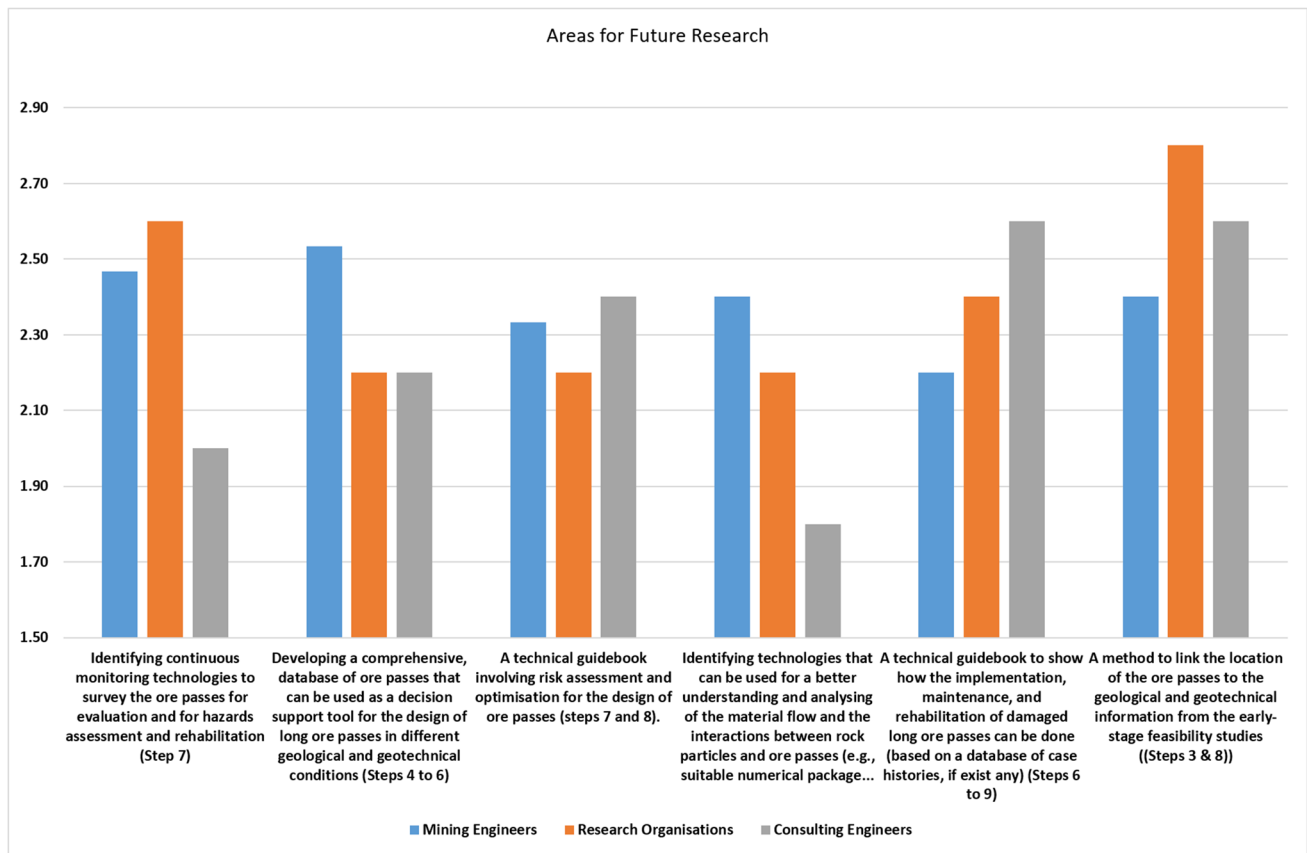


Fig. 14 Breakdown of average ratings related to critical areas to perform further research related to the design, implementation, and maintenance of long ore passes

of several interesting factors that have been summarised in Table 2. The majority of the suggested factors have already been considered in either the “operational and design” or the “geological or geotechnical parameters”. However, there are several interesting comments such as “the compaction of the particles in vertical ore passes”, the “importance of the local geology”, and the “design of gates and ensuring if they work for long ore passes”.

The experts were requested to identify additional “Geotechnical factors” to be included in the analyses (see Table 3). However, as can be seen, most of these factors have already been included in the previous group of factors such as “Design and Operational Factors”. However, the “abrasiveness” of the rock was overlooked in the initial analyses and must also be included in any future designs. This is consistent with the findings of [69].

The experts also suggested a few other critical issues that must be considered in the design of long ore passes and these suggestions have been tabulated in Table 4.

3 Discussion

Safe and efficient mining calls for the effective and smooth operation of material transfer in ore and waste passes as there are constraints in the overall operation. Resilient engineering design by creating systems that are robust and adaptable in the face of unforeseen challenges [110, 111] is needed to overcome unforeseen issues in material movement in underground mining.

Resilience in a system can be defined as the capacity to uphold necessary functionality even when faced with challenging circumstances. Unlike risk, which involves the potential for value loss due to uncertain future events [112], resilience focuses on crafting the system to uphold a predetermined level of performance after an interruption occurs [110, 111]. A key aspect of resilience is the concept of “satisficing” which means an acceptable level of functionality is the desired outcome for a system, without

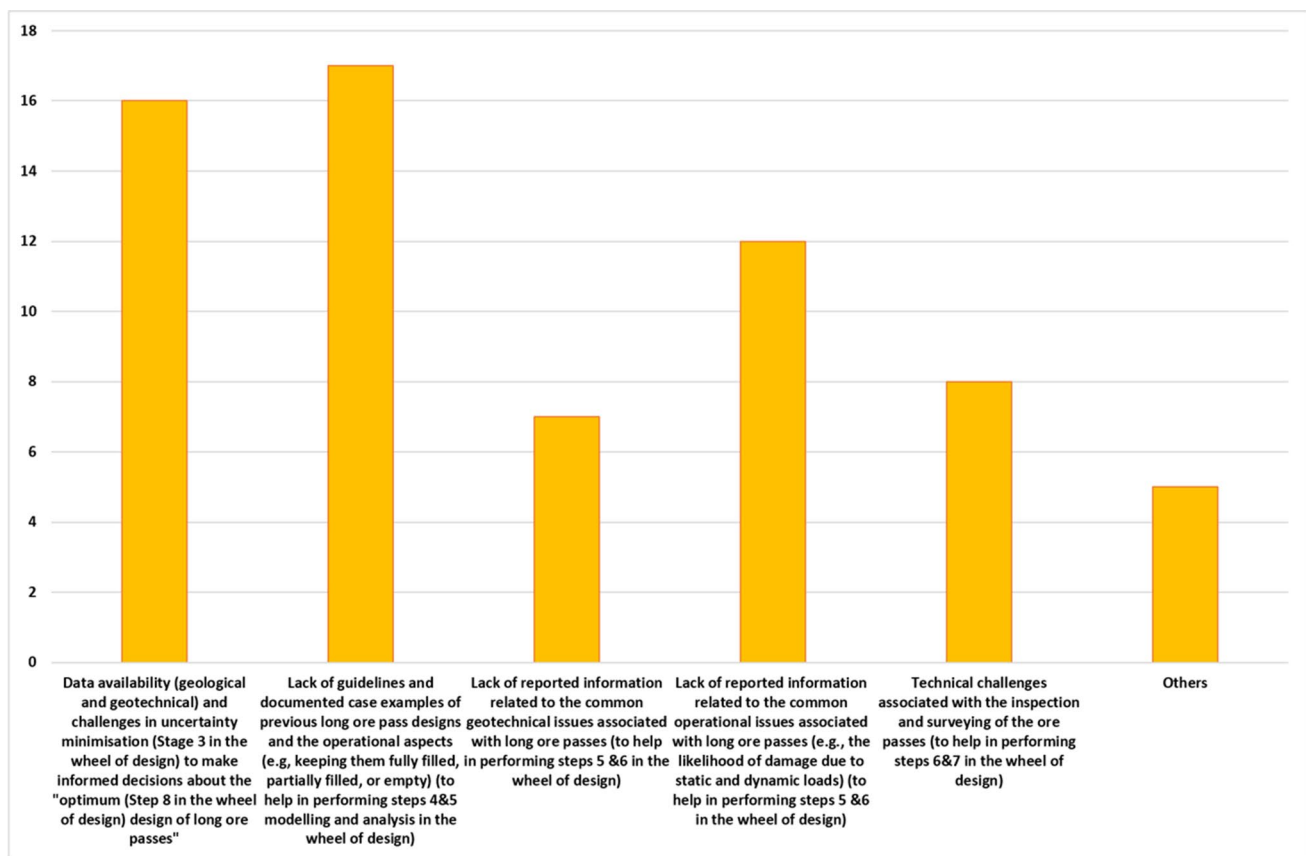


Fig. 15 The identified barriers in the design of long ore passes

an absolute need for complete restoration [113]. For example, when an interruption in the functionality of long ore passes occurs due to incidents such as hang-ups, or wear and tear of supports and liners, the capacity to identify the problem and quickly treat it, and return to functionality to meet the mine production target, which directly depends on the performance and throughput of each ore pass, is the resiliency in ore pass design.

It is also noted that engineering judgment is a crucial factor in resilient engineering design, which entails engineers using their expertise to make informed decisions when dealing with uncertainties and incomplete information (e.g. lack of reliable geotechnical information in greenfield mining projects), and trade-offs (e.g. abandoning a damaged and clogged or pass and excavating a new one or rehabilitating the old one). In ore pass design, engineering judgment helps to cover aspects like the selection of the best location for ore passes, choosing the construction methods (e.g. raise boring, Alimak raise), and hang-ups risk management while balancing cost-effectiveness, functionality, and resilience objectives [16, 29, 32, 114].

Subject matter expert experiences are most often provided as paid consulting. Collating opinions from many of these experts around the world can contribute to the development

of resilient engineering designs by consistent identification of potential risks and vulnerabilities as well as by providing specialised knowledge and insights to inform the design process. Collated expert knowledge can also provide improved technical recommendations for selecting materials and methods (e.g. method of excavation and the support method for stabilisation), and strategies (e.g. location; and number of passes, and fingers) that enhance resilience and assist in ensuring that engineering decisions are well-informed and aligned with resilience objectives. In a field such as long ore pass design, where there are limited historical examples, and yet each new implementation is a key constraint to a new mining operation, grouping these experiences and ideas can also help design engineers develop and adapt strategies to evolving challenges and uncertainties in their long ore pass projects.

In addition, finding the optimum location for ore passes in the early stages of mining, specifically in greenfield applications, where limited data is available, is a challenging task for engineers and involves significant uncertainties. The uncertainties include aleatory uncertainties, because of the variation of the rock mass properties in space and time: the rock mass characteristics could be different in different locations, and they can be affected in time due to several factors

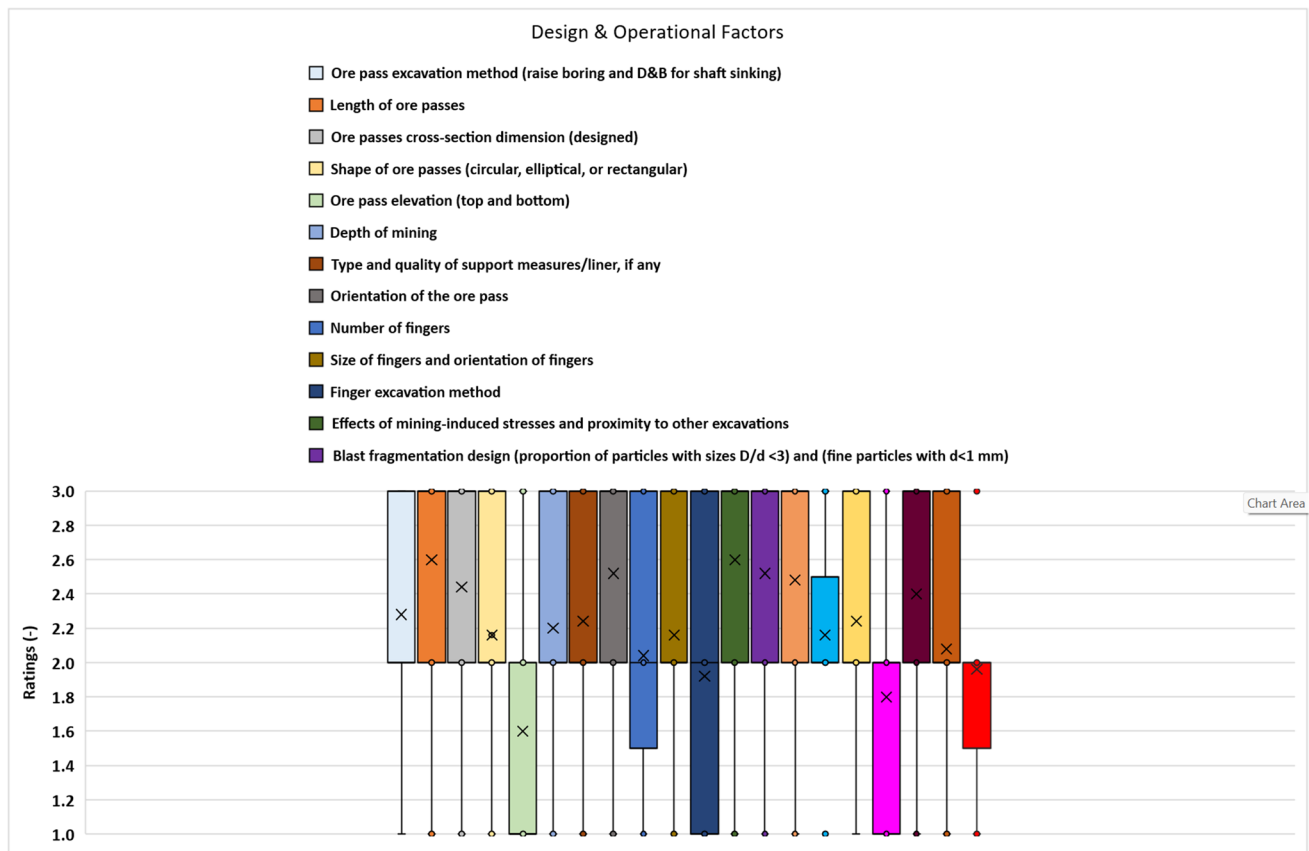


Fig. 16 Variations in the ratings related to different design and operational factors

such as mechanical damage because of impact loads, and weathering. The uncertainties also include epistemic uncertainty due to the lack of information [115]. The concept of Bayesian thinking [83, 116] is the fundamental element of adaptive management from environmental engineering [117] and “observational methods” [81, 115, 118, 119] which can help to deal with such uncertainties in long ore pass design. This approach provides a formalised version of Terzaghi’s “learn-as-you-go” method [120, 121], which allows building the framework to further collect, refine, and process the geotechnical and geological data as the construction of long ore passes begins and progresses.

Hazard and risk analysis in geotechnical engineering also generally depends on decision-making by engineers in the form of engineering judgment and expert opinion [112]. Human decision-making can, however, be flawed by the effects of heuristics and cognitive biases. The influence of these psychological factors may invalidate the results of risk assessments. Experts’ opinions should, therefore, be carefully investigated and managed to minimise any potential adverse effects [122]. Ramsey [123] was perhaps the first person to discover and develop subjective probability, which is also known as the Bayesian view of probability.

The concept is widely used in risk assessment. In brief, the subjective view of probability can be expressed in terms of “degrees of belief”. According to this Bayesian or subjective view of probability, probabilities are not an objective property of the real world. Instead, probabilities are simply the subjective expression of one’s personal view of the world. In other words, the probability of a particular proposition being true is just a particular individual’s degree of belief in the truth of that proposition [124]. Bearing in mind such matters helps to better interpret the result of a survey of SMEs.

In this study, contrary to the lack of effect that the experience or location had on responses, it seems that the field of work had a small effect on how each expert responded. The results show that different occupations (researchers, consultant engineers, and industry experts) may have different ideas for the same problem. Understanding each perspective can help to draw a larger picture and ensure that the overall results are not biased. A study of Fig. 7, Fig. 8, and Fig. 9 indicates that the average ratings for several of the effective parameters assigned by consulting engineers are slightly lower than the other two groups of researchers and mining engineers. However, this is not consistent across all the effective factors. Possibly, consultants are willing to

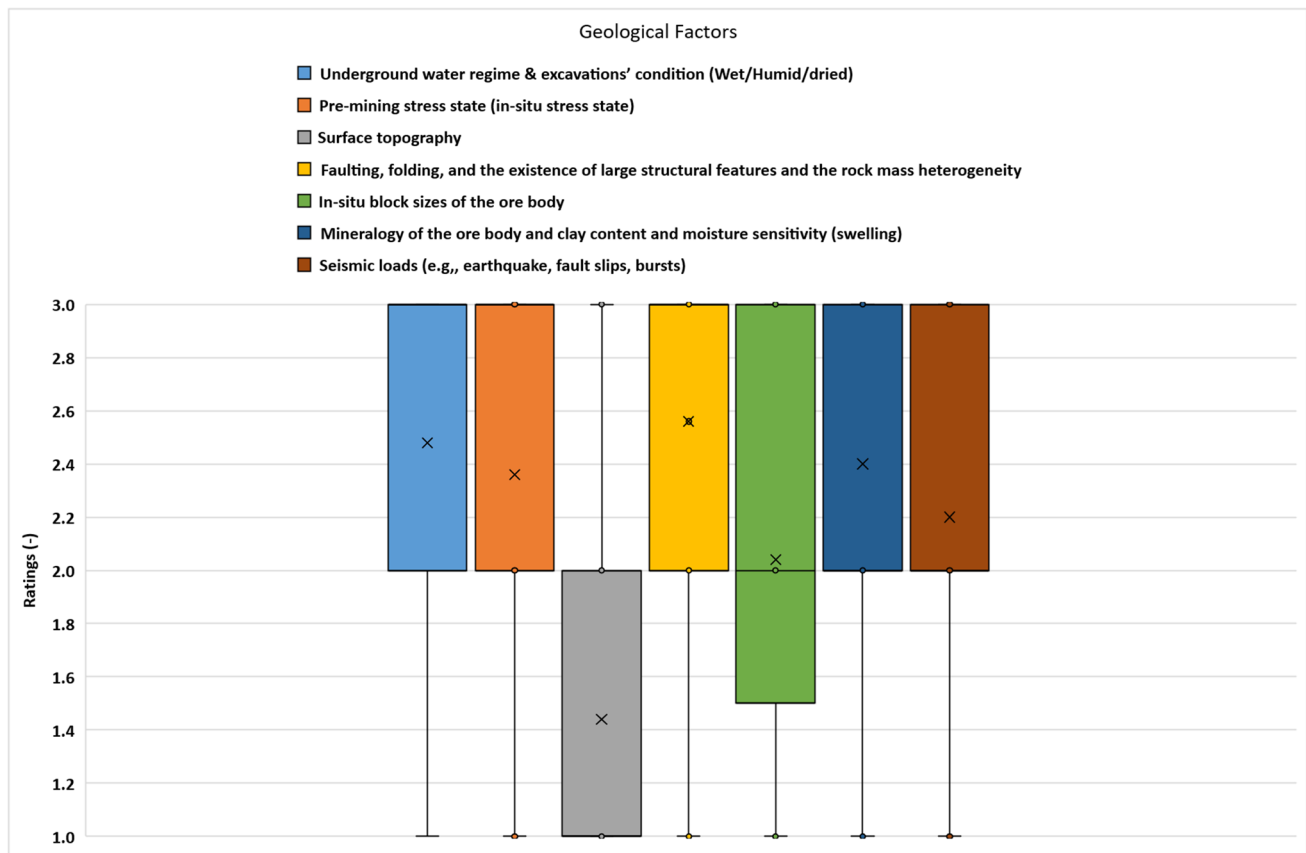


Fig. 17 Variations in the ratings related to the geological factors

take more risks than their counterparts. This assumption stems from their lower willingness to rank more factors as less critical, or it shows that there is more confidence in the current technologies (available for the design, implementation, and maintenance of long ore passes) than in the other occupations. This might also be because of the requirements of operational engineers to make decisions with existing information and may reflect a slight bias in these results due to the relatively low number of research and consulting participants. It is also noted that researchers have assigned the highest average rankings against the effective factors for most of the parameters. But, similarly, this is not consistent across all 39 questions related to the effective operational and design, geological, and geotechnical parameters (see Fig. 7, Fig. 8, and Fig. 9).

Overall, the difference between the average ratings does not seem to be very sharp and the average ratings computed from all the allocated ratings are almost consistent in these three different groups. This consistency validates the quality of the results. As the opinions are not very different, there is no need to isolate each occupation for future studies to determine the impact of the factors. Interestingly enough, all the key factors (*from the three groups of*

design and operation parameters, geological factors, and geotechnical factors) identified from the technical survey were consistent with the previous desktop study conducted earlier [38]. This means that the results of the expert survey confirm the research knowledge gained from the gap analysis and vice versa.

The information collected from the technical survey shows that all the key parameters must be carefully investigated to understand how they will affect the long ore passes in the design, planning, construction, and operation phases. This means that having access to reliable and accurate data is a critical part of the ore pass design and construction, especially for long ore passes. These data can be collected from the initial exploration phases and gradually refined and improved as the developments/accesses are excavated. The process of the design of long ore passes should, therefore, be dynamic, as the wheel of design suggests, and the design shall be improved and amended as further geological and geotechnical data are collected. This is also consistent with the observational method proposed by experts in geotechnical risk assessment [82, 83, 117, 125].

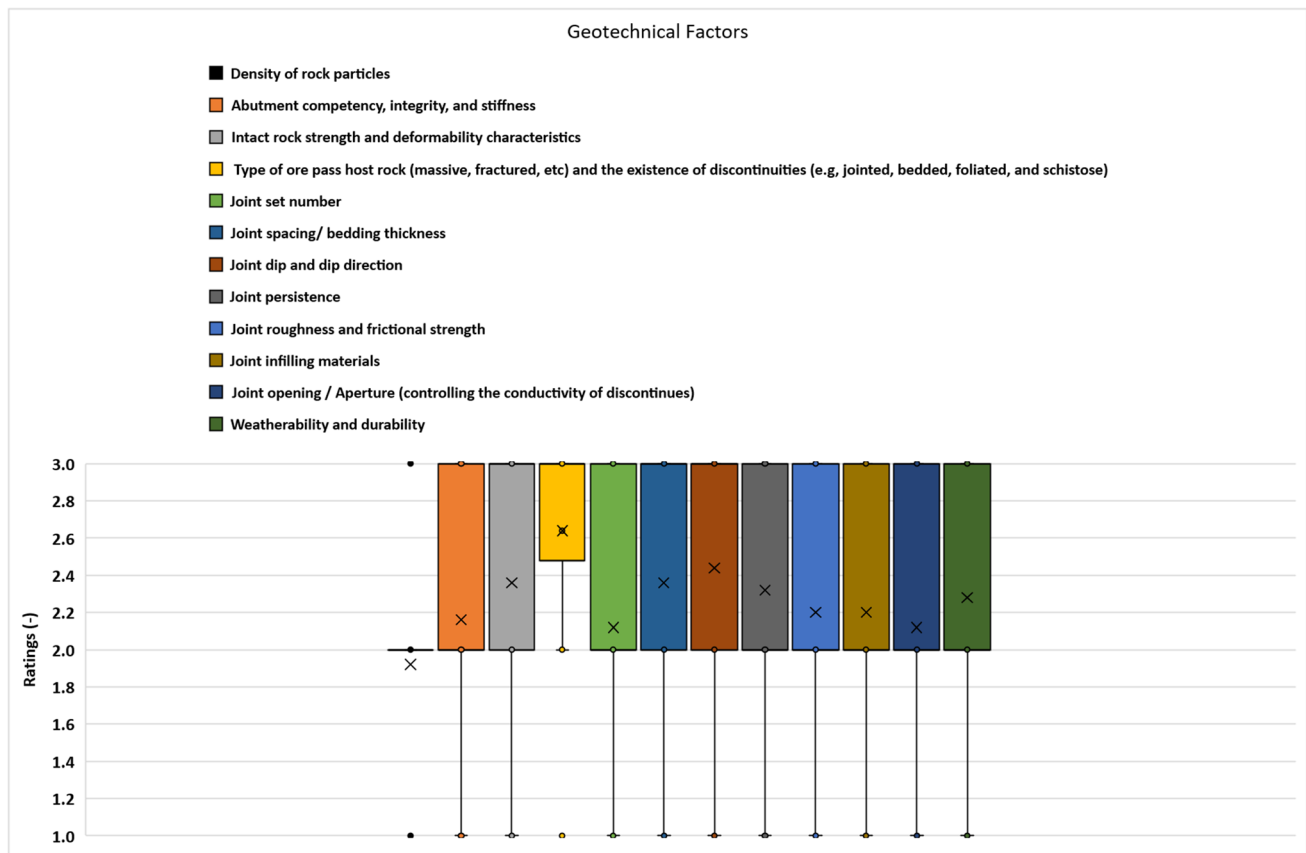


Fig. 18 Variations in the ratings related to the geotechnical factors

4 Conclusions and Recommendations

The application of long ore passes may be a potential solution for mining companies to reduce the developments and the sizes of the developments needed for underground mining, and the machinery needed for the transport of ore and waste from the stopes to the surface. This can also help mining companies reduce energy consumption and the emissions associated with material handling.

As the lengths of ore passes increase, the likelihood that they pass through weak geological formations or intersect faults and large discontinuities also increases. The magnitude of dynamic and static loads affecting the ore pass walls and the gates may 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 main objective of this paper was, therefore, to describe a comprehensive gap analysis on the methodologies that are used for the design of ore passes, specifically, long ore passes, and to conduct a desktop study to identify the critical risk factors that must be considered in the design of long ore passes. The gap analysis indicated that

the concept of the wheel of design [99], which is also the backbone of the recently proposed quantified value-created process (QVP) [29], can provide engineers with a powerful tool for the strategic design of long ore passes.

This research, therefore, thoroughly explored the literature on ore pass design. It aimed to uncover the latest and most effective techniques used in designing these crucial rock structures. Along the way, we also pinpointed the shortcomings of current methods and identified areas where improvements can be made.

The research team also performed a comprehensive technical survey to engage SMEs in identifying and ranking key factors. Such data are needed for the development of a methodology for the design of long ore passes in complex geological and geotechnical conditions, specifically in greenfield applications where limited data is available. The outcomes of the comprehensive gap analysis showed that there is very little information documented and available about the design of long ore passes (with a length above 300 to 500 m and approaching 1000 m). To address this issue, the research team conducted a technical survey of the subject matter experts, from all around the world, to identify the main risk factors in the design of long ore

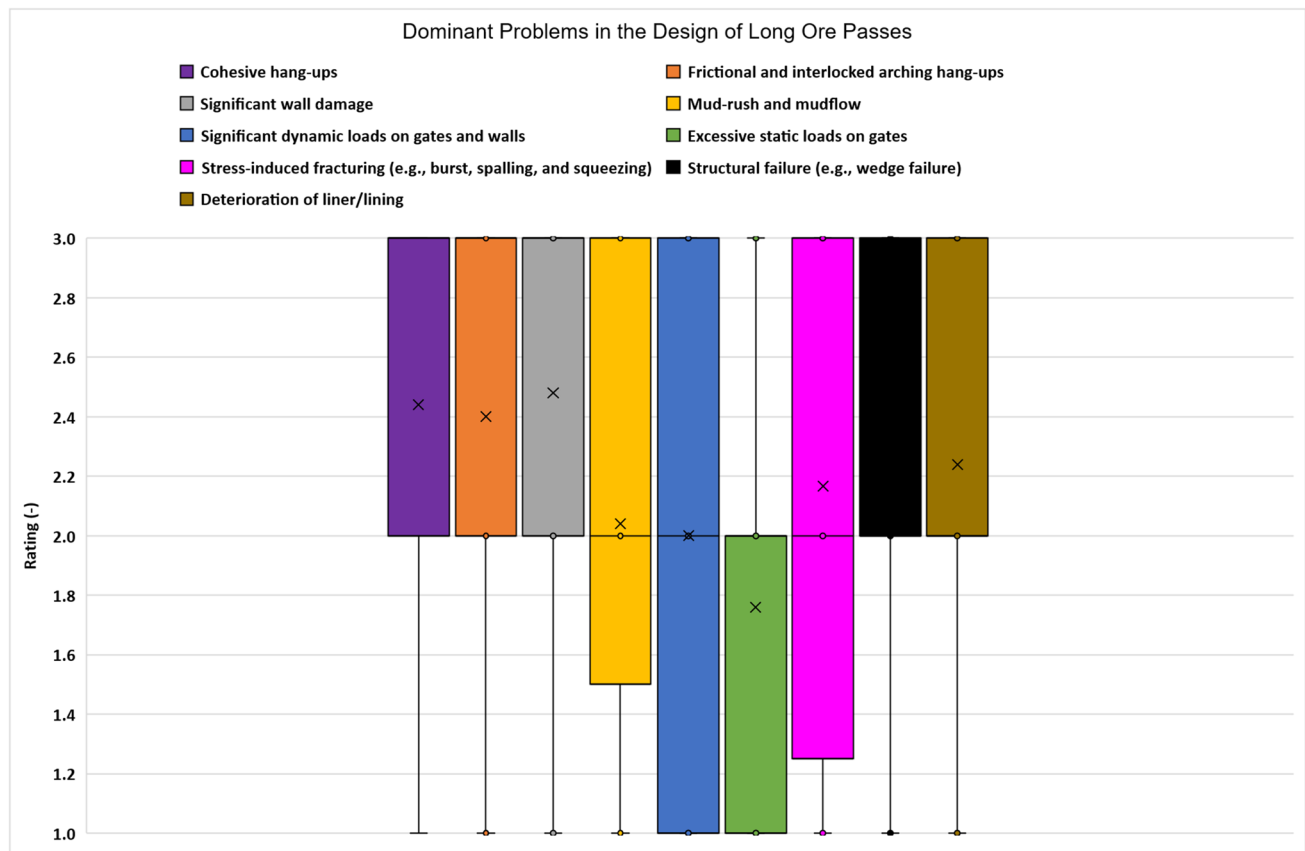


Fig. 19 Variation in the ratings related to the dominant problems in the design of long ore passes (all responses)

Table 1 List of operational and design and operational factors suggested by experts

No.	Parameter	Rating
1	If drill and blast is considered as a method of excavation (bad/ideal for long ore passes), then ventilation and inspection are critical items to plan	(3)
2	When the ore pass is long, the chance of intercepting a weak/highly fractured ground condition will be increased. This is problematic as the failure can initiate from the weaker zone and can propagate to the stronger ground conditions	(3)
3	Proximity to mined-out voids and excessive stress concentrations are critical	(3)
4	Preventing water from entering pass systems as much as possible unless to try to release hang-up	(-)
5	Design inspection holes to monitor passes and place concussion bombs if required	(-)
6	The age of the ore pass in terms of throughput is critical	(-)
7	More criteria around material flowing through the pass (PDS, clay content, abrasiveness, etc.) are needed	(-)

passes. We then took a practical step forward by surveying experts in the field to compile a comprehensive list of the key factors that matter most in the resilient design of long ore passes and the main risks involved.

From the survey, several pieces of information were found that have been confirmed to be correct and critical to the design of long ore passes. Several critical factors grouped into the “design and operational”, “geological”,

and “geotechnical” factors were identified and rated in terms of their criticality by the experts.

When looking at the results, it became evident that there are some very slight trends in the responses from the survey depending on the occupation of the respondents. Respondents from consulting companies are relatively likely to put less importance on design and geological and geotechnical factors and researchers put the most importance on them.

Table 2 A list of other critical factors identified by experts and their ratings

No.	Parameter	Rating
1	Alignment and orientation relative to the geological layering and structures	(-)
2	Accuracy of mechanical development of the long ore passes	(-)
3	Planning and considering an inspection raise could be very useful. This raise will allow access in case of hang-ups where the distance between levels is high. It is also important if the ore pass has planned to be straight or bended	(-)
4	The importance of rating can vary from one case to another based on local geological and operational conditions. For example, the size distribution of material that is dumped into the ore pass, the inclination angle of the ore pass, etc. are critical but could have different impacts in different cases.	(-)
5	For designs of such length (500 to 1000 m), one may not use chutes or feeders at the base but an open hole that is never opened to avoid issues	(-)
6	Structure-induced fracturing	(3)
7	Remediation-induced wall damage	(2)
8	Ore passes infeed (finger rises) — installation-induced wall damage	(2)
9	Deterioration of rock support	(3)
10	The angle of the pass is critical. Vertical passes compact and hang up more. Passes should be angled 10 to 15° off vertical so that material “rolls” down or slides down the footwall of the ore pass	(-)
11	Abrasion and impact loading of fractured or geologically disturbed rock. The greater the length, the greater the velocity of rocks falling down the ore pass	(3)
12	The proximity of ore passes to one another and other excavations	(3)
13	Orientation of ore passes relative to major principal stress orientation	(3)
14	Angle of inclination	(3)
15	Maximum particle sizing	(3)
16	% fines < 20 mm	(3)
17	“Air cushion” in the raise — a result of vertical ore passes	(-)

Table 3 List of geotechnical factors suggested by experts

No.	Parameters	Rating
1	Stress conditions associated with mining abutments	(-)
2	Mining-induced stress	(3)
3	The abrasiveness of rock passing through the ore passes	(-)
4	Induced stress (e.g. destressed, or concentrated (pillar-abutment) stress conditions)	(3)
5	The shape of rock fragments	(3)
6	The density and hardness of rock fragments	(3)

Table 4 A list of other critical issues identified by experts

No.	Factors
1	The need for access to the entire length to later fire hang-ups is critical
2	All of the above (geological, geotechnical, design, etc.) parameters contribute to uncertainty, but keeping the ore pass near full can help to avoid dynamic loading of facilities below and the walls
3	Rock fragment size versus ore pass diameter is critical
4	Technical challenges associated with the clearing of blockages and the rehabilitation of damaged ore passes must also be considered in the design phase

However, this was not a consistent trend in all responses. Nevertheless, the analysis showed that these biases related to the occupation are very minor and can be overlooked. In addition, the theory of the “wisdom of crowds” implies that the mean or median of the combined ratings could be a much better estimation of the criticality of the parameters.

Several key research barriers were also identified through the survey process. The most critical of these was identified as the lack of clear guidelines that are in place for designing and building long ore passes. This information is key to identifying how any future research in this area should be implemented. The second barrier was identified as the lack of data that is available when making decisions regarding the construction of long ore passes for SLC. This lack of data was brought up often by the respondents, especially regarding the identification of the best ore pass locations and the geological and geotechnical information required for the assessment of the potential of raise boring and stability analysis. These will be difficult tasks for geotechnical and mining engineers to undertake due to the length and consideration that would need to be made during the planning process of the long ore pass. The inspection of ore passes of such lengths and having access for the removal of any blockages are the other key factors to be considered when designing long ore passes.

There was also interest from some participants in expanding the work to include ore passes that are < 300 m long. This interest can be assumed to be generated by a lack of guidelines or standards for ore pass construction, in general, which has also previously been identified by other scholars [15]. Considering how the length is a key factor to ore pass life span, any information found to assist in long ore pass design would be relevant to shorter ore pass design as well.

Following this survey, the information can be used to carry out a second survey where the knowledge can be narrowed down to further determine the approaches that should be taken to implement the guidelines for ore passes of such length. It would also be beneficial to conduct research into the optimisation of the location of ore passes regarding the shape of the ore body, and the geology and geomechanics of the area. It might also be helpful to develop a database of ore passes to see what methods different mines have used for the design, implementation, operation, inspection, and maintenance of their ore passes to further expand the work initiated by Joughin and Stacey [35], Lessard and Hadjigeorgiou [36], and Hadjigeorgiou et al. [37]

The survey can be considered successful, since the main goals were achieved, and a better understanding of the main effective factors and risks associated with the construction and management of ore passes was gained. The participants also identified several research areas to focus on, which could be an opportunity for researchers and consulting engineers. The main issues were also identified, the most critical being data availability for ore pass planning and a clear set of design guidelines and standards for long ore pass construction. This analysis provides the mining industry with valuable insights to develop strategies for controlling and mitigating the risks, based on a thorough cost-benefit analysis. Ultimately, our research aimed at fusing the data available in the literature with experts' opinions to identify the key effective factors and the main risks in the design of long ore passes for deep mass mining operations to overcome the lack of information and enhance the efficiency and safety of these structures and the bring the resiliency into the engineering design.

Appendix

List of repositories considered for search to find SMEs and related publications on ore pass design

Australasian Institute of Mining and Metallurgy (website, <https://www.ausimm.com/>)

Australian Centre for Geomechanics (website, <https://papers.acg.uwa.edu.au/>)

Canadian Institute of Mining, Metallurgy, and Petroleum and CIM Journal (website, <https://www.cim.org/library/cim-journal/cimjournallogin/>)

The Journal of the Southern African Institute of Mining and Metallurgy (website, http://www.scielo.org.za/scielo.php?script=sci_serial&pid=2225-6253)

Council for Scientific and Industrial Research (CSIR) (website, <https://researchspace.csir.co.za/dspace/>)

The National Institute for Occupational Safety and Health (NIOSH) (website, <https://www.cdc.gov/niosh/pubs/default.html>)

Luleå University of Technology (website, <https://www.diva-portal.org/smash/search.jsf?dswid=5735>)

Onemine (website, <https://onemine.org/>)

OnePetro (website, <https://onepetro.org/>)

Sciadirect (website, <https://www.sciencedirect.com/>)

Springer Link (website, <https://link.springer.com/search?query=orepass>)

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s42461-024-00979-3>.

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Data Availability The raw data associated with this research are confidential, as per privacy and ethics approval, and may not be shared with any third parties. However, technical anonymised data may be available upon request.

Declarations

Conflict of Interest The authors declare no competing interests.

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