Mining, Metallurgy & Exploration (2025) 42:2101–2115
https://doi.org/10.1007/s42461-025-01283-4

REVIEW

A Survey of Current Planning, Design, and Geotechnical Practices for Orepasses

Kristin Guerin-Davey[1] · **Andrea Brickey**[1]

Received: 30 January 2025 / Accepted: 16 May 2025 / Published online: 28 May 2025

Abstract

Determining the location, design, and construction method for orepasses in underground mining operations can be challenging. Existing studies and literature contribute useful content but stop short of offering standardized methodologies for design and placement decisions. Past surveys have documented operational procedures at select operations, with the most recent published survey being from 2013. This paper presents the results of a survey conducted in 2024 of numerous underground operations in Canada and the United States. The survey obtained information regarding orepass design, construction, and planning. Responses are compared to industry best practices and case studies found in the available literature. Topics covered in this article include construction methods, orepass dimensions, guarding, mechanical support, causes of hang-ups, corporate policies on placement, and geotechnical factors, among others. The survey responses provide valuable insights into the current state of orepass practices and the benefits of orepass placement for effective and efficient strategic and operational mine planning.

Keywords Underground mining · Orepass design · Finger raises · Orepass hang-ups · Survey

1 Introduction

There are a variety of underground mining methods that are used for different commodities, geologic conditions, and other deposit characteristics. Determining the most economic, safe, and productive underground mining method is based on numerous factors such as the orientation and depth of the mineral deposit, the grade of the deposit, and the geotechnical properties of both the ore and the host rock. A key aspect of any mining method is how material is extracted and moved throughout the mine. Movement of ore and waste can be accomplished via wheeled mechanical equipment, trains, hoisting systems, conveyor belts, orepasses, or a combination of these methods. This paper reports on the current use of orepasses in underground mining operations within Canada and the United States (US) and provides a detailed discussion of available literature.

✉ Andrea Brickey
Andrea.Brickey@sdsmt.edu

[1] Mining Engineering and Management, South Dakota School of Mines and Technology, 501 E. St. Joseph St, 57701 Rapid City, SD, USA

Orepasses utilize gravity to efficiently move material from a production level to a lower haulage level. From there, the material can be moved to the surface via trucks, conveyors, or a skip within a shaft [1, 2]. In Canada, orepasses are strictly used for production material, whereas the term wastepasses refers to those used for low-grade or barren material. In South Africa, orepasses are referred to as rockpasses. Figure 1 provides a schematic of an orepass with identified key components. At the origin of an orepass is the tipping point, i.e., dumping point, which may include a material sizing device such as a grizzly (e.g., bars spaced at a desired distance to prevent oversize material), and dust control systems, e.g., enclosure. The terminal end of the orepass may include a chute (for loading material onto railcars), a drawpoint, a hopper (to feed material onto a conveyor or into trucks), or other material control devices to prevent uncontrolled material movement into the haulage drift. While not a physical device, the integration of a knuckle, i.e., a change in orepass direction, can be incorporated to reduce the speed of the material as it travels down the orepass. When an orepass is connected to multiple working levels, a finger raise is used to connect the secondary level to the main orepass. The infrastructure at the origin of a finger raise is similar to that of the tipping point.

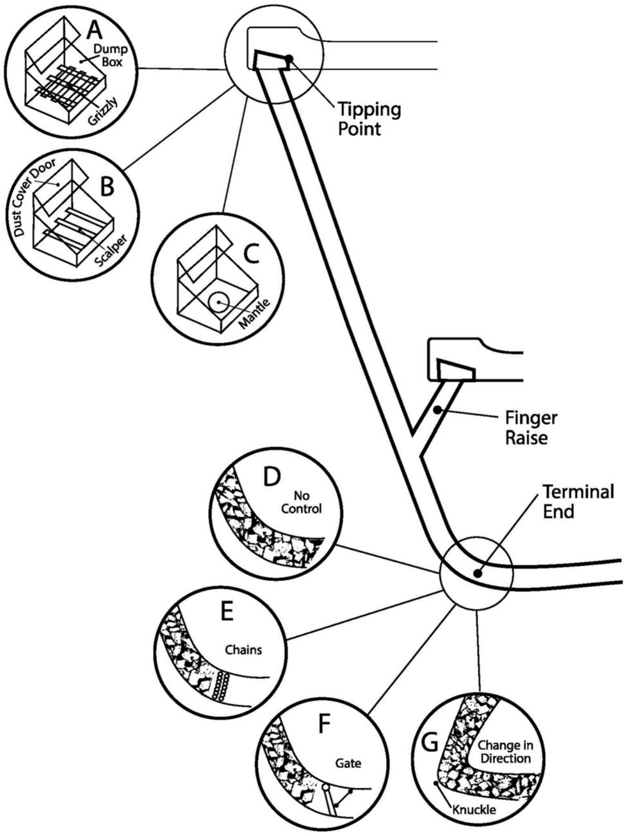

Fig. 1 Schematic of an orepass showing various material movement control methods and components. A, B, and C show a grizzly, scalper, and mantle, respectively, at the tipping point. D, E, F, and G show no control, chains, a gate, or a knuckle, respectively, to control material flow at the terminal end. A finger raise is also depicted. Adapted from Lessard & Hadjigeorgiou [3])

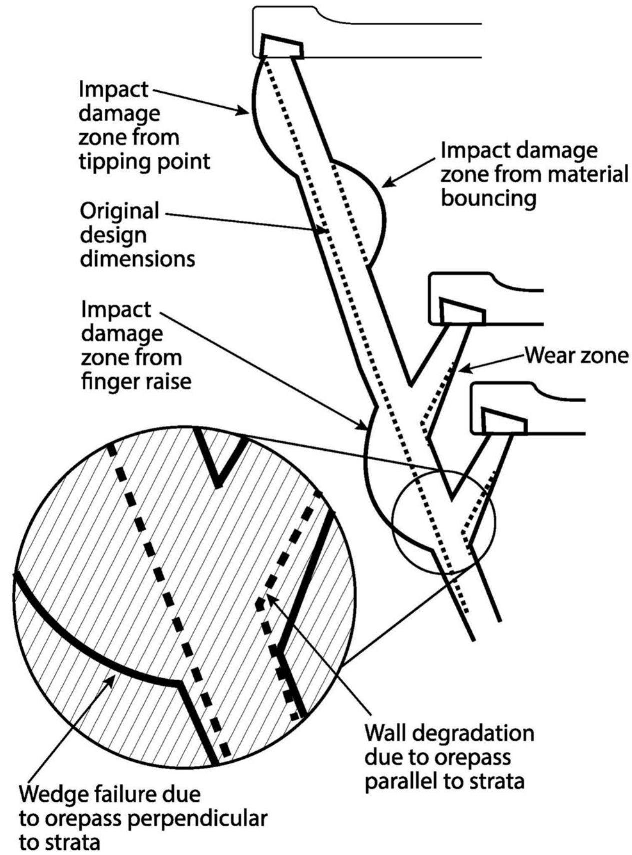

Fig. 2 Typical damage seen in an orepass, (i) impact damage at the tipping point, (ii) impact damage from material bouncing on the orepass walls, (iii) impact damage from the finger raise discharge point, (iv) wall degradation from strata, (v) wedge failure. Adapted from Hadjigeorgiou et al. [6]

Orepasses are subject to challenges related to hazardous conditions from blockages and cross-sectional expansion. Orepass failure, i.e., orepass is no longer functional, can be associated with wall degradation, e.g., collapse or excessive widening of the orepass, or with excessive wear from material eroding the walls. Orepasses placed in geotechnically unstable regions can experience additional challenges to maintain functionality [4], as shown in Fig. 2. If an orepass is poorly designed, located, and/or constructed, rock impacting the walls can create fractures, resulting in a widening of the cross-sectional diameter and eventual wall collapse. The most common locations for impact damage are just after the tipping point or on the opposite wall from the discharge point of the finger raise, see Fig. 2 for illustrations. Furthermore, material hang-ups, i.e., rock blockages internal to the orepass, can block the orepass, rendering it unusable. Uncontrolled material flow, i.e., rapid descent of material, can result in excessive damage to the bottom of the orepass. Some orepass damage can be repaired, and some hang-ups, i.e., blockages, may be resolved with water or secondary blasting, but there can be significant hazards associated with these situations and methods. There are drawbacks to these clearing methods—secondary blasting can cause excessive damage to the walls of the orepass, the use of water can create "mud rushes," and that water can lead to other challenges (especially when the hang-ups are due to "sticky ore"). Unresolved hang-ups can result in the decommissioning of the orepass [5].

While there are a number of documented site-specific case studies related to orepass implementation, there are only a few papers that provide a general discussion of orepass planning and construction. By reducing the gap in understanding between theoretical best practice and operational realities, companies have the potential to improve safety and production.

Much of the available literature is focused on single operation case studies or surveys that evaluate fewer than 10 operations. Survey papers are intended to provide a more comprehensive overview of the industry's current state by comparing operational and design decisions across various operations and identify areas that require further research. Previous surveys, [5, 7–12], provide valuable information on orepass planning and operation, but are limited in operational responses, typically as a result of grant restrictions or other limitations.

Advances in excavation methods, e.g., raiseboring, have changed orepass design and construction considerations. While not every operation uses finger raises, when they are used, it is important to understand their potential impact on the orepass. Finger raises are noted as a potential cause of wall degradation both from construction and operation [4]. It is noted by Hadjigeorgiou and Mercier-Langevin [13] that finger raise use can have a negative impact on orepass longevity.

This paper offers a comprehensive review of past orepass surveys and related literature, addressing gaps between established best practices and operational realities. The 2024 survey, conducted to document the current state of orepass design, construction, and placement, provides insights into methods, procedures, and challenges related to orepass planning. Insights are identified by analyzing the recent survey data results and whether or not the results are supported or contradicted by existing literature.

2 Literature Review

Compared to other aspects of mine planning, e.g., stope placement and scheduling, there is limited documented research on orepass design, construction, operation, monitoring, and planning. Furthermore, the research that is available is not always adopted by industry as best practice. In fact, Lessard and Hadjigeorgiou [3] noted in 2006 that "the design and operation of ore pass systems is often based on past experience, which can be anecdotal and at times contradictory in nature." A more comprehensive review of orepass design, construction, operation, and maintenance, as well as new techniques, can be found in the 2024 review paper by Salmi et al. [14] entitled *A review on the geotechnical design and optimisation of ultra-long ore passes for deep mass mining*.

2.1 Orepass Survey Papers

There are several orepass survey papers identified in the literature, with the most recent being by Hadjigeorgiou and Stacey in 2013 [12]. The following discussion of orepass survey papers includes the countries covered by these surveys, the key lessons learned, and the number of operations involved. It must be noted that the US Bureau of Mines (1910–1996) limited the number of mines included in a grant contract to prevent being a burden on the industry; therefore, these surveys were often limited to fewer than 10 operations.

One of the earliest studies on orepass design recommendations, published in 1983 by Hambley et al. [7], surveyed nine mines to develop guidelines for avoiding material flow issues such as arching and piping. The criteria they established helped both the surveyed operations and others with orepass planning. In 1999, Hagan and Acheampong [8] published a paper on orepass design, support, and maintenance processes used in South Africa. Based on a literature review and consultations with 14 mines, the study aimed to reduce failure rates by analyzing failures at deep-level operations. That same year, Stewart et al. [5] surveyed five US mines to study safety concerns related to orepasses, particularly hang-ups, and causation factors.

In 2001, Beus et al. [9] authored a chapter on orepass design factors, including chute design and safety considerations, based on an undisclosed number of mines in the US. The following year, Lessard et al. [10] surveyed seven mines in Quebec, Canada, focusing on design characteristics, support systems, and common challenges such as wall degradation and hang-ups. Hadjigeorgiou et al. [6] expanded on these findings in 2005 by surveying 10 mines in Quebec and additional mines in Ontario, Canada. Their paper examined orepass configuration, reinforcement techniques, and material flow control, with a particular focus on issues such as wall degradation and hang-up clearing methods. Also in 2005, Stacey and Erasmus [11] compiled accident data from a number of South African mines, aiming to reduce orepass-related accidents. Lessard and Hadjigeorgiou's 2006 study [3], which surveyed 10 Quebec mines between 2001 and 2003, summarized current practices and created a database on orepass configuration, support systems, and overall performance.

Most recently, in 2013, Hadjigeorgiou and Stacey [12] surveyed an undisclosed number of mines across both Canada and South Africa, concluding that there was a significant lack of strategic planning, design, and management for orepasses throughout the industry.

2.2 Orepass Design and Planning

As mentioned by Lessard and Hadjigeorgiou [3], orepasses are often placed ad hoc, with no definitive method or process to determine the best location. Stacey and Erasmus noted that "design considerations should be aimed at avoiding problems in the passes" [11], meaning orepass design should be part of a mines overall plan. There are general methods presented in some texts [9, 15], but may not be suitable for all operations. On the other hand, methods derived from a case study of a specific mine may be hard to apply to an operation that does not have the exact same conditions as the case study operation [16].

One of the earliest texts providing a systematic methodology for orepass design, construction, and operation was by Selleck and Pfleider in 1968 [17]. The authors emphasize the important factors to consider for orepass design (e.g., size distribution, shear strength of ore, characteristics of orepass rock walls, flow rate) and provide an overview of the orepass systems at several operations. Later, Hambley authored a design guide for orepasses in 1987 [15]. This paper detailed both theory and case studies of orepass geometries, dimensions, inclination, and use of finger raises. Hambley also presented tips and equations on how to prevent hang-ups and piping, drawpoint design, and other design features along with some operational problems and real-world examples.

More recently, Sachse and Westgate [18] published a guide on excavation methods for orepasses. The paper provides a systematic approach to selecting an excavation method based on the total length of the orepass. This approach showed the safety risks of different excavation methods and provided a matrix, based on the length of the orepass, showing whether each method is able to be used, too dangerous to be used, or too cost prohibitive to be used. Cross-sectional diameter and shape is dictated by the chosen excavation method. Contractors are often used for new orepass development, which can limit the available method options. When the drill-and-blast method is used, blast design is a critical factor. Bunker et al. [19] published guidelines for orepass use in sub-level caving operations which included factors such as geometry, dimension, length, and inclination. They noted that "...design methodologies are generally limited to empirical methods, rule of thumb and limited case studies."

Orepass planning is a crucial aspect of mine operations, as preplanned decisions on when and where to place orepasses can increase productive and longevity. In their 2013 paper, Hadjigeorgiou and Stacey [12] highlighted the industry's lack of orepass planning and proposed a flexible strategy to reduce orepass problems. By adopting a planning strategy similar to that used for horizontal excavations, mines can avoid costly rehabilitation and production losses. They emphasized that "...vertical or near-vertical excavations, such as orepasses, are not given the same level of attention as horizontal excavations" [12].

In 2015, Sjöberg et al. [20] proposed a numerical model to assist in orepass planning and placement based on stress modeling at the Malmberget Mine in Sweden. The model was used to study orientations and locations of orepasses to develop a design process for selecting optimal positions. By analyzing stress patterns and orebody dip direction, orepasses can be placed in more advantageous areas of the mine. In 2019, Dabula [21] submitted a master's thesis on an optimization model for orepass placement at the Venetia Mine in South Africa. The model calculated the cost per tonne for each orepass based on the distance from stopes, aiming to reduce LHD tramming distances and resulting in cost savings from lower fuel consumption and extended machine life. This thesis advanced the orepass planning process by quantifying the operating costs of orepasses at different potential locations within a given operation.

The latest advancement in orepass planning tools was introduced by Halilović et al. in 2023 [22], who developed an optimization model using fuzzy logic. This model factors in both the distance to orepasses and development costs and selects the optimal number and location of orepasses by minimizing the total costs of ore transportation and development while accounting for dynamic constraints. This paper represents a significant step forward in orepass placement, as it considers both development costs and distance, rather than focusing solely on distance. Models like this can help engineers plan orepasses more efficiently, safely, and cost-effectively.

2.3 Orepass Support and Geotechnical Conditions

Understanding geotechnical conditions is crucial factor in determining the need for orepass support systems, such as linings, bolts, or other reinforcements to stabilize the orepass and prevent cross-sectional expansion [15, 23]. However, limited literature exists on when the benefits of support systems outweigh the costs. In his 1987 paper, Hambley [15] addressed orepass support requirements based on geotechnical factors. Vieira and Durrheim's 2005 study [23] focused on orepasses as deep as 5 km (3.1 miles) below the surface and proposed a numerical model to reduce failure risks, concluding that current support methods are sufficient for ultra-depth orepasses. Hadjigeorgiou et al. [24] examined orepass support system selection, providing equations for determining the need for support or liners. They noted that the cost of support systems should be considered against the cost of an orepass failure or need for rehabilitation. Hadjigeorgiou and Mercier-Langevin highlighted how "The introduction of effective ground support and liner can increase ore pass longevity..." [13].

Potvin et al. [25] discussed optimizing ground support, emphasizing the role of numerical modeling in improving design methods. Salmi et al. [14] presented equations for geotechnical factors and called for research into new support technologies to improve orepass productivity. Furthermore, the required level of orepass support system maintenance should be considered prior to selection.

2.4 Orepass Issues and Impact

Orepass hazards include wall degradation, hang-ups, and gate loading, among others. Accidents, some resulting in fatalities, have been caused by the unexpected release of hang-ups, mud rushes (when water is used to try and clear hang-ups and suddenly breaks free), blocked gates, structural failures, and excessive water pressure [5].

Wall degradation can result from material impacts to orepass walls, misalignment with geological structures, lack of support system, stress changes due to mining, and/or a combination of these factors. Wall degradation can significantly expand the orepass cross-sectional area, leading to unpredictable material flow, wedge failures in the surrounding rock, and additional stress on nearby openings or infrastructure. Esmaieli and Hadjigeorgiou [26] studied the damage of impact on orepass walls and found that degradation is more likely to occur when the orepass is oriented unfavorably in relation to rock bedding direction. They highlighted the significant production losses caused by poorly positioned orepasses relative to rock bedding. The research was expanded by Skawina et al. [27], who examined orepass loss in a sub-level caving mine. They found that wall degradation, stability issues, blockages, or poor design led to reduced production rates as the number of available orepasses decreased. The impact of such failures extends beyond the cost of clearing or rehabilitating the orepass, but also to production. Repeated failures and clearing attempts may worsen the original hang-up issue. Research and case studies on these effects have only recently been documented [27–31]. Overall, "mine management should develop a strategy for orepass loss situations to mitigate production disruptions and minimize fluctuations in production rates" [27].

Hang-ups in orepasses occur from (i) interlocking rock fragments forming an arch, (ii) "sticky ore" made of fines and water, or some ore types, creating a cohesive arch, (iii) material oxidizing in the orepass, and (iv) a single large rock resulting from wedge failure. Jenike [32] pioneered research on bulk flow of solids, highlighting how improper orepass design can lead to arch formation. He recommended that the smallest dimension of the orepass aperture be at least twice the intermediate dimension of the largest rocks to ensure reliable flow. Additionally, he suggested designing orepasses as converging channels, not straight, to avoid the risk of piping. Johanson and Colijn [33] studied ore bin and hopper geometry to minimize flow issues, while Kvapil [34, 35] conducted extensive research on ore flow in hoppers and bins. Colijn and Hanson [36] laid the foundation for quantitatively analyzing various ore hopper and bin designs. These studies explored different flow regimes to understand how to design for both blocky and fine ore and prevent hang-ups or accidents. Stacey and Erasmus [11] analyzed 10 years of accident data, focusing on wall degradation and hang-ups, and provided orepass design guidelines to mitigate these issues. Hadjigeorgiou and Lessard [37] surveyed 10 mines to study arching hang-ups. The result was a model that examined the impact of orepass geometry, as well as rock fragment shape and size distribution, on material flow. More recently, Salmi et al. [14] thoroughly discussed the conditions under which various types of hang-ups occur, offering a detailed history of flow dynamics.

There are two general tools used to clear hang-ups in an orepass: water or explosives. As mentioned, the use of water is not recommended in some situations, but high-pressure water can be used to clear hang-ups. Explosives can be placed via drillholes, launched with a Sputnik (an air-propelled device that can carry an explosive charge up into the orepass), or placed with a rod [38]. More detailed descriptions of hang-up mechanisms and factors that lead to them can be found in the 2024 review paper by Salmi et al. [14].

Gate loading refers to the impact of material on the gate at the bottom of the orepass (dynamic loading) or the weight of the material within the orepass on the gate (static loading). Failure can occur when these loads exceed the gate's design capacity [39]. Significant research, funded by the National Institute for Occupational Safety and Health (NIOSH) at the Spokane Research Laboratory in the 1990 s, aimed to understand and prevent accidents related to orepasses. Beus et al. [40] explored the hazards of orepasses, linking hang-ups and gate loading to safety incidents, and proposed mitigation strategies for the mining industry. In 1997, Beus and Ruff [41] constructed a scale-model shaft and orepass at the Spokane research facility, focusing on reducing orepass accidents by creating a computer model to analyze designs and flow to identify safety issues. Later that year, Beus et al. [42] used this facility to study both gate loading and wall degradation, aiming to improve safety. In 1998, Larson et al. [43], in collaboration with NIOSH, used particle flow code to research and predict dynamic loads on orepass gates. Beus et al. [44] also summarized NIOSH's research approaches, discussing field observations from five US underground mines, and computer modeling to better understand static and dynamic loads. In 1999, Beus et al. [45] published a report on static and dynamic loads, comparing field measurements and computer models to identify areas for improving dynamic material flow modeling and reducing impact forces on gates.

All of aforementioned hazards pose significant risks to miner safety. Blasting to clear hang-ups can endanger miners if the material unexpectedly breaks loose, and the blast itself may comprise the structural integrity of the orepass. Significant wall degradation can lead to inaccurate stress predictions, increasing the risk of orepass collapse. This not only presents a major safety hazard, but also increase the potential for air blasts, excessive dust, or uncontrolled material movement [11]. When an orepass fails to meet planned throughput, whether temporarily or permanently, it jeopardizes both the mine's production capabilities [30] and overall safety and economics. Other operational challenges include ensuring cushion guidelines are followed during production disruptions, handling oversize material caused by poor basting or overbreak in the stopes, clearing hang-ups, and determining how long material can remain in the pass.

3 Survey Methodology

To gather current information on orepass use and planning procedures within Canada and the US, the authors developed a 26-question survey (Appendix A) which was distributed via SurveyMonkey® to 65 operations. Of those sent, 37 responses were collected. Operations were selected based on commodity type (e.g., gold, copper, silver, and base metal mines) and location (Canada or the US), excluding coal and industrial minerals. To identify potential respondents, the authors conducted internet searches for underground metal mines in Canada and the US, utilized the Mine Safety and Health Administration (MSHA) online tool to find US mines. The authors also contacted numerous industry professionals through email, LinkedIn®, and referrals. The survey included small, medium, and large operations, as well as surface mines transitioning to underground mining. The authors felt this was a reasonable representation of the industry as the operations selected were from multiple commodities, regions, and mining methods.

Initial contacts were made with geotechnical or mine engineering personnel via LinkedIn® on July 11, 2024. Follow-up communication was conducted through LinkedIn® or corporate email. If an individual lacked the information to complete the survey, they were asked to refer the authors to a more appropriate contact. Periodic reminders were sent to encourage the completion of the survey. To minimize potential bias, various methods were used to identify operations, and multiple attempts were made to reach personnel if initial contacts did not respond. The survey was anonymous; therefore, specific operations that responded were not identified. The survey closed on September 29, 2024, and all responses were immediately downloaded from SurveyMonkey®.

Of the 37 responses, 33 were completed, meaning all questions had responses, and four were partially completed. An additional three mines declined to participate, stating that they do not utilize orepasses at their operation. Of the 37 operations that did respond, 26 use orepasses. The four partial responses were included in this analysis with at least 40% of the survey completed, with one response exceeding 75%. It is noted that with the partial responses, some questions have fewer responses. Specific questions allowed for multiple selections, such as what construction methods are used, so the total number of responses may exceed the number of respondents. Some questions required follow-up questions, which meant that only some respondents would receive the additional questions based on previous responses.

For the 11 operations that do not use orepasses, the reasons selected were incompatible deposit orientation (3 responses), depth of the deposit (2 responses), mining method (1 response), haulage method (5 responses), production rate (1 response), and "other" (5 responses). The "other" responses included (i) orepasses not yet in use due to the operation's short lifespan, (ii) ramp system implemented instead of orepasses, (iii) prohibitive ground conditions, (iv) geotechnical challenges in finding suitable locations for orepasses, and (v) two orepasses had been built but were not presently utilized (one was flooded, the other was used for 6 years before being retired).

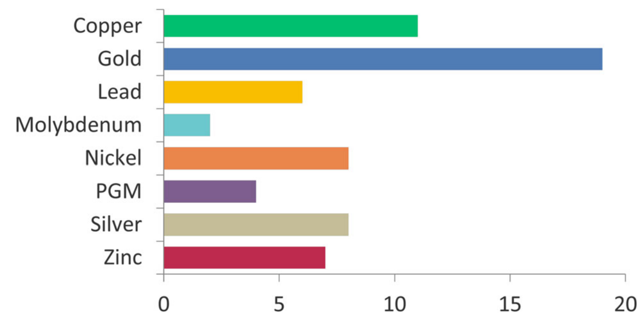

Fig. 3 Survey results for primary and secondary commodities: 37 individual responses. Survey allowed for multiple selections

4 Survey Results

The results of the survey are separated into different themes to highlight potential connections between best practices and operational realities. The survey is intended to provide a broader perspective of the state of the industry. Additionally, responses to certain questions are cross-referenced against other responses to provide a deeper understanding of efficient and productive practices and identify potential root causes to failures.

Figure 3 provides the number of respondents by commodity. The majority of operations listed gold as their primary commodity, with copper being the second most common. Silver and nickel tied for third most common. Operations of all sizes were represented in the survey results, with most falling between 1000 and 5000 tons per day, as shown in Fig. 4.

4.1 Orepass Design and Construction

The survey results indicated that the primary construction method employed is conventional drill and blast drop-raising, followed closely by raiseboring. Alimak raise construction

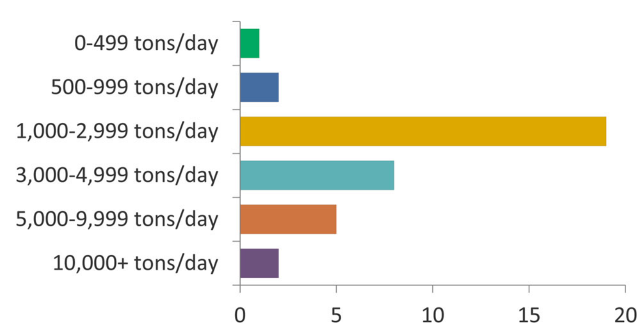

Fig. 4 Survey results for daily ore production range: 37 individual responses

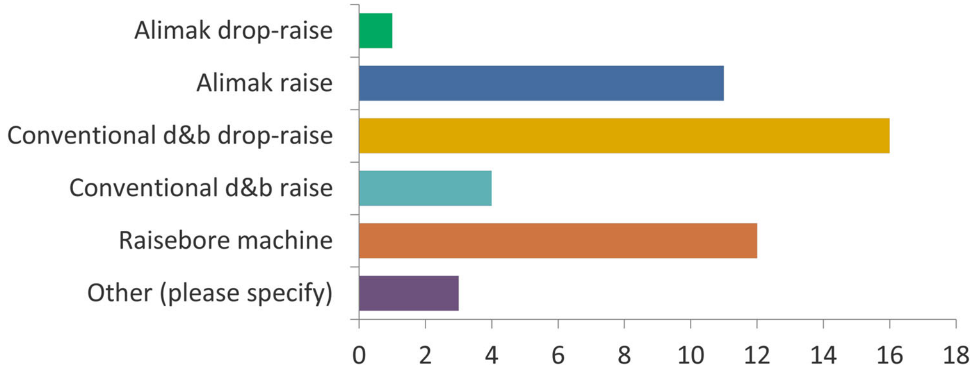

Fig. 5 Survey results for orepass construction method(s): 25 individual responses. Survey question allowed for multiple selections

is also used by many operations, as shown in Fig. 5. "Other" responses included the use of historically orepasses, the use of raiseboring to pilot the orepass before expanding it to the design width with drill and blast, or unknown. Respondents could select all applicable construction methods (see Fig. 5), and of the 25 respondents, 17 indicated that they use multiple methods.

The 44% use of Alimak raise construction differs from Hadjigeorgiou et al. [6]. They reported that 63% of orepasses in Quebec, Canada, used Alimak raises, attributing this to local contractors' expertise. Their survey also found that in Ontario, Canada, Alimak raises were only used for 39% of orepasses, though there was a reported shifting toward Alimak raises.

Rock conditions, design, and layout all play a significant role in determining an appropriate excavation method. In 1954, MacLeod [46] documented that adapting excavation methods to layout and rock conditions could reduce orepass excavation time. For example, raiseboring is typically used for longer sections [6], though challenging rock conditions require additional considerations (e.g., how to support the orepass walls and excavation during the drilling process). Edelbro et al. [47] developed design charts based on case studies to improve wall stability when using a raisebore. Rojas et al. [48] found that in a poor quality rock mass, grouting prior to raiseboring was significantly beneficial to orepass longevity.

The most common orepass shape reported was square (19 out of 36 responses), followed by circular (14 responses). Additionally, two operations used rectangular openings and one reported using an oval/ellipse shape. Of the 25 operations, 10 indicated that they used multiple shapes for orepasses. It should be noted that certain excavation methods dictate the shape of the orepass, e.g., raiseboring.

Orepass cross-sections ranged from 6 feet (1.8 m) in diameter to 20 x 20 feet (6 x 6 ms) square, with the most common size being 10 x 10 feet (3 x 3 ms). Operations with higher daily production tended to use larger diameter orepasses, though it was not a strong correlation. The typical length of orepasses exceeded 125 feet (37.9 ms), with 75–99 feet (22.5–30 ms) being a close second, as shown in Fig. 6. This aligns with the reported mean length of 87 ms (285 feet) reported by Hadjigeorgiou et al. [6] for Canadian mines. It should be noted that orepass length is often determined by the overall level interval distance.

The reported inclination angles were predominantly between 80.1 and 90° from horizontal (13 out of 25 responses). Other inclinations included 70.1–80° (8 responses), 60.1–70° (3 responses), and 50.1–60° (1 response). This differs from the findings of Lessard and Hadjigeorgiou [3], where the average orepass inclination was 70°, indicating that the mines (surveyed here) are utilizing steeper orepasses.

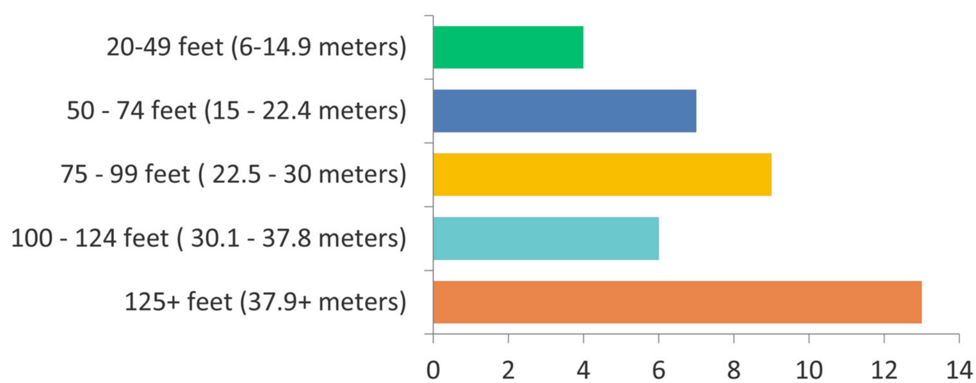

Fig. 6 Survey results for typical orepass length(s): 25 individual responses

4.2 Orepass Wall Degradation and Dynamic Loading

While orepasses are used to transport material between levels, they can also serve as temporary storage, i.e., stockpile. Furthermore, orepasses may be kept full to reduce dynamic loading at the terminal end and also to minimize wall impact. The survey asked if orepasses are kept full or partially full for temporary storage, blending, or other uses; 16 of the 25 operations responded yes. The remaining nine operations responded that they operate their orepasses empty. Of the given options, the primary reason for operating the orepasses full or partially was for temporary storage, though some did indicate it is to act as a buffer for dynamic loading or for blending purposes. Iverson et al. [49] demonstrated that the dynamic loading force on the gate increases drastically as the height increases. This force is greatly reduced if the orepass is partially full. Wall degradation can also occur when material slides along the orepass walls, as shown in Esmaieli's 2010 thesis [50]. This degradation is reduced when the orepass is kept full or near full, reducing the material's free fall distance.

Survey respondents were allowed to select multiple orepass guarding options. The most common guarding method was a grizzly (20 responses), followed by a mantel (6 responses) and chains (3 responses). Only one operation utilizes a scalper, while six "other" responses included barricades, berms, unguarded orepasses, or a rope and sign. Hadjigeorgiou and Mercier-Langevin [13] note that the use of infrastructure like a grizzly to control block size can reduce the impact load up to 20 times due to material spreading out as it falls. Manzoor et al. [31] emphasize the productivity risks of not using material screening methods, as hang-ups caused by oversize fragments can cause production delays. The reported case study, using the Malmberget Mine in Sweden, showed that the cost of installing an oversize handling system could be paid off solely by productivity improvements. Based on the recent survey responses, the majority of operations employ a material sizing device.

Mines often use a material control device or method at the terminal end of orepasses. The survey indicated that the most common terminal end method is allowing material to fall directly onto the ground or a chute with a bar and chain gate, as shown in Fig. 7. "Other" responses included keeping enough material in the orepass to be above the brow, using an ore bin that feeds onto a conveyor belt, and employing a hydraulic press frame and control chains. These findings align with those of Hadjigeorgiou et al. in 2005 [6], who found that chutes with control chains were the most common flow control method in Quebec mines. Flow control infrastructure helps regulate the speed and consistency of material flow. Nazeri and Rozgonyi [51] also note that orepass inclination significantly affects dynamic gate loads when orepasses are run empty.

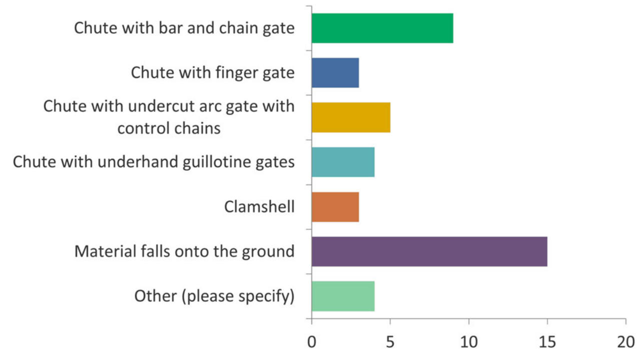

Fig. 7 Survey results for terminal end of the orepass control system(s): 24 individual responses. Survey question allowed for multiple selections

Regarding wall degradation, approximately half of the operations (11 of the 23 responses) reported no significant degradation, while the other 12 operations indicated positively. The degradation was attributed to seismic activity, erosion from material over time, deficiencies in the design, the presence of groundwater, impact damage from falling material when the orepass was not kept full, and ground or geotechnical issues. A recurring theme was that orepasses tended to degrade more when orepass management was poor, such as failing to maintain orepass levels or repair liners. As Hadjigeorgiou and Mercier-Langevin [13] noted, "A full pass prevents wear and damage due to impact from blocks falling at high velocity."

One operation reported the loss of two orepasses. The first was due to a large wedge failure and the second from wall degradation, resulting in the orepass boundary expanding close to critical infrastructure. The only remediation for this was to abandon and backfill the orepass to stabilize the area. Another operation indicated that a wedge failure near the bottom of the orepass, which blocked the ore bin and led to abandonment. These reported problems align with Esmaieli and Hadjigeorgiou [26] findings that "The impact of rock fragments striking the foliated rock can result in the delineation of rock wedges along the ore pass walls."

A senior ground control engineer [52] at a Canadian operation shared insight into design challenges contributing to excessive wall degradation. They explained that the pass orientation must align so that the lateral acceleration from dumping ore matches the pass geometry, minimizing wear and impact damage. If the orepass length is kept relatively short, the cross-sectional geometry can be enlarged, allowing for more storage and reducing wall damage.

4.3 Orepass Support and Geotechnical Challenges

The number of orepasses in use at any given time ranged from 1 to 3 (10 responses) to 10 or more (6 responses). Oper-

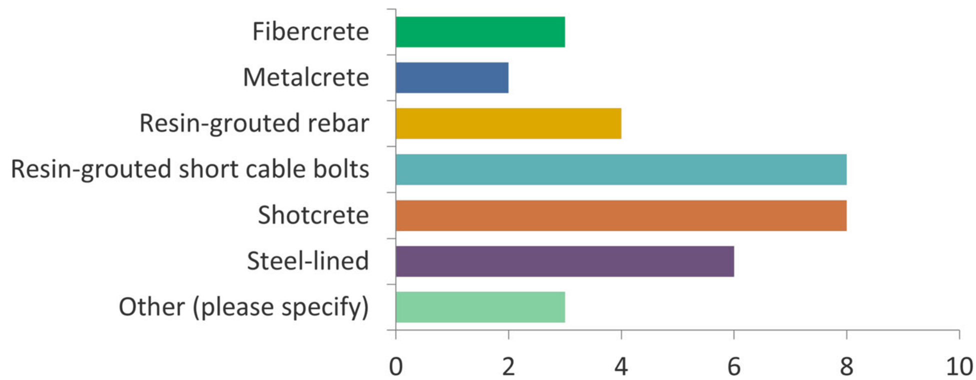

Fig. 8 Survey results for utilized ground support system(s): 17 individual responses. Survey allowed for multiple selections

ations with higher ore production tended to have more active orepasses, although the correlation was not perfect. Three-quarters of the responding operations (18 of 24 responses) employ some form of engineered rock support. These supports include shotcrete, resin-grouted short cable blots, and steel-lined orepasses, as shown in Fig. 8. The three "other" response mentioned long cable blots, external cable bolts, metalcrete, dynamic bolts, and double layer 9-gauge chain link with 4-gauge mesh finished with a concrete liner.

In 2003, Sjöberg et al. [53] studied wall degradation and orepass support at the Kiirunavaara Mine in Sweden. The recommendations for reducing orepass instability included additional rock reinforcement, screening oversize material, keeping orepasses full to reduce impact loading on walls, and improving the understanding of the geomechanical conditions. Similarly, Maree [16] discussed support techniques used at the South Deep Mine in South Africa, comparing different options for supporting orepass segments to determine the best approach.

Operations consider numerous geotechnical factors when determining the placement of an orepass. The survey found that the most common factors include geotechnical structures and alignment with faults. Other factors include rock mass rating (RMR), rock quality designation (RQD), and rock type, as shown in Fig. 9. The "other" category included hydrologic modeling, proximity to existing or planned excavations, seismic and stress models, ore grade, and placement outside the mining influence.

An interview with a principal geotechnical engineer [54] at a Canadian company highlighted the key geotechnical risks associated with orepasses, particularly burst-prone ground conditions or geological structures vulnerable to gravitational failures. This sentiment is echoed by both Hart [55] and Gardner and Fernandes [56], who note that orepass failure, particularly in ultra-deep mines, is often associated with geological structures rather than stress-related issues. Findings from the Hart case study of the Kloof No. 3 Shaft Mine in South Africa emphasized that "Geologic features do increase the risk of failure in rockpasses and should be avoided if possible" [55].

Of the survey respondents, six do not provide engineered rock support for orepasses. Interestingly, only one of these six operations reported significant wall degradation, and that particular orepass was noted to be older. None of the six operations reported regular hang-ups or the loss of an operational orepass. This suggests that when an orepass is located in geotechnically competent ground, issues are rarely experienced. It also implies that support is crucial in unfavorable geotechnical conditions, where deterioration of liners or support systems is likely to lead to issues. Unfortunately, as noted in Hadjigeorgiou et al. in 2004 [24], "There is an absence of generally accepted guidelines for the selection of reinforce-

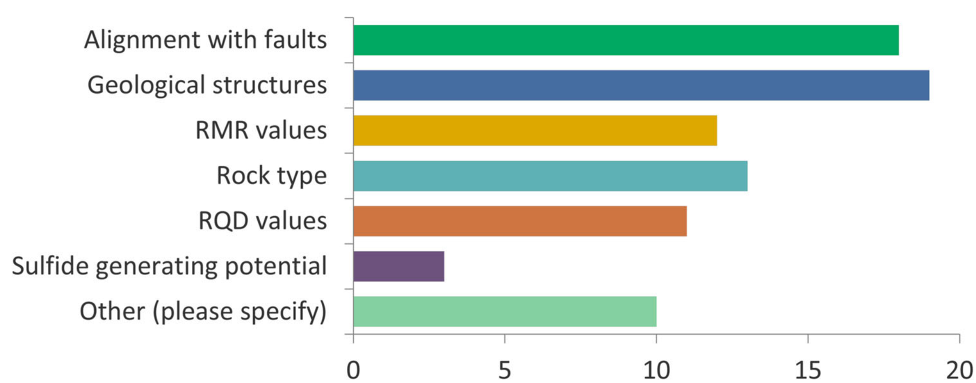

Fig. 9 Survey results for geotechnical factors considered when making orepass placement and design decisions: 22 individual responses. Survey question allowed for multiple selections

ment specific to ore passes," making it more challenging for engineers to determine appropriate support solutions.

4.4 Finger Raises

Finger raises are used to connect multiple levels to a single orepass. A slight majority of operations (14 of 23 responses) employ finger raises, which aligns with the findings of Lessard and Hadjigeorgiou [3] in their survey of Canadian mines using orepasses. The most common angle used between the finger raise and orepass (angle of intersection as shown in Fig. 10) is 20.1–30° (8 of 13 responses), followed by 30.1–40° (4 responses) and 10.1–20° (1 response). Interestingly, four operations with finger raises have an interception angle between 35 and 40°. Esmaieli and Hadjigeorgiou [57] found that this range produces the highest (worst) impact force on the orepass wall opposite the finger.

Of the 14 operations using finger raises, ten have orepasses longer than 100 feet (30.1 ms), and eight of the 14 produce between 1000 and 2999 tons of ore per day. In addition, nine of the 14 operations report significant wall degradation. Two operations specifically noted that finger raises contribute to the degradation. One operation reported frequent damage to the orepass wall opposite the finger raise, while another explained that with multiple finger raises, the level of material in the orepass must be kept below the lowest finger, which leads to wear to the opposite wall. Both of these operations use a 20.1–30° intersection angle, which is considered acceptable for minimizing impact force on the orepass wall opposite the finger raise discharge point [57].

Additionally, four operations with finger raises have lost an orepass before the end of the designed life, although none of these failures were directly attributed to wall degradation from the finger raises. Esmaieli and Hadjigeorgiou [4] recommended that the inclination of a finger raise itself should not exceed 60° from horizontal.

4.5 Orepass Hang-ups

The majority of survey respondents (10 of 23 responses) reported an average of zero hang-ups per month. However, six operations indicated experiencing five or more hang-ups monthly, as noted in Fig. 11. The cause of orepass hang-ups were fairly evenly distributed across three categories: (i) oversize material or boulders, (ii) sticky ore (a mixture of fines and water), and (iii) "other" category. The "other" category included issues such as oxidizing ore, accidental dropping cement into the orepass, scrap steel, failing steel liners, small orepass diameter, backfill mixing with ore, general degradation, and the amount of time the ore spent in the orepass.

The use of finger raises does not seem to be a significant factor contributing to orepass hang-ups. Instead, most operations that experience hang-ups attribute them to oversize material, particularly due to the lack of a material control device at the tipping point. While maintaining and repairing material control devices require both time and cost, they do prevent oversize material from entering and potentially blocking the orepass. Oversize material can also contribute to increased wall degradation, as noted by Manzoor et al. [31]. This is supported by the survey results, which report that six operations that identified oversize material as a cause of hang-ups also reported significant wall degradation in their orepasses.

Hambley et al. [7] suggest that the ratio of the orepass diameter (D) to the particle dimensions (d) should be between 4 and 5 to prevent interlocking arches. Additionally, blasting to resolve hang-ups can contribute to further wall deterioration. Szwedzicki [58] and Hadjigeorgiou and Lessard [38] provide detailed descriptions of methods to restore flow in an orepass blocked by a hang-up, along with an overview of the associated safety risks.

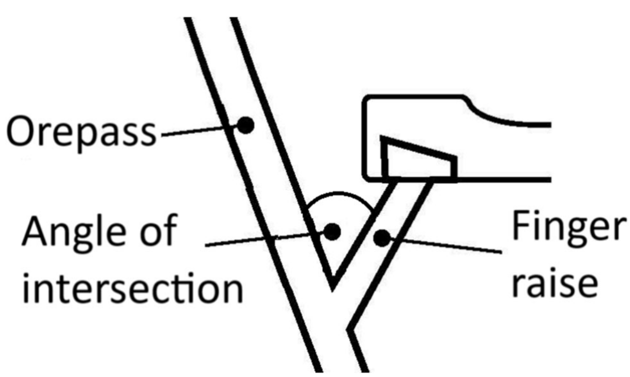

Fig. 10 Angle measurement between finger raise and orepass

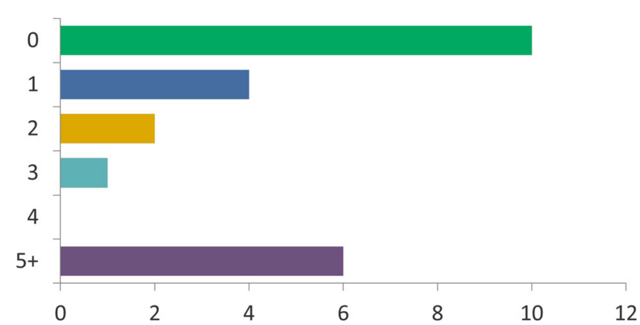

Fig. 11 Survey results for average number of hang-ups experienced per month: 22 individual responses

4.6 Orepass Failure Impacts on Production

The majority of operations (17 of 23 responses) have never lost an operational orepass due to a hang-up that could not be cleared. However, six operations reported such losses, even with the use of a grizzly to keep oversize material out of the orepass. The causes for losing an orepass before the end of its useful life include geotechnical issues, groundwater, fused ore, high seismic activity, blast damage from removing hang-ups, the age of the orepass, oversize material, wall sloughage, unfavorable alignment with geotechnical structures, and wedge failures at the bottom of the pass. Most respondents indicated that the planned orepass useful life ranges from 2 to 10 years, although some operations expect their orepasses to be utilized for the entire life-of-mine (> 10 years).

Of the six operations that had experienced orepass loss, four of them also utilized finger raises. These operations report increased wall degradation with finger raises, particularly on the opposite wall of the orepass from where the finger raise discharges material. One operation reported that they have not implemented orepass support systems in the past but had recently started applying metalcrete because of wall degradation. All six operations that have lost an orepass employed some sort of support system. Four of these operations individually maintain at least 10 operational orepasses at any given time. All four of these mines have production rates greater than 3000 tons/day. Additionally, three operations empty the orepass, which contributes to increased wall degradation and potential loss.

The terminal ends of the six operations that have experienced a failed orepass vary significantly in material control. Some do not utilize control methods, while others employ multiple control methods. Interestingly, none of these operations consider RMR when determining orepass placement, although most of the operations reported considered RQD, alignment with faults, rock type, and geological structures. However, the RMR plays a significant role in wall degradation and orepass longevity, as documented in the orepass longevity calculator created by Hadjigeorgiou and Mercier-Langevin [13] and updated by Sredniawa et al. [59]. Two of the operations place orepasses based solely on the overall mining plan, considering factors like ore grade or placing them outside of the mining influence.

An interview with a senior ground control engineer [52] at a Canadian operation provided further insight into the challenges of orepass failure. The engineer explained that although production throughput demands, particularly at the end of an accounting period, often force operators to lower pass inventory to meet throughput targets, this practice can lead to excessive wear on the orepass. Maintaining orepasses below the prescribed material level can result in more delays caused by material hang-ups and large structural wedge failures, which can create a "vicious cycle." The engineer noted that operating orepasses at lower-than-recommend material levels increases the risk of failure.

Rose et al. [60] stressed the importance of understanding orepass failure risks, as shown in their case study of the Olympic Dam Mine in Australia. The risk of failure can be estimated by monitoring orepasses, evaluating operational conditions, and observing hang-up clearing methods. This helps give engineers the data to prepare backup production plans or remediation strategies in advance. Skawina et al. [29], evaluating the Malmberget Mine in Sweden, found that it was impossible to maintain production levels if an orepass was lost, even with additional trucks. Skawina and Salama [30] noted that other operational costs increase when an orepass fails because of the need for higher-cost alternative transportation. Skawina et al. [61] observed that orepasses which are kept relatively full tend to experience fewer stability issues.

4.7 Orepass Planning

When asked whether a corporate policy or mine policy governs orepass design and layout requirements, only seven of the 22 respondents confirmed the existence of a formal policy. The policies described included general guidelines such as recommended design processes, geotechnical analysis requirements, excavation techniques, and orepass access placement. Other specific requirements mentioned were a single orepass per level, minimum orepass dimensions, layout approval by a qualified individual, and guidelines on the dip of the orepass. For operations without a formal policy, the orepass placement process largely relies on the experience of miners or engineers, often following a "rule of thumb" approach. This aligns with the findings of Lessard et al. [3] who observed similar practices in their survey of Quebec mines.

The vast majority of operations reported cross-departmental collaboration in deciding where to place an orepass. This collaboration involves various departments such as geotech, mine management, mine planning, and production

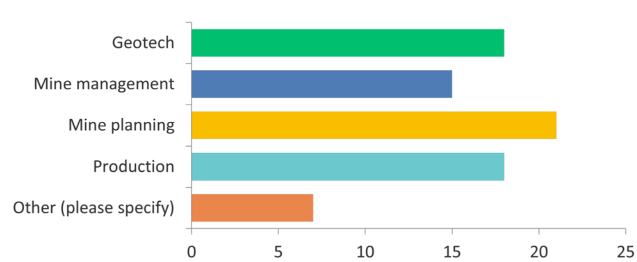

Fig. 12 Survey responses for which departments are involved in the orepass placement approval process: 22 individual responses. Survey question allowed for multiple selections

(see Fig. 12). Survey respondents noted "other" departments that included technical services, safety, mine operations, geology, finance, electrical, communications, and ventilation. The final decision on orepass placement (Fig. 13) was made by mine management and mine planning, though in some cases, the geotechnical department or other associated department (such as technical services) must sign off as well. Given the significant impact of orepass placement on production, especially in geotechnically challenging conditions, the survey responses highlighted that most operations involve multiple departments in decision-making process.

None of the surveyed mines indicated the use of optimization techniques for orepass placement, suggesting that the process is somewhat iterative, with all relevant departments needing to agree on a final location. Only one operation noted that orepass planning is incorporated into the long-term planning process, indicating that, for most operations, orepasses are not considered in the strategic plan. The common ad hoc approach to orepass placement mirrors the findings of Hadjigeorgiou and Stacey [12], who noted the absence of a strategic approach in orepass planning, design, and management. Vieira and Durrheim [23] emphasized the importance of orepass planning, particularly in ultra-deep operations, where orepass stability can be affected by the overall layout design. Stacey and Hadjigeorgiou [62] proposed a value-based approach for mine design and operational decisions, which could be applied to orepass planning.

To support orepass planning, Hadjigeorgiou and Mercier-Langevin [13] developed an orepass longevity calculator, which considers both design and operational factors. Sredniawa et al. [59] modified this calculator using data from the Kiruna Mine in Sweden, expanding the categories for each factor and presenting results from eight orepasses. This tool could assist engineers at other operations in orepass design by predicting potential throughput and indicating when adjustments (e.g., liners, support, or modifying operational conditions) may be necessary to ensure the orepass life aligns with the mine plan.

Insights from an interview with a senior ground control engineer [52] highlighted another key challenge in orepass planning. The engineer noted that if orepass wear is not considered from the outset, it can risk the integrity of other infrastructure if orepass cross-sectional expansion occurs. Even with many operations having standard offset distance from other infrastructure, rapid orepass cross-sectional expansion can place unplanned stresses on adjacent openings, potentially leading to failure in both the orepass and critical openings, such as shafts stations or ventilation raises.

5 Conclusions and Future Work

Upon review of the available literature and the 2024 survey, it seems apparent that incorporating orepass planning into the long-term mine planning process, rather than as ad hoc process conducted during operations, would have many positive benefits. Without clearly defined guidance, operations have traditionally relied on "rule of thumb" methods for the location, design, and construction of new orepasses. In particular, guidelines for specific aspects like finger raises are scarce, with fewer than ten relevant texts offering useful best practices. While many researchers have developed useful tools, e.g., longevity calculators and an excavation method selection guide, adoption of these tools is not clearly demonstrated in the survey results.

Out of 65 targeted operations, 37 responses were received, with 26 of these operations utilizing orepasses. Orepasses are employed across various commodities and mine sizes in both Canada and the US. The most common excavation method is conventional drill and blast drop-raises, which correlates with the most common shape being square. Typical orepass cross-sectional dimensions are 10 x 10 feet (3 x 3 ms), extending over 125 feet (38 ms) in length, and inclined between 80 and 90° from horizontal.

Operational conditions reveal that while most mines use a grizzly at the tipping point, few employ infrastructure at the terminal end, allowing material to fall directly onto the ground. Generally, one to three orepasses are operated concurrently and are often kept full or partially full for material

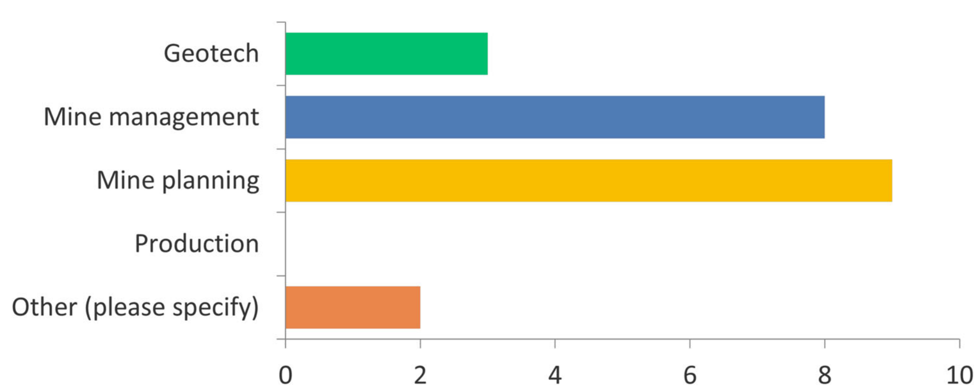

Fig. 13 Survey results for which department makes the final decision regarding orepass placement: 22 individual responses

storage and/or to provide stability. The typical operation lifespan of an orepass is between 2 and 10 years. Shotcrete and resin-grouted short cable bolts are the most commonly used methods for supporting orepasses. Geotechnical factors such as geologic structures and alignment with faults are critical factors when deciding orepass placement. Additionally, many mines utilize finger raises despite the potential for increased wall degradation. The angle between the orepass and finger raise is most commonly between 20 and 30°.

A concerning observation in the survey data is that just over half the operations reported significant wall degradation, with half of those also reporting more than five hang-ups per month due to oversize material, "sticky ore," or wall degradation. Additionally, a quarter of respondents lost an orepass before the end of the planned useful life, despite utilizing mechanical support. As noted in the literature review, the failure of a single orepass can severely disrupt production, emphasizing the need for careful orepass planning as part of the overall mine plan.

Currently, there is no industry widely accepted methodology for orepass planning and placement, and even companies with multiple underground operations lack formal, publicly available policies. Consequently, many mines rely on informal practices or simply continue previous methods. Various departments, including geotechnical, mine management, mine planning, production, and ventilation, are involved in orepass placement decisions, but the ultimate decision typically rests with mine planning or management. Without formalized policies or industry guidelines, there is a risk of losing valuable knowledge when experienced (geotechnical) engineers retire.

Survey results indicate that no comprehensive guide exists for planning, constructing, or designing orepasses. While strategic orepass placement is crucial for ensuring orepass longevity and maintaining mine productivity, only one operation reported incorporating orepass placement into a long-term mine planning strategy. Documenting and sharing practices across different operations could provide valuable insights for engineers involved in orepass placement.

An especially challenging issue in industry is determining orepass placement when an idea geotechnical location is unavailable. Potential future work could involve adapting the orepass longevity calculator developed by Hadjigeorgiou and Mercier-Langevin [13] and further expanded by Sredniawa et al. [59] into a geotechnical risk calculator. By removing operational categories, this tool could offer an easy-to-use template for assessing the geotechnical risk of individual orepasses. This could allow engineers to proceed with caution, adjust parameters to reduce risk (such as orientation or finger raise configurations), or determine that the geotechnical risk is too high to proceed with the proposed location.

Appendix A. Orepass Use and Design Survey

1. What are the primary commodities that you produce?
2. What is your average daily ore production range?
3. Do you use orepasses at your operation?
4. Why doesn't your operation use orepasses?
5. What type of method do you use to construct your orepasses?
6. What shape of orepass do you typically use?
7. What size of orepass do you typically use?
8. What length of orepass do you typically use?
9. What angle from vertical do you typically have your orepasses?
10. Does your operation utilize orepasses for temporary storage, blending, or other uses?
11. What type of guarding do you have at the top of your orepasses?
12. What does the terminal end of your orepass look like?
13. How many operational orepasses does your operation have at any given time?
14. Do you provide mechanical support to your orepasses, such as cables or lining?
15. What method do you use to support your orepasses?
16. Do you use finger raises to connect multiple levels to a single orepass?
17. What is the angle that you use between your finger raises and your orepasses?
18. Do you experience a significant amount of orepass wall degradation?
19. How often does your operation get hang-ups per month?
20. What have been the cause(s) of your hang-ups?
21. In the past, have you ever 'lost' an operational orepass (an orepass prior to the end of its useful life) due to a hang-up that couldn't be cleared?
22. What is the average useful life of your orepasses in months?
23. Do you have a corporate policy, or mine policy, that dictates orepass design and layout requirements (ex. Place orepasses every 200 feet, 50 feet away from main drift)?
24. If you don't have a corporate policy to determine orepass placement, what is your orepass placement process?
25. Who (or what department) is involved in the decision about where to place orepasses?
26. Who (or what department) makes the final decision about where to place orepasses?
27. What geotechnical factors do you consider when determining your orepass placement?

Acknowledgements We would like to thank the National Institute for Occupational Safety and Health (NIOSH) for partially funding this research under contract 75D30119C06090 and contract 75D30124C20 308. We would also like to thank all of the engineers and operation representatives that completed the 2024 survey. In particular, we would like to thank the two personnel who participated in the email interviews. We would like to extend our appreciation to Dave Counter and the anonymous reviewers for their critiques and suggestions to improve the technical content of the paper.

Declarations

Conflict of interest The authors declare no competing interests.

References

1. Hamrin H, Hustrulid W, Bullock R (2001) In: Hustrulid W, Bullock R (eds) Underground mining methods: engineering fundamentals and international case studies. Society for Mining, Metallurgy and Exploration Inc, Littleton, CO, pp 3–14
2. Hartman H, Mutmansky J (2002) Introductory mining engineering, 2nd edn. John Wiley, New York, p 592
3. Lessard J, Hadjigeorgiou J (2006) Ore pass database: Quebec underground metal mines. CIM Bull 99(1093):12
4. Esmaieli K, Hadjigeorgiou J (2011) Selecting ore pass-finger raise configurations in underground mines. Rock Mech Rock Eng 44:291–303
5. Stewart B, Inverson S, Beus M (1999) Safety considerations for transport of ore and waste in underground ore passes. Min Eng 51(3):55–60
6. Hadjigeorgiou J, Lessard J, Mercier-Langevin F (2005) Ore pass practice in Canadian mines. J South Afr Inst Min Metall 105(11):809–816
7. Hambley D, Pariseau W, Singh M (1983) Guidelines for open-pit ore pass design. Final report on contract J0205041 with US Bureau of Mines. Engineers International, Inc., Westmont, IL
8. Hagan T, Acheampong E (1999) Current design, support and maintenance of rockpasses and assessment of practices applicable at depth. In: Proceedings of the 2nd Southern African rock engineering symposium, pp 62–79
9. Beus M, Parlseau W, Stewart B, Iverson S (2001) In: Hustrulid W, Bullock R (eds) Underground mining methods: engineering fundamentals and international case studies. Society for Mining, Metallurgy and Exploration Inc, Littleton, CO, pp 627–635
10. Lessard J, Hadjigeorgiou J, Turcotte P (2002) Rock pass operational problems in Quebec underground mines. Canadian Institute of Mining, Metallurgy and Petroleum
11. Stacey T, Erasmus B (2005) Setting the scene: rockpass accident statistics and general guidelines for the design of rockpasses. J South Afr Inst Min Metall 105(11):745–752
12. Hadjigeorgiou J, Stacey T (2013) The absence of strategy in orepass planning, design, and management. J South Afr Inst Min Metall 113(10):795–801
13. Hadjigeorgiou J, Mercier-Langevin F (2008) Estimating ore pass longevity in hard rock mines. In: The 42nd U.S. Rock Mechanics Symposium (USRMS) (U.S. Rock Mechanics/Geomechanics Symposium, San Francisco, CA), pp ARMA–08–165
14. Salmi EF, Phan T, Sellers EJ, Stacey TR (2024) A review on the geotechnical design and optimisation of ultra-long ore passes for deep mass mining. Environ Earth Sci 83(10):301
15. Hambley D (1987) Design of ore pass systems for underground mines. CIM Bull 897:25–30
16. Maree J (2011) Orepass best practices at South Deep. J South Afr Inst Min Metall 111(4):257–272
17. Selleck DJ, Pfleide E (1968) In: Pfleide E (eds) Underground mining methods: engineering fundamentals and international case studies. The American Institute of Mining, Metallurgical, and Petroleum Engineers, New York, pp 637–648
18. Sachse N, Westgate U (2005) Rockpasses: a guide to excavation methodology. J South Afr Inst Min Metall 105(11):759–763
19. Bunker K, Campbell A, O'Toole D, Penney A (2015) Guidelines for orepass design in a sublevel cave mine. In: Design methods 2015: proceedings of the international seminar on design methods in underground mining. Australian Centre for Geomechanics, Perth, pp 585–600
20. Sjöberg J, Bolin A, Sanchez Juncal A, Wettainen T, Mas Ivars D, Perman F (2015) Input to orepass design—a numerical modelling study. In: Design methods 2015: proceedings of the international seminar on design methods in underground mining. Australian Centre for Geomechanics, Perth, pp 571–584
21. Dabula G (2019) Comparison of the genetic algorithm and linear programming approaches to optimally locate orepasses in the Venetia underground project. Ph.D. thesis, University of the Witwatersrand, Johannesburg
22. Halilović D, Gligorić M, Gligorić Z, Pamučar D (2023) An underground mine ore pass system optimization via fuzzy 0–1 linear programming with novel Torricelli-Simpson ranking function. Mathematics 11(13):2914
23. Vieira F, Durrheim R (2005) Design and support of rockpasses at ultra-deep levels. J South Afr Inst Min Metall 105(11):783–794
24. Hadjigeorgiou J, Lessard J, Mercier-Langevin F (2004) Issues in selection and design of ore pass support. Ground support in mining and underground construction, p 916
25. Potvin Y, Hadjigeorgiou J, Wesseloo J (2019) Towards optimising ground support systems in underground mines. In: Ground support 2019: Proceedings of the ninth international symposium on ground support in mining and underground construction. Australian Centre for Geomechanics, pp 493–502
26. Esmaieli K, Hadjigeorgiou J (2014) Impact-induced damage on foliated ore pass walls. CIM J 5(1):39–47
27. Skawina B, Greberg J, Salama A, Gustafson A (2018) The effects of orepass loss on loading, hauling, and dumping operations and production rates in a sublevel caving mine. J South Afr Inst Min Metall 118(4):409–418
28. Brenchley P, Spies J (2006) Optimizing the life of ore passes in a deep-level gold mine. J South Afr Inst Min Metall 106(1):11–16
29. Skawina B, Greberg J, Jonsson K, Salama A (2016) Ore pass loss mitigation approach in Malmberget mine. Conference & exibition on mass mining: 09/05/2016-11/05/2016. The Australian Institute of Mining and Metallurgy, Melbourne, pp 617–622
30. Skawina B, Salama A (2021) Analyzing the electricity consumption and costs of electrical-powered machines when there is orepass failure in underground mine. Tanzania J Sci 47(1):180–193
31. Manzoor S, Gustafson A, Schunnesson H (2023) Dumping oversize rock fragments in orepasses: the impact on the production cycle of a sublevel caving operation. Min Technol 132(3):215–224
32. Jenike AW (1961) Gravity flow of bulk solids. Bulletin No. 108, Utah Engineering Experiment Station, Univ. of Utah
33. Johanson J, Colijn H (1964) New design criteria for hoppers and bins. Association of Iron and Steel Engineers
34. Kvapil R (1965) Gravity flow of granular materials in hoppers and bins. In: International journal of rock mechanics and mining sciences & geomechanics abstracts, vol. 2. Elsevier, pp 25–41
35. Kvapil R (1965) Gravity flow of granular materials in hoppers and bins in mines—II. Coarse material. In: International journal of rock mechanics and mining sciences & geomechanics abstracts, vol. 2. Elsevier, pp 277–292
36. Colijn H, Hanson P (1970) Practical applications of hopper and bin design. Can Min Metall Bull 63(699):791

37. Hadjigeorgiou J, Lessard J (2007) Numerical investigations of ore pass hang-up phenomena. Int J Rock Mech Min Sci 44(6):820–834
38. Hadjigeorgiou J, Lessard J (2010) Strategies for restoring material flow in ore and waste pass systems. Int J Min Reclam Environ 24(3):267–282
39. Stacey T, Swart A (1997) Investigation into drawpoints, tips orepasses and chutes. Safety in mines research advisory committee, vol 1
40. Beus M, Stewart B, Iverson S (1996) Design and hazard assessment of mine ore passes. In: Proceedings... international conference on ground control in mining, vol. 15. Department of Mining Engineering, College of Mineral and Energy Resources, West Virginia University, p 297
41. Beus M, Ruff T (1997) Development of a mine hoist and ore pass research facility. Tech. rep., National Institute for Occupational Safety and Health (NIOSH) - The Spokane Mining Research Division (SMRD), Spokane, WA
42. Beus M, Iverson S, Stewart B (1997) Application of physical modelling and particle flow analysis to evaluate ore-pass design. Trans Inst Min Metall Sect A: Min Technol 106:A110–A117
43. Larson M, Iverson S, Stewart B, Walker K (1998) Preliminary assessment of particle flow code as a tool to assess ore pass safety. Int J Rock Mech Min Sci 35(4):533–533
44. Beus M, Iverson S, Stewart B (1998) Design analysis of underground mine ore passes: current research approaches. In: The 100th CIM conference. Montreal, p 8
45. Beus M, Iverson S, Dreschler A, Scott V (1999) Static and dynamic loads in ore and waste rock passes in underground mines. In: ARMA US rock mechanics/geomechanics symposium. ARMA, pp ARMA–99
46. MacLeod M (1954) Conversion of long ore pass raises at H.B. Mine, Salmo, B.C. CIM Bull
47. Edelbro C, Brummer R, Pierce M, Sandstrom D, Sjöberg J (2019) Raiseboring in difficult rock conditions. In: Ground support 2019: proceedings of the ninth international symposium on ground support in mining and underground construction. Australian Centre for Geomechanics, Perth, pp 185–198
48. Rojas C, Anani A, Cordova E, Nyaaba W, Wellman E, Adewuyi SO (2024) Analysis of raise boring with grouting as an optimal method for ore pass construction in incompetent rock mass—a case study. Min Metall Explor 41(4):2177–2191
49. Iverson S, Jung S, Biswas K (2003) Comparison of ore pass computer simulations for designs against dynamic load. In: Annual meeting of the Society for Mining, Metallurgical, and Exploration. Cincinnati, p 11
50. Esmaieli K (2010) Stability analysis of ore pass systems at Brunswick Mine. Ph.D. thesis, University of Laval
51. Nazeri H, Rozgonyi T (2003) The modeling of gravity flow of ore in ore passes. In Annual meeting of the Society for Mining, Metallurgical, and Exploration. Cincinnati
52. Canadian Senior Ground Control Engineer (2024) Personal communication by email
53. Sjöberg J, Lundman P, Nordlund E, Quinteiro C (2003) Stability analysis of ore passes in the Kiirunavaara Mine. In: The 10th ISRM Congress. International Society for Rock Mechanics, Sandton, South Africa, pp 1093–1098
54. Canadian Principal Geotechnical Engineer (2024) Personal communication by email
55. Hart R (2006) Case study of the rockpass system at Kloof No. 3 Shaft. J South Afr Inst Min Metall 106(1):1–4
56. Gardner L, Fernandes N (2006) Ore pass rehabilitation-case studies from Impala Platinum Limited. J South Afr Inst Min Metall 106(1):17–23
57. Esmaieli K, Hadjigeorgiou J (2009) Influence of finger configuration on degradation of ore pass walls. In: Proceedings of the 3rd CANUS rock mechanics symposium, vol. 4003. Toronto, Canada, pp 4001–4012
58. Szwedzicki T (2007) Formation and removal of hang-ups in ore passes. Min Technol 116(3):139–145
59. Sredniawa W, Skawina B, Rapp J, Shekhar G, Gunillasson J (2022) Longevity chart for planning production and the renovation of orepasses. In: Caving 2022: proceedings of the fifth international conference on block and sublevel caving. Australian Centre for Geomechanics, Perth, pp 369–380
60. Rose J, Grant D, O'Toole D (2016) Orepass monitoring and management at Olympic Dam Mine. In: Proceedings seventh international conference and exhibition on mass mining (MassMin 2016). The Australasian Institute of Mining and Metallurgy, Melbourne, pp 609–616
61. Skawina B, Salama A, Gunillasson J, Strömsten M, Wettainen T (2022) Comparison of productivity when running filled, near-empty, or flow-through orepass using discrete event simulation. Mining 2(2):186–196
62. Stacey T, Hadjigeorgiou J (2022) Quantified value-created process (QVP) - a value-based process for mine design and operating decisions. J South Afr Inst Min Metall 122(2):73–82