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Risks associated with paste filling for underground mining

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Abstract

The main objective of using paste fill in underground mining is to provide stable ground conditions to optimise mining recovery and productivity while ensuring safety and the stability of the mine.

Like all mining methods, implementing paste fill will alter the mine's risk profile. These new risks can affect the mining operation in different ways, from slight ore dilution to significant production losses. In severe situations, they could lead to injuries or fatalities, halted operations, and harm to the company's reputation. If these risks are not thoroughly evaluated and properly addressed in a timely manner, they could significantly impact daily operations, the owner, and stakeholders.

A comprehensive risk assessment and effective control measures are key components to achieving a paste fill system that is safe, functional, optimised, and cost-efficient.

This paper will provide some recent examples of risks associated with application of underground paste filling and will focus on the risk assessment and the mitigation measures completed as part of operational readiness of the Rosh Pinah paste fill system.

Keywords: *risk assessment, hazard and operability (HAZOP), operational readiness, paste fill system, paste management system*

1 Introduction

1.1 Literature review

Conducting a thorough risk assessment and implementing effective control measures for high-risk activities is crucial in the practice of paste filling underground. The paste system has been around for close to 50 years, despite this there are very few papers published on the risks and failures associated with paste fill.

Isagon (2017) discusses risk assessments for paste tailings projects and examines the key factors that should be incorporated into risk assessments for high solids concentration tailings applications in mining, including underground paste backfill and surface paste tailings deposition. However, the critical risks associated with paste fill and how to effectively identify and mitigate these risks have not been discussed. This literature review explores the various methods of conducting risk assessments and effective control measures of risks associated with paste fill.

1.1.1 Methods of risk assessment

Risk assessment methods are systematic approaches used to identify, evaluate, and manage potential hazards. The purpose of risk assessment is to minimise the likelihood and impact of adverse events, ensuring safety, compliance, and efficiency while optimising decision-making and resource allocation in complex and high-risk paste filling situations.

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Some common methods used for risk assessments at mines are listed below:

- Risk register: a risk register is a tool used to document identified risks, their potential impact, likelihood, and mitigation measures. It serves as a centralised record of risk management efforts.
- Hazard and operability study (HAZOP): the HAZOP is a structured technique used to identify hazards and operational problems. It involves a detailed review of each step in a process to identify potential risks and their effects on the system.
- Triggered action response plan (TARP): the TARP is taken from a mine's major hazard management plan. It consists of a set of documented and known workplace hazards that need to be continuously checked for.
- Qualitative risk assessment: this method involves subjective evaluation of risks based on expert judgment, experience, and available data. It often utilises risk matrices or qualitative scales to categorise the severity and likelihood of risks.
- Quantitative risk assessment: this approach relies on numerical data to calculate the likelihood and impact of risks. Techniques such as probabilistic risk assessment, fault tree analysis, and event tree analysis are commonly used to model and quantify risks.

1.1.2 Effective control measures

Effective control measures are essential for ensuring safety, efficiency, and productivity in paste filling operations. They help mitigate risks, prevent accidents, and ensure consistent paste fill quality while optimising resource use. Additionally, control measures aid in compliance with regulations, cost management, and environmental sustainability. By proactively addressing potential issues, they contribute to smoother operations, reduced downtime, and overall long-term success.

Examples of effective control measurements include:

1. Safe designs: ensuring underground paste fill system is designed with safety in mind.
2. Safety procedures: ensuring safety procedures are up to date and readily available.
3. Safety protocols: implementing personal protective equipment requirements, safety training, and emergency response plans to minimise accidents and injuries.
4. Process monitoring: using real-time sensors and CCTV to monitor key parameters (e.g. pressure, flow rates) to ensure processes remain within safe and optimal ranges.
5. Preventive maintenance: scheduling regular inspections and maintenance of equipment to prevent breakdowns and ensure smooth operation, thus reducing downtime and repair costs.
6. Quality control: implementing testing and inspection procedures at various stages of production to ensure the final product meets required standards and specifications.
7. Risk assessments: conducting regular hazard identification and risk assessments to proactively address potential issues before they escalate.
8. Environmental controls: installing filtration systems, waste management protocols, or emission controls to reduce environmental impact and comply with regulations.
9. Training and education: regularly training staff on operational procedures, safety standards, and emergency protocols to ensure preparedness and effective response to incidents.
10. Automated control systems: using computer-based systems to control processes, reduce human error, and ensure consistent operation within desired parameters.

2 Examples of paste fill system risks

2.1 Paste wall failures

The reported examples of paste wall failures in paste fill operations are typically due to several factors including inadequate design, poor construction, lack of quality control, poor fill placement regime, and ineffective tight-filling practices that result in excessive pressures on fill walls. Incorrect fill wall orientation can significantly weaken its load-bearing capacity. Additionally, inconsistencies in shotcrete batch mixing, poor spray quality, and a non-uniform thickness below the design specification are often major causes of paste leakage and wall failures.

There are numerous wall failure incidents that have occurred under tight-filling conditions (Figures 1 and Figure 2). Filling of the crown of the stopes, either through the crown walls or from upholes or downholes are the most critical as the reticulation pressure exceeds the limited capacity of shotcrete walls.

A West Australian mine had a paste wall failure in a drive at the top of a stope, which could have claimed lives. The cause of failure was due to the excessive hydraulic pressure being exerted from the paste fill. As a result of the incident, it was recommended to conduct an engineering and risk assessment for individual stopes when using paste fill. Using remote monitoring devices, establishing and enforcing exclusion zones and training worker in all operating aspects of the paste fill process was suggested for preventing similar occurrences (AMSJ 2020).

Figure 1 Example of shotcrete paste wall failure during tight filling (Gray 2019)

Figure 2 Examples of paste wall failure consequences (Yumlu 2007)

2.2 Reticulation failures and blockages

The risk of paste fill reticulation blockage is an inherent challenge in mining operations, influenced by factors such as the variability of input feed parameters, the positioning of the delivery point within the underground workings, and the complexities involved in delivering a high-yield paste mixture through a gravity or pump assisted reticulation system. It is therefore critical to have effective control measurements in place.

A reticulation failure is often due to an event such as a pipe wall failure, or a coupling failure. It results in paste mixture escaping from the pipe work, into the mine workings. Numerous reticulation failures and blockages have been reported in paste fill systems (Figure 3) which can have major impact on the safety and production.

The following are examples of paste reticulation blockages:

- Paste reticulation blockage at CSA mine owned and operated by Cobar Management Pty Ltd in July 2018. The blockage was caused by a failure in an unlined inter-level borehole. This failure obstructed the flow of paste, leading to a buildup and subsequent curing of the material inside the reticulation system. Attempts to flush the blockage were initially unsuccessful due to the high binder content, which caused the paste to harden over time. The issue was ultimately resolved by removing sections of the pipe and using a mobile flushing head, but the borehole had to be redrilled to restore full operation. As a result of the incident, the importance of a well-established emergency procedure was emphasised to help overcome a blocked paste line with high potential losses (Morcombe 2019).
- Reticulation blockage at the Independence Group NL (IGO) Nova Mine located in the Fraser Range, Western Australia. The blockage was caused by a build-up of paste in the underground reticulation system, which likely began after the paste plant tripped due to an equipment fault. Through a combination of water flushing, isolations, and manual intervention the thick cured paste was progressively evacuated. After 7 hours of coordinated effort, the blockage was fully cleared, and paste filling resumed. As a result of the incident effective control measurements were put in place such as having a reliable fibre optic communications network, having experienced paste operational personnel and having clear escalation processes (M Griffiths 2019). These control measurements were used to prevent the likelihood of the risk occurring again.

Figure 3 Examples of reticulation failures and pipe blockages

2.3 Plant equipment failure

Paste plants have numerous equipment which needs to be designed, installed and maintained correctly to avoid equipment failure. Some equipment failures at paste plants include:

- tailings surge tank failure
- filter failure
- mixer failure
- cement dosing system failure
- pump failure
- valve and instrument failure

During the commissioning of a paste plant a 200 m^3 filter tank failed, injuring a worker. The tank was being filled with thickened tailings (slurry) for the first time. The cause of the failure was due to poor design, as the bolted tank did not have the required Factor of safety.

A. Damaged structure:
   i. displaced wall cladding
   ii. deformed I-beam
B. Filter tank
C. Former tank wall location (prior to failure)
D. Remnant slurry
E. Displaced tank wall

Figure 4 Example slurry tank failure (WorkSafe 2019)

2.4 Plant commissioning delays

Commissioning delays can have a major impact on planned production (African Mining 2021). In Golden Star's Wassa mine the impact on production was 21% of the planned production (Golden Star Resources 2021). This required the resequencing of the mine to minimise the impact of the commissioning delay. The commissioning of the paste system was delayed by some quality assurance testing returning lower than expected fill strengths in the test stope.

3 Risk assessment methodology

3.1 Overview

Risk refers to the chance that specific hazards or threats may arise, potentially hindering the achievement of defined goals. Risk assessment is conducted to analyse the likelihood and impact of these events. By ranking risks, the most critical incidents can be identified, allowing for prioritisation of mitigation efforts. This process necessitates a solid commitment from the risk assessment team and complete backing from management to ensure alignment with the stated objectives for optimal safety, efficiency, and cost-effectiveness.

The risk assessment process begins with a well-defined objective, context, and scope. To carry out an effective assessment, a team of qualified individuals is necessary. For underground backfill applications, the primary goal is to ensure stable ground conditions to enhance safety, mining recovery, and productivity.

To complete an effectively defined risk assessment process are as follows:

- well-defined and precise objective
- skilled and accessible resources assigned
- efficient use of time and budget
- risks identified based on facts and evidence
- flexible, consistent, and practical for implementation
- delivers value for essential stakeholders
- adheres to company policies and standards
- complies with health, safety, and environmental regulations
- regularly monitored and updated.

3.2 Objective

The primary objectives of risk assessment are to:

- identify, analyse, and assess the specific risk issues associated with operating and maintaining the paste fill system to be installed
- this risk assessment addresses the fill engineering and management, fill production, reticulation, placement, exposure, quality assurance and management components of the system only
- a HAZOP needs to be completed for the process, mechanical and structural aspects of the paste plant
- identify and analyse current controls
- recommend additional controls to reduce the risk to 'as low as reasonably practicable' (ALARP)
- ensure compliance with relevant standards and government legislation.

The following items are identified as desired outcomes from the process:

- a consolidated list of recommended actions
- a document and risk table suitable for review by the risk assessment team and aligned to companies risk assessment and management policies.

3.3 Scope

The scope of the risk review on the paste fill system is to (BGMC 2024):

> *'Conduct a detailed design, construction, operability and maintainability process risk review of the proposed pastefill system. The process should identify the hazards, analyse the risks, determine acceptability of risk and develop recommendations for additional controls.'*

Other clarifying aspects of the risk review includes (BGMC 2024):

- **Time**: the risk assessment will cover from design to completion of backfill operations.

- **Function**: the intended function of the risk assessment is to consider operability, constructability and maintainability aspects of the proposed paste fill system and incorporate risk mitigation through design wherever possible. Additionally, more specific operations and maintenance risk assessments may be required at a later stage including job safety analysis (JSA) through construction and operation.
- **Mandate**: the mandate of the team is to (BGMC 2024):

  'The team is to recommend controls for addressing identified risks. There will be an action plan with By Whom and By When'.

3.4 Process

The international risk management standard, ISO 31000:2018 Risk Management (International Organization for Standardization 2018), is used to provide guidelines on managing risks. The risk management process entails the systematic implementation of policies, procedures, and practices across activities such as communication and consultation, defining the context, as well as evaluating, addressing, monitoring, reviewing, documenting, and reporting risks.

3.4.1 Framework

Figure 5 shows the common steps for the Risk Management process as per Risk Management – Guidelines (ISO 31000:2018; International Organization for Standardization 2018).

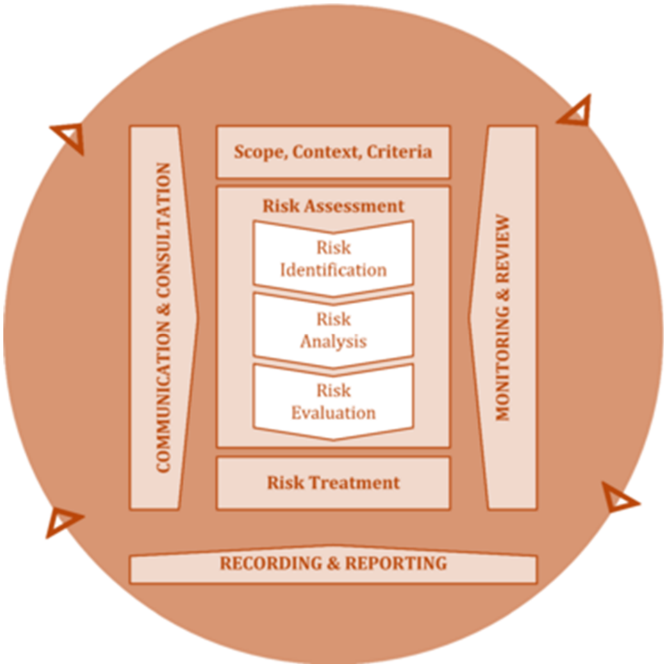

Figure 5 Process (ISO 31000:2018 [Risk Management – Guidelines])

3.4.2 Key steps

The key steps in the Risk Assessment (RA) process is:

1. planning (scope, context, criteria)
   a. confirm the scope of the risk review and mandate of the team
   b. list the key assumptions on which the risk review is based
   c. collate and review available data on the paste fill system.
2. conduct team-based multi-disciplinary risk assessment

   a. risk identification – identify and assess the potential risks
   b. risk analysis – determine current controls
   c. risk evaluation – identify and recommend additional actions to be considered
   d. rank hazards/issues using the site's risk assessment tool.
3. risk treatment
4. recording and reporting
   a. issue draft action plan for immediate review and action
   b. team member review and modification as required
   c. write draft report for review by personnel
   d. finalise report and issue as controlled copy for ongoing use.
5. monitoring and review
6. communication and consultation.

3.4.3 Risk criteria

The risk criteria utilised is to reduce the risk to ALARP. This concept involves reducing risks to a level that is as low as possible, given the current circumstances, but without incurring disproportionate costs, effort, or difficulty.

Figure 6 shows an example of the ALARP principle.

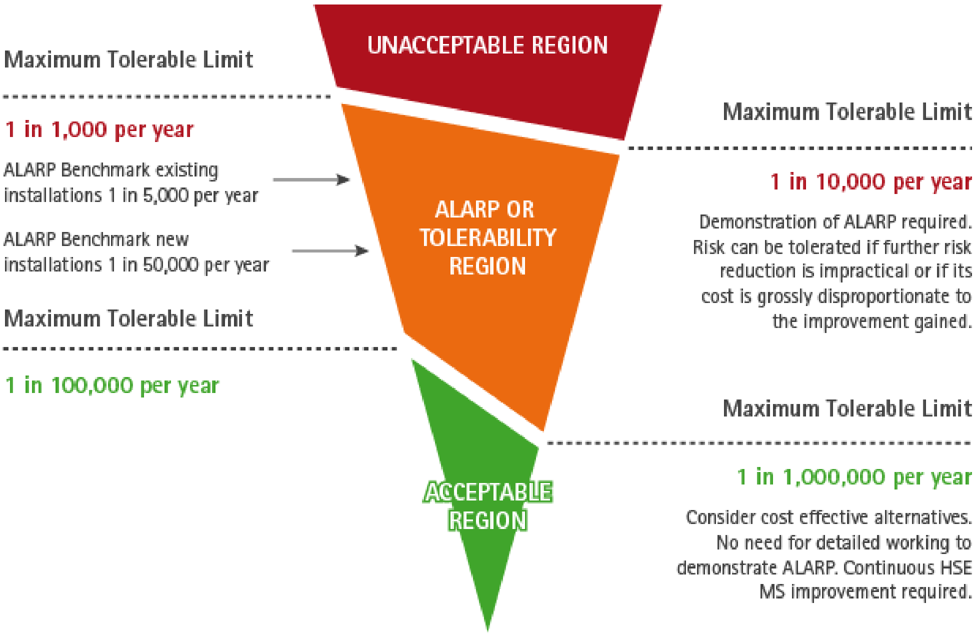

Figure 6 Risk criteria (as low as reasonably practicable)

4 Case study: Rosh Pinah Zinc mine paste fill system

4.1 Overview

Rosh Pinah Zinc Corporation (Pty) Ltd is currently constructing a paste backfill system at Rosh Pinah Zinc mine. The paste plant is currently being constructed and initial paste fill operations are expected to commence in the first quarter of 2025. Paste backfill will be used as primary backfill method to improve underground stability and maximise ore recovery.

4.2 Mine location

The Rosh Pinah Zinc mine is in south Namibia near the town of Rosh Pinah, 800 km southwest of the capital city of Windhoek, and 20 km north of the Orange River at the edge of the Namib Desert (Figure 7).The Rosh Pinah 2.0 expansion project comprise the construction of new processing facilities, which also includes the construction of a paste fill plant, water treatment plant and a new portal and decline for larger trucks to increase production. The project will increase the underground mining and mill throughput from current 0.7 million tonnes to 1.32 million tonnes of ore per annum.

Figure 7 Rosh Pinah Zinc mine location

4.3 Key risk areas at Rosh Pinah Zinc mine

4.3.1 Execution strategy/operations readiness/documentation/technical manual/paste management system/checklists/standard operating procedures

The purpose of these documents is to outline systems and procedures that should be utilised by personnel who are involved with the paste fill design and operations to ensure the paste fill is produced safely, effectively, sustainably, and economically to support the mine plan. It is critical to have the correct documentation, including a paste fill management system or paste management plan – which outline the systems used to ensure safe and efficient backfill design and placement. These documents define all related activities associated with paste fill placement underground and assigns responsibilities to personnel to ensure filling is conducted in a safe, systematic, and responsible manner.

Below is a list of key risks associated with lack of documentation and systems:

1. lack of risk assessment causing unsafe operation and working practices, plant and equipment failures and substandard work practices
2. poor system design or lack of robust engineering design
3. lack of commissioning and handover documentation
4. lack of systems and procedures causing operational delays
5. lack of holistic and overarching fill strategy covering the entire mine which has the risk of not achieving a functional, optimised and cost-effective paste system

6. lack of efficient communications and signoffs causing delays when overall backfill is not meeting the demand from underground mining
7. lack of organisational chart, resourcing and training
8. lack of job description, roles and responsibilities not clear or understood
9. lack of sufficient testwork for establishing relationship between cement rate, cure age and solids content which could cause barricade failures and fill inrush
10. lack of stope specific exposure design method
11. lack of emergency response plan and safety drills
12. lack of systems and procedures for investigating and reporting paste related incidents.

4.3.2 Paste plant

The paste plant at Rosh Pinah Zinc mine is currently in progress, and it is expected that the paste fill system will be commissioned in the second quarter of 2025. The filtered tailings, cement binder and process water will be mixed in a continuous mixer to produce paste fill – as per mix design specifications. Paste fill will be pumped underground via the surface pipeline, decline pipeline, internal boreholes, and level pipelines to fill the stopes voids.

There are potential risks associated with the paste plant including:

1. Plant location, layout and size not being suitable, can cause damage to the paste plant structure and not be able to achieve life of mine backfill schedule.
2. Change in ore feed or grinding operations resulting in unexpected tailings sizes can cause operational issues with paste production and paste quality.
3. Low pH of tailings slurry impacting the strength and flow of paste fill causing failure or dilution.
4. Inadequate integration of process plant, tailings and paste plant can cause operational issues and production delays and loss.
5. Paste solids content being too high or too low can cause operational issues that lead to failure.
6. Changes in tailings minerology can decrease paste strength which can result in failure during exposure and increased bulkhead loads.
7. Substandard binder causing poor quality paste can result in barricade failure and liquefication, or major fill failure upon exposure.
8. Inadequate handover procedure/lack of handover documentation can impact plant operation and safety, which can cause production delays.

4.3.3 Reticulation

The paste fill reticulation system at Rosh Pinah is comprised of a delivery pump and surface pipeline that connects the surface paste plant to the underground distribution system, which is used to divert paste to the stope voids via a network of internal boreholes and lateral pipelines. The reticulation system is pump assisted. Paste will be delivered to open stope voids via pipeline at the filling horizon from top level stope access, or crown fill holes drilled as blind upholes from stope mucking levels.

There are several potential risks associated with the reticulation system including:

1. Paste pump failure due to hardened paste or high pump pressures causing damage to equipment and production and schedule delays.
2. Surface pipeline damage due to surface traffic or inadequate interface between surface and underground connection causing pipeline blockages which impacts production and scheduling.

3. Borehole failure during drilling, lack of spare borehole, borehole casing wear and unclean boreholes which impacts cost, project schedules, and blockages which leads to production loss.
4. Inadequate flushing of the lines using water and air, which causes blockages and can delay production.
5. Lack of pipeline isolation which can lead to personnel injury and health, safety and environment (HSE) issues.
6. High operating pressures causing pipeline failure which can cause blockages and result in personnel injury, production delays and HSE issues.
7. Power failure causes production delays and blockages as the paste delivery pump can't be operated and dump valves cannot be opened.
8. Pipe installation can cause personnel injury during the handling and transportation of pipes.
9. Incorrect pipe specs/type can result in pipe failure.
10. Inadequate pipe support design can result in pipe movement and failure which can cause personnel injury and production loss.
11. Lack of communication between surface and underground operational personnel.

4.3.4 Barricades

The stability of paste fill barricades forms an integral part of safe and efficient filling operations. Liquefaction or mobilisation of fill because of barricade failure is a core geotechnical risk that can have serious consequences, including endangering the safety of personnel and causing property damage and production losses and delays.

Some of the critical barricade risks are as follows:

1. Inadequate paste wall design or design not suitable for the operating conditions can lead to paste wall failure and paste being mobilised into mine workings.
2. Lack of suitable shotcrete mix design and QA/QC testing can lead to paste wall failure and fill inrush causing personnel injury.
3. Failing to identify hazards from ground conditions can cause personnel injury.
4. Fall-off within stope and insufficient catchment area and bund at the stope brow to prevent material from flowing into drive.
5. Paste fill placed too quickly into stope and subjecting paste wall to excessive pressure which causes paste wall to fail and paste to mobilise into mine workings.
6. Lack of managing groundwater can lead to paste not curing due to excessive groundwater/water overloaded due to water pressure.
7. Lack of control during tight filling can cause the fill to back up, rise in the pipe, and exert excessive pressure on the paste wall, leading to its failure (Veenstra 2024).
8. Barricade not being constructed in accordance to design can cause paste to remobilise and flow into workings.
9. Inadequate drive length for exclusion zones can cause paste wall failure and expose underground crew to paste fill inrush.
10. Developing through paste wall can cause inrush of unconsolidated paste fill resulting in injury to personnel or damage to equipment.

4.3.5 Filling, placement and exposure

Cemented backfill will be an integral component of the mining process at Rosh Pinah. Paste fill restrains rock mass unravelling, helps maintain stable ground conditions, remain self-supporting during nearby blasting activities, and maintain stability when exposed vertically and horizontally during adjacent mining activities. To adequately service the mining process, the backfill system must be capable to produce fill with a specific range of strength and flow properties, delivered at a rate that does not constrain mining activities for the duration of mining operations.

As part of this process there are several critical risks including:

1. Inadequate stope filling strategy and fill placement management can cause pipeline failure, barricade failure, fill failure and inrush causing personnel injury.
2. Barricade failure during filling can lead to inrush of fill material which can cause personnel injury.
3. Firing of nearby development/stopes causes liquefication or fall-off in the stope and can lead to persons exposed to inrush event.
4. Ground or service water entering stopes during filling operations can reduce paste solids density and quality which can cause fill failure when exposed and increase bulkhead loads leading to bulkhead failure.
5. Paste fill strength inadequately designed for vertical exposure dimensions and undercut exposure dimensions can lead to potential for major fill dilution and loss of ore and loader damage.
6. Excessive cement from paste in ore can cause materials handling and process recovery issues.
7. Developing through paste can be hazardous, as personnel or equipment may encounter an exposed and unstable fill face, increasing the risk of injury or damage.

5 Conclusion

In conclusion, conducting thorough risk assessments for paste filling for underground mining is essential for ensuring the safety of workers, protecting the environment, and maintaining operational efficiency. These assessments help identify potential hazards, allowing for the implementation of effective mitigation strategies that reduce the likelihood of accidents and health issues. By prioritising risk management, mining companies not only comply with regulatory requirements but also foster a culture of safety that can lead to enhanced productivity and reduced operational costs. Ultimately, comprehensive risk assessments are vital for safeguarding lives, preserving natural resources, and supporting the sustainable development of the mining industry.

6 Acknowledgement

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