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Practical primer: a cave management system for safe and successful mining

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Abstract

Cave mining methods are among the most complex mining techniques used in the mining industry today, owing to their large scales, strong interdependence of geotechnical conditions and operational practices, and presence of caving-specific hazards. Challenges are further amplified as operations move to greater depths with higher stresses and increased geotechnical and operational risks. Despite these challenges, companies are increasingly turning to caving methods due to their capacity for high-tonnage, low-cost production from large underground orebodies. These organisations must learn to manage the complexities of cave mining, often with minimal institutional caving experience.

A strong cave management system is fundamental for the safe, successful and profitable extraction of planned reserves through all stages of caving. These systems integrate cave design and governance protocol with responsive hazard-specific management plans and performance monitoring programs (e.g. inrush, airblast, seismic hazard and subsidence) to guide mine operations and control risks. This paper outlines an experience-based management plan framework, including typical components, key considerations and performance metrics, which may be adopted by caving operations as a foundation for successful cave execution.

Keywords: *cave management, caving risks, hazards management, geotechnical monitoring*

1 Introduction

Underground cave mining methods are among the most complex and technically demanding extraction techniques used in the mining industry today. At the same time, block and sublevel caving methods continue to grow in popularity due to their ability to economically extract large, low-grade deposits at relatively high production rates. The strong economic incentives have led many organisations to adopt caving methods despite having limited institutional experience implementing or managing this type of mining.

Cave mining, unlike other underground mining methods, relies on stress- and gravity-induced controlled rock mass failure to break and recover the ore. This process introduces unique caving-related hazards and challenges operators due to the close interconnection between mine design, day-to-day operational practices and geotechnical conditions. The challenges become increasingly pronounced as caving mines pursue deeper orebodies, where higher in situ stresses, more complex rock mass behaviour and elevated seismic hazards are typical.

Successful cave operations require a high level of coordination between the engineering design, technical services and mine operations disciplines due to the integrated relationship between mining activity, rock mass response and associated potential for caving-related hazards (e.g. inrush, airblast, seismic hazard and subsidence). A robust cave management system provides the essential structure needed to link cave design principles, governance processes and operational controls with observed cave and rock mass performance

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throughout the life of the mine. These systems leverage governance protocols and responsive hazard-specific management and monitoring plans to guide mine operations and control risks.

This paper presents an experience-based cave management system framework, including typical components, key considerations and performance metrics. Important linkages and interactions between the various management plans are highlighted and serve as critical controls between disciplines. This overview information is intended as a practical primer for individuals and/or operators new to the management of cave mining operations. Such a system, when appropriately tailored to site-specific conditions and risks, may be adopted as a foundation for successful cave execution.

2 Objectives and structure of the cave management system

2.1 Overview of cave management system framework

Cave management systems are fundamental to the safe, successful and profitable extraction of ore in accordance with plans developed during the mining study and mine design phases. The purpose of these systems is to document the controls, procedures, guidelines and strategies supporting the safe and successful operation of the mine. The system facilitates good communication of, and adherence to, management strategies and expectations. The overall framework and associated management plans should be tailored specifically to each operation, and it is the responsibility of mine management to have an appropriate system in place to manage identified operational risks and hazards.

The two core components of the cave management system are operational cave management and caving-related hazard management:

- *Operational cave management* relates to guidelines and rules established for the design and execution of a cave mine, such as undercut protocol and draw control measures.
- *Caving-related hazard management* relates to the evaluation and management of risks directly associated with cave mining, including airblast, mud rush, seismic hazard, ground control hazard and subsidence. While these risks occur in other underground mining methods, the caving methods are especially susceptible.

2.2 Risk assessment: the basis of the cave management system

The management plans within the cave management system must be founded on a solid, site-specific understanding of operational risks and potential hazards. Risks to the mining operation should be assessed and quantified through a formal and documented risk assessment process. These assessments serve as a basis from which to develop tailored operational protocol, surveillance requirements, performance objectives and risk mitigation protocol.

Study objectives commonly include:

- identifying operational risks and potential caving-related hazards
- assessing risks (likelihood and consequence) associated with the identified operational risk or safety hazard
- developing monitoring protocol and risk-based thresholds to identify changes in risk associated with each operational risk or safety hazard
- determining appropriate control measures to mitigate risks associated with each risk/hazard; these may include heightened surveillance, modified operational protocol, etc.

All management plans discussed herein should be informed by the results of these risk assessments.

2.3 Performance objectives and trigger action response plans

Quantifiable performance objectives (QPOs) and associated trigger action response plans (TARPs) are used throughout the cave management system to evaluate the level of risk to the operation based on observed conditions such as muckpile fines and drainage, ground displacement or interpreted airgap. An example of a tiered QPO-TARP framework is shown in Table 1. This organisational structure (or similar) is commonly used to prompt actions such as heightened monitoring, operational changes and/or emergency response measures commensurate to the interpreted level of risk.

The following are typical components of a QPO-TARP framework:

- *Risk classifications* – tiered risk classifications that are applied based on observed conditions.
- *Triggers* – QPO thresholds are defined to assign a risk classification based on observed conditions.
- *Response actions* – predefined response actions within each risk classification (e.g. heightened monitoring, mitigation measures and emergency response, as warranted).
- *Monitoring and assessment requirements* – surveillance methods and frequencies and required QPO evaluation intervals when each risk classification is active.

Table 1 Example QPO-TARP framework

Quantifiable performance objective	Minimal risk	Low risk	Moderate risk	High risk
Performance category				
Performance objective description	Trigger: condition that must be met to remain within the minimal risk classification Response: N/A Monitoring: routine monitoring within minimal risk classification	Trigger: condition that triggers low risk classification Response: actions required in response to low-risk classification Monitoring: monitoring requirements within low risk classification	Trigger: condition that triggers moderate risk classification Response: actions required in response to moderate-risk classification Monitoring: monitoring requirements within moderate risk classification	Trigger: condition that triggers high risk classification Response: actions required in response to high-risk classification Monitoring: monitoring requirements within high risk classification

2.4 Governance structure

A clear and effective governance structure is essential to the success of a complex management system. This section outlines key framework components that are essential to all management plans.

2.4.1 Roles and responsibilities

Establishing well-defined roles and responsibilities is critical to the implementation of a successful cave management plan. It is important to set clear expectations and accountabilities for tasks and decisions within the management plans to promote alignment throughout the disciplines. Responsibilities should be documented for personnel supporting the cave management system, including those at all organisational levels: executives, mine management, the technical services team and mine operations. This structure should clearly define who is responsible for day-to-day operational and monitoring tasks and who is responsible/accountable for communicating and implementing mitigation measures and/or making key decisions should elevated operational risks or safety hazards be detected.

2.4.2 Review and change management

Management plans should be considered living documents, formally reviewed annually (typical frequency; adjusted relative to level of risk) and revised as needed to reflect current mining practices, phase of caving, and learnings and experience gained from the mine's performance history. Updates may also be required to include changes to legislative or permitting requirements, to reflect updated operational practices, or to incorporate new technologies. It is important, however, that any changes be endorsed and approved by key stakeholders and documented following a defined change management process.

2.4.2.1 Internal review

Management plans should be reviewed to verify they remain appropriate, with review frequency commensurate to the level of risk and changeability of conditions and practices within their scope. It is important that review occurs across all levels of the organisation, from operations general supervision, technical team and upper management.

2.4.2.2 External review

It is considered best practice to engage independent caving and geotechnical review boards to regularly review major technical and operational-related findings, practices and risks, with emphasis on ensuring that the operation follows industry-accepted practice and complies with internally defined procedures. The focus for each review meeting should be directed by the technical services team with close involvement of the mine management group. To be most effective, the independent review board should have a direct reporting line to senior management, with findings and recommendations communicated to that level following each engagement. A report summarising the meeting findings should be produced following each engagement as formal documentation.

The responsibility of the independent technical experts is to provide advice and recommendations based on their technical expertise and knowledge from other caving mines. Annual external reviews are typically considered most effective for actively caving operations; however, frequency should be tailored to site-specific conditions and levels of risk.

3 Operational risks and caving-related hazards

The primary objective of the cave management system is to safely achieve production targets while minimising operational risks and caving-related hazards. Descriptions of caving-related hazards and common operational risks are provided in the following subsections.

3.1 Caving-related hazards

3.1.1 Seismicity

The proactive management of seismic risk is critical for mines operating in seismically active conditions. Seismicity and seismic hazard are not unique to cave mining; however, the nature of the caving process causes significant changes to stress conditions throughout the mine, commonly inducing seismic events above the propagating caved zone, in the abutment regions around and below the footprint, in proximity to mine workings, and along geological structures within the influence of the mine. As such, management of seismic risk is considered an especially important consideration for caving mines.

3.1.2 Airblast

An airblast is defined by the industry as a "rapid displacement of large quantities of air, often under pressure, in a constrained underground environment caused by a fall of ground or other material" (New South Wales Department of Primary Industries 2006). If the cave void is sufficiently large, the air volume discharged into connected drives may have high velocities and/or generate substantial pressures, resulting in personnel injury or fatality along with significant damage to equipment and infrastructure. These types of failures are most common during the cave initiation and propagation stages of caving due to the need to create a void to progress cave growth and are typically alleviated following breakthrough to the surface or overlying pre-existing caved zones, if present (Thomas et al. 2024).

3.1.3 Mud rush

A mud rush is a sudden, uncontrolled ingress of water and solids into underground workings. Such events can result in injury, loss of life, property damage, dilution, production delays and even mine closure (Jakubec 2019). Potential for mud rush risk should be evaluated early in the project, and controls should be established well ahead of production as part of a mud rush risk management plan.

There are three mechanisms that are needed to create the potential conditions for a mud rush to occur:

- water and material fines content
- a discharge point (e.g. drawpoints)
- a trigger mechanism (e.g. mucking, blasting).

Any mining activity that causes the formation of fine particles and accumulation of water may create a mud rush risk. However, mines that employ cave mining methods are particularly susceptible to mud rush events for four reasons:

1. The caving process causes comminution of the orebody, creating finely fragmented, mud-forming material.
2. Cave breakthrough to the surface can introduce surface water (precipitation and runoff) and fine overburden to caved ore. Water can saturate fine material to a point at which it will flow.
3. Drawpoints connect directly to the cave, providing a discharge point through which saturated material can flow into underground workings.
4. Production activities, such as mucking and blasting, cause disturbances that can trigger mud rushes.

3.1.4 Subsidence

Subsidence is the deformation (lowering) of the ground surface due to the underground extraction of ore or other resources. Caving mining methods typically cause significant deformation of the ground surface, as material extracted from underground is not backfilled. This can pose a serious risk to the site, as surface infrastructure is often situated close to the mining area to optimise production. An initial subsidence prediction analysis should therefore be carried out as part of the feasibility study to confirm that surface infrastructure is sited and managed without unacceptable interaction with mining-induced subsidence (Davies et al. 2018). Throughout operations, it is important to have a strong understanding of potential and actual subsidence progression to manage subsidence-related infrastructure and personnel risks (Kamp et al. 2020).

3.2 Operational risks

Caving mines must also manage a broad set of operational risks that can significantly influence production performance, with potential long-term implications to the success of the mine. Common operational risks are described in the following subsections.

3.2.1 Dilution/sterilisation

Dilution and sterilisation pose significant risks to the economic performance of a cave mine. The ingress of waste or inability to recover the caving orebody are often the result of sub-optimal draw control practices (e.g. inconsistent compliance with planned draw strategies or loss of drawpoint access) or geological conditions or cave behaviour that differ from expectations.

3.2.2 Ground conditions

Cave mines are especially susceptible to a range of challenging ground conditions due to the caving process. Caving induces large-scale rock mass deformation, progressive fracturing, and changes in stress paths that can significantly amplify geotechnical hazards. These conditions evolve throughout the cave life cycle. Mines must effectively manage fall of ground hazards, drive convergence, and prevent damage to drawpoints. Conditions can progress substantially if left unmitigated, resulting in widespread convergence, drawpoint unavailability, and/or loss of access to entire production drives. These occurrences can substantially impact production and operational continuity and put reserve recovery at risk.

3.2.3 Hang-ups and drawpoint blockages

Drawpoint hang-ups are a typical occurrence in cave mines and occur due to oversized material attempting to pass through the drawpoint during the initiation and/or early-stage propagation phases. Hang-ups pose a potential safety hazard and impact drawpoint availability/production and must be routinely and proactively managed. Chronic drawpoint hang-ups can lead to disrupted draw sequencing, load imbalances in the cave column, stress concentrations and drawpoint damage from secondary blasting.

3.2.4 Wet muck and material handling

Elevated muck moisture levels may pose an operational risk in caving mines, in addition to the aforementioned inrush hazard. Wet material must be managed such that it does not create secondary mud rush risk in ore passes, ore bins, crusher and the conveyor systems, typically through blending. Wet material and material with a relatively high clay component may also increase materials handling system downtime and clean-up requirements through increased spillage and gumming up chutes or mechanical systems.

4 Management plan descriptions

A strong framework of management plans, executed in sync with one another, provides the foundation for managing operational risks and caving-related hazards while maintaining a profitable mining operation. The individual management plans within the cave management system commonly comprise the following:

- cave management plan
- ground control management plan
- seismic risk management plan
- airblast risk management plan
- mud rush risk management plan.

The organisation, scope and quantity of management plans may differ from mine to mine, depending on the complexity of the operation and severity of risks. It is common for the major caving-related hazards (i.e. fall of ground, seismic risk, airblast and mud rush) to have their own dedicated risk management plans. In some cases, different aspects of operational and hazard risk management may be grouped into shared management plans as best suits the situation and needs of the operation. Important linkages and interactions between the various management plans are highlighted in Figure 1 and serve as critical controls between disciplines.

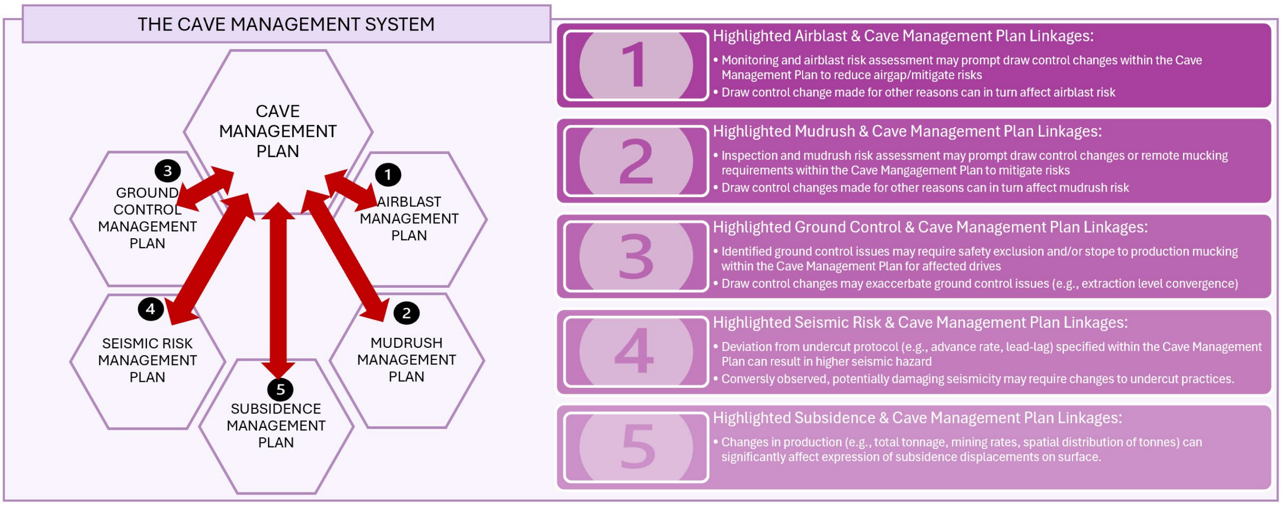

Figure 1 Overview of management plans and highlighted linkages between them

4.1 Cave management plan

It is essential that all stages of the cave mining process be managed carefully to ensure the integrity and success of the operation. Designing and executing a cave in alignment with industry best practices and guidelines is critical for the cave to be mined safely and successfully. The cave management plan provides the central foundation for establishing and implementing these standard practices and strategies.

The objective of the cave management plan is to standardise the design, execution and monitoring guidelines and strategies used to manage the operational caving mining risks associated with undercutting, cave initiation, cave propagation, cave interaction, steady-state cave production and cave closure.

Cave management plans typically contain a combination of caving guidelines and site-specific rules. Guidelines represent established industry best practices and principles that should be considered in the design, planning and execution of the cave. The operational rules established in the cave management plan should be considered strict directives for the execution of the cave. Specific rules may be updated or adjusted based on experience or new learnings; however, guidelines should stay in place for the life of the mine (Parsons et al. 2024).

Cave draw is the only mechanism that can be used to control cave performance. As such, cave draw control is fundamental to properly managing the cave during all stages of caving. Inadequate draw control practices can lead to serious issues related to the propagation of the cave, the drawdown of the muckpile, the ingress of dilution, compaction of the ore column and stress loading damage on the production levels.

4.1.1 Monitoring and data analysis

The primary data source required for effective cave management is accurate draw data from both the drawpoints and undercut level, as well as undercut and construction physical reports. Draw data should be analysed in relation to cave monitoring data to ensure the cave response to mucking is within expectation. Other operational data monitoring requirements would be determined by the plans and rules established in the cave management plan to track and ensure compliance with the cave management plan.

4.1.2 Trigger action response plans

TARPs should be developed for key operational caving risks identified in a formal and documented risk assessment process. These should be tailored specifically to the operation and its individual complexities and challenges.

The critical caving risks discussed are all the direct result of the operation of the cave. The cave management plan must be developed and executed in sync with the critical caving risk management plans for it to be effective in ensuring a safe and effective caving operation. A cave management plan may also contain TARPs related to any of the other caving hazard risks if individual management plans have not been developed.

4.2 Ground control management plan

A ground control management plan (GCMP) provides a consistent framework for the planning, design, and implementation of all aspects of ground control. A GCMP will also ensure that adequate information and training regarding the site's geotechnical conditions is given to the development and production crews on the mine. The successful implementation of this plan ensures the health and safety of the workforce and assets and aims to prevent unexpected delays due to ground control issues. GCMPs are not unique to cave mining methods; however, they are especially important due to the geotechnical complexities and challenges of cave mining.

A GCMP sets out the design criteria and the ground support elements that will be installed under varying geological and geotechnical conditions and for different design life requirements. Support standards should be developed based on industry-standard geotechnical engineering practices. The exact scope of a GCMP should be specific to the mine it pertains to and should be based on the understanding of ground control principles and the geological, geotechnical and mining conditions that apply at the time of the current revision. The GCMP must also conform to all current local mining regulations and safety standards.

The core components of a GCMP typically include:

- geological information
- geotechnical data collection and data analysis
- geotechnical monitoring and interpretation
- ground control and support standards
- ground control procedures.

4.2.1 Monitoring and data analysis

Monitoring and data analysis functions related to GCMPs typically include:

- routine geotechnical inspections of mine workings
- rockbolt, grout and shotcrete testing, and QA/QC
- convergence monitoring
- geotechnical instrumentation monitoring
- rehabilitation inspections.

4.2.2 Trigger action response plans

TARPs should be established to respond to adverse or worsening ground conditions throughout the mine. These may include responses to observations such as visible damage to the ground support system, loose material in the mesh, spalling shotcrete, accelerating convergence rates or anything not within the standard of the GCMP. They should also include responses to major events such as drawpoint failures and falls of ground.

Depending on the severity of the conditions, responses may include increased inspections and monitoring, increased ground support designs, area closures, small rehabilitation work packages, or in extreme cases, major re-excavation and rehabilitation campaigns. These responses should be site specific, at the discretion of the geotechnical team and in accordance with the standards established in the GCMP.

4.3 Seismic risk management plan

The objective of a seismic risk management plan is to establish a framework of processes and controls for the mining operation to avoid or mitigate risks associated with seismic hazards. Seismic risk management in mines is a complex process with best practice being governed by site-specific conditions.

The ACG benchmarking study “Seismic Risk Management Practices in metalliferous mines” (Potvin et al. 2019) establishes that there are four core components of seismic risk management:

- data collection
- analysis of the seismic response to mining
- control measures
- seismic risk assessment.

4.3.1 Monitoring and data analysis

Seismic monitoring systems are the foundation for management of seismic risk. The installation of a mine-wide seismic system is also considered an industry best practice and critical for the monitoring of the cave response during undercutting and propagation, as well as managing the cave-induced seismic risks. Analyses of the cave seismic data are very informative and can be used to understand the dominant caving mechanisms as well as tracking of the progression of the cave seismogenic zone and, to a lesser extent, the actual cave back ‘region’ (Lynch et al. 2018). Should any rock mass preconditioning or cave induction be required to facilitate caving, then the seismic response to these processes proves invaluable in quantifying their success/effectiveness.

4.3.2 Trigger action response plans

TARPs should be established to provide controls to mitigate seismic risk in the mine following large seismic events or periods of increased seismicity. Response plans should be tailored to the specific mine and context; however, the typical reactive control for these events is personnel exclusion zones and re-entry protocols. Exclusion protocols have a location and time component and may be established reactively to seismic events, as well as proactively following blasts or other work which may increase seismicity.

4.4 Airblast risk management plan

The objective of an airblast risk management plan is to evaluate and control the airgap present between the cave back and muckpile during the cave initiation and propagation phases to minimise potential airblast hazard.

The following key factors may affect the potential and/or consequences of an airblast event, which should be considered in the management plan:

- Geotechnical conditions such as structure or contrasting rock mass strengths may accelerate or inhibit caving or produce variability in cave growth.
- Proximity to surface and/or other caves affects the duration of the propagation period.
- Direct cave connections allow high-velocity airflow from the cave zone in the event of an airblast.
- Muckpile height above the extraction level provides a protective cover, limiting velocities and pressure change resulting from an airblast.

The primary control for managing airblast risk is strict draw control practices during the early stages of caving, during which the draw rate must be constrained to less than the cave propagation rate. During undercutting, only swell tonnes should be mucked, and open-brow controls and safety practices should be strictly enforced. Another control for managing airblast risk is the installation of air-obstructing barricades; however, there is no generally recognised design (Thomas et al. 2024).

4.4.1 Monitoring and data analysis

A strong network of underground cave propagation monitoring instrumentation is necessary to provide an accurate assessment of the cave back position as an input to estimate airgap volume and assess risk level. Monitoring methods should be selected to directly observe the cave back position, top of muckpile position, and/or airgap extent. Furthermore, it is recommended to have redundancy between instrumentation systems to allow for cross-verification of findings between systems and minimise loss of coverage in the event of a single-system outage (Davenport & Kamp 2024).

Instrumentation systems for cave propagation monitoring typically comprise the following:

- open observation boreholes to monitor the cave back and top of muckpile positions
- Geo4Sight or Networked Smart Markers to monitor cave back progression
- Networked Smart Markers, Cave Tracker beacons, or equivalents to verify the height of draw (HOD)
- time-domain reflectometers to monitor displacements generally associated with the yielded zone
- seismic monitoring system to track progression of microseismic events overlying the cave.

Interpretations and analyses required for assessment of airblast risk include:

- production mucking data (i.e. drawbell tonnages and estimated HOD)
- interpreted cave back position
- interpreted top of muckpile position (based on estimated HOD and preferably verified by direct monitoring data, when available)
- estimated airgap extent.

4.4.2 Trigger action response plans

An airblast QPO and associated TARP should be established to evaluate the airblast risk and implement mitigation measures should an elevated airblast risk be identified. It is common for airblast QPO thresholds to be assigned based on void volume, void-to-muck ratio, or estimated air velocities from piston or Boyle's Law calculations. These parameters are calculated from monitoring and production data using various assessment methodologies, ranging from simple rough estimates (e.g. simple void volumes or void-to-muck ratios) (New South Wales Department of Primary Industries 2006) to more sophisticated methods based on complex models (Palma et al. 2018; Rojas et al. 2023).

Typical TARP response actions to elevated airblast risk may include the following:

- increased data interpretation and airblast risk assessment frequency
- exclusion of personnel from high-risk areas
- requirement for remote or automated mucking
- reduction, change in, or stop to cave mucking
- probe hole drilling to determine cave location (if risk elevated due to uncertain cave back interpretation)
- assisted caving for stalled cave zones using techniques such as hydraulic or blasthole fracturing.

During the early stages of caving, the airgap QPO should be assessed frequently (e.g. weekly) so elevated risks can be proactively identified and responsively managed. Airblast risk to the extraction level typically lessens as muckpile head cover increases with cave propagation. The hazard is effectively alleviated following the breakthrough of the caved zone to the surface or to pre-existing mobilised zones from prior lifts (when present). A published operational case study of an airblast QPO-TARP framework, including monitoring methods, threshold selection, and response actions during cave initiation and propagation, is presented by Ormerod et al. (2024) for the Carrapateena cave.

4.5 Mud rush risk management plan

The objective of a mud rush risk management plan is to provide a risk management framework for reducing the likelihood and severity of mud rush events in the mine. This is typically done through the development of a mud rush risk classification matrix (Table 2) and associated risk mitigation measures. A risk classification matrix considering combinations of fines and water content should be constructed based on site-specific materials testing results.

Table 2 Example mud rush risk classification matrix

Moisture/muck	Coarse muckpile	Fine muckpile
Dry	Coarse-dry (low risk)	Fine-dry (low risk)
Damp	Coarse-damp (low risk)	Fine-damp (moderate risk)
Very wet	Coarse-very wet (moderate risk)	Fine-very wet (high risk)

Mud rushes occur commonly in caving mines and are very challenging to completely prevent. As such, it is critical that the severity and consequence of mud rushes that do occur be reduced. A risk classification matrix is typically used to classify mud rush potential and ensure proper controls are in place when a higher risk is present.

Proactive measures which may reduce the likelihood and severity of mud rush events include:

- strict adherence to draw control best practices
- surface and underground water management programs, underpinned by a detailed site-wide water balance, including in-pit water interception, storage and sumps, and routine reconciliation of water inflows against estimates
- sealing off of access points to the cave other than operating drawpoints.

Controls for proactively limiting water inflow into the cave are especially important for reducing mud rush risk in the mine.

4.5.1 Monitoring and data analysis

Having a strong understanding of the site hydrology and hydrogeology, as well as conditions in the drawpoints, is critical to assessing mud rush risk. The following ongoing monitoring and data analysis is typically required to support mud rush risk management systems:

- site and underground water balance
- drawpoint visual inspections
- drawpoint material size analysis (fines and clay content) and moisture content measurement
- drawpoint mucking data.

4.5.2 Trigger action response plans

A TARP should be established to identify and mitigate mud rush risk. Triggers are typically based on material size distribution and moisture/drainage, using a site-specific variation of the classification matrix shown in Section 4.5. Response actions typically focus on managing discharge points and trigger mechanisms.

These may include:

- increased inspection and moisture sampling frequencies
- berm placement in wet drawpoints and production drives
- remote or automated mucking of wet and adjacent drawpoints
- exclusion zones and periods following mucking of wet and adjacent drawpoints
- draw call adjustments in wet drawpoints and adjacent drawpoints.

4.6 Subsidence risk management plan

The objective of a subsidence risk management plan is to monitor the onset and progression of mining-induced subsidence, evaluate risks associated with surface displacements, and implement controls as required to mitigate these risks. Subsidence-associated risks commonly comprise potential damage to surface and/or near-surface infrastructure (e.g. milling facilities/open pit slopes and vent raises/declines, respectively). The scope and requirements of a subsidence risk management plan should be commensurate with the potential risks: higher when critical facilities are present within or in proximity to the subsidence zone or lower when this is not the case.

The core components of a subsidence risk management plan include:

- predicted subsidence displacements (extents, magnitude, and timing) from numerical modelling strategy for subsidence estimates
- subsidence-related site infrastructure risk assessment, controls and response
- subsidence monitoring requirements and monitoring methods
- data review and interpretation requirements.

Industry best practice is to use numerical models to forecast subsidence and serve as a basis to evaluate potential impacts to surface and near-surface infrastructure. It is noted, however, that some industry-reported cases suggest numerical modelling has been unreliable in accurately predicting actual subsidence response, especially in early 'data poor' phases of the project.

The following are some points of guidance from the authors in this regard:

- Actual manifestation of subsidence is often complex due to factors including geological variability and surface topography, and these influences may not be well represented in the model.
- Numerical models should be used with caution and understanding of their limitations. Furthermore, models should be recalibrated with real observed subsidence monitoring data and updated mine plans as frequently as is warranted by the potential risk of inaccurate subsidence predictions.
- Use of more than one numerical modelling consultant may be warranted if subsidence-related risks are significant to enable cross-verification of model predictions.

4.6.1 Monitoring and data analysis

Operational assessment of subsidence relies on monitoring data from in situ instrumentation and remote sensing techniques. Common subsidence monitoring objectives include:

- identifying the initial onset of subsidence as the caved zone breaks through to surface or remobilises a pre-existing caved/subsidence zone
- monitoring progression of displacements towards and/or impacts to surface infrastructure.

General subsidence monitoring objectives for sites without critical infrastructure within or proximal to the subsidence zone can typically be achieved using some or all of the following monitoring methods:

- *Remote-sensing techniques*, including aerial photogrammetry and/or satellite InSAR, provide relatively infrequent data (e.g. quarterly, monthly) to monitor cumulative vertical displacement magnitudes and displacement rates throughout the subsidence zone.
- *Survey monuments* to frequently (e.g. daily to monthly) monitor displacement magnitudes at key points within the subsidence zone and facilitate cross-verification with remote sensing techniques.
- *Surface crack mapping* to identify progression of the fractured zone extent.

When critical infrastructure is present within or near the subsidence zone, additional monitoring methods and higher measurement frequencies are commonly warranted, such as:

- *Ground-based radar* is applied mainly when subsidence has potential to destabilise open pit slopes.
- *Slope inclinometers, Geo4Sight markers, and/or time-domain reflectometers* are installed to monitor displacements in proximity to or on approach towards surface infrastructure.

It is recommended that subsidence monitoring plans use multiple monitoring methods to provide redundancy in case of a single-system outage and to cross-verify findings. This is particularly important when ongoing subsidence has the potential to interact with critical infrastructure.

4.6.2 Trigger action response plans

Subsidence management QPOs and TARPs are typically specified to warn of substantial deviation from expected subsidence progression or heightened risk to project infrastructure and personnel on the mine site. Some common subsidence QPOs include thresholds based on observed:

- subsidence zone extent relative to projected extent (sometimes a regulatory condition)
- rate of subsidence zone progression towards critical surface infrastructure
- displacement magnitudes or subsidence-derived damage affecting critical surface infrastructure
- discrepancy between underground production and observed subsidence.

Typical TARP response actions to elevated subsidence-related risk may include the following, depending on the level of risk and application:

- heightened monitoring and/or increased evaluation frequency
- implementation of safety exclusion zones in areas where subsidence is progressing
- relocation of infrastructure or installation of redundant infrastructure
- reduction of mining to slow subsidence, in extreme cases.

5 Application of the cave management system: real-world examples

This section presents common real-world examples of how the cave management system is used to detect elevated operational or safety risks and implement response actions (i.e. heightened monitoring and/or mitigation measures). The selected examples conceptually illustrate how QPOs-TARPs initiate key linkages between management plans to control the identified risks.

5.1 Elevated airblast potential during early-stage cave propagation

Cave monitoring data (e.g. Geo4Sight, time-domain reflectometers, seismic systems) identified the development of a relatively large airgap above the muckpile. The gap was interpreted as resulting from a cave stall while production mucking continued in accordance with the cave management plan's draw plan.

The interpreted airgap volume triggered an elevated TARP risk classification in the airblast risk management plan. An airblast risk management draw plan was initiated to reduce draw in select areas, increase scrutiny of draw compliance, and establish draw limits based on permissible airgap and minimum muckpile cover requirements. These strict draw management measures allowed production to continue safely by maintaining the airblast risk level within safe limits. Sustained cave propagation was subsequently confirmed by the monitoring program, and the airblast TARP was de-escalated. This scenario illustrates the direct linkage between the cave management plan's draw control execution and the airblast risk management plan's TARP-driven response.

5.2 Draw management in an area of elevated mud rush risk

Muckers reported a sudden increase in visible water and muck moisture in an active production drawpoint to the mud rush team. The observation and confirmatory testing (i.e. visual inspection and moisture sample) triggered a high risk TARP classification. The elevated risk classification initiated a mud rush risk management draw strategy, whereby the wet drawpoint and its adjacent drawpoints must be mucked on automation, with the draw split between shifts. Furthermore, berms were maintained, and a personnel exclusion zone was active for 7 hours following mucking. These draw control and access restrictions were aimed to reduce both the likelihood and consequence of a mud rush. These heightened control measures were maintained until the moisture level decreased, after which the drawpoint was returned to the standard cave management plan draw plan. The response demonstrates the integration of the mud rush risk management plan with the cave management plan's draw protocol and the site's personnel safety controls.

5.3 Subsidence progression approaching surface infrastructure

Subsidence monitoring indicated that surface displacements were progressing more rapidly towards a critical vent raise than predicted by numerical modelling, indicating the potential for subsidence interaction with, and damage to, the raise. An elevated risk classification was triggered in the subsidence risk management plan TARPs, initiating a coordinated response across multiple surface and underground technical teams. Increased inspection and monitoring frequencies were initiated – including the installation of supplementary inclinometers and additional Geo4Sight markers in the vent raise vicinity – while technical teams advanced design work on a contingent replacement vent raise. Monitoring continues at the heightened cadence to provide early warning should further escalation occur, with the contingency designs ready for execution if required. This example demonstrates the linkage between the subsidence risk management plan and the ground control management plan.

Conclusion

A strong cave management system framework comprised of interrelated management plans and founded on risk assessment establishes the essential controls and strategies for managing cave mine operations and management of risks inherent to cave mining. While each individual risk management plan – whether focused on seismicity, airblast, mud rush, subsidence, or general ground control – addresses specific hazards, their true effectiveness depends on consistent, coordinated execution throughout the entire life cycle of the cave. Cave mining demands an integrated approach since operational decisions directly influence geotechnical responses, and in turn, geotechnical conditions may require changes to operational practices. As such, the management plans must remain tightly linked, mutually responsive, and grounded in a clear governance structure.

Risk management plans should be developed well in advance of the onset of caving-related risks to ensure that appropriate controls, monitoring strategies, and TARPs are firmly in place before undercutting, cave initiation and propagation. Early establishment of these plans supports proactive identification of emerging hazards, facilitates timely intervention and strengthens the mine's ability to adapt to changing conditions. Equally important is the recognition that these plans must remain living documents, evolving as operational experience, monitoring data and site-specific knowledge are accumulated.

The cave management system presented herein provides a basic understanding and framework for mine personnel and operators with limited institutional caving experience. This structure provides a practical, experience-based foundation that can be tailored to site-specific risks and mining practices for any organisation seeking to manage the complexities of modern cave mining.

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