

# Managing excavation closure risk in caving operations

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## ABSTRACT

A framework has been developed to manage production horizon excavation closure risk in caving operations. The focus is on monitoring and response procedures, which are linked to transient geotechnical hazard and remnant reserve value. The study encompasses an analysis of various factors influencing high-closure event risk, including the consequence of asset loss, contributing factors to potential high-closure events, and resisting factors such as rock strength, ground control measures, and rehabilitation work.

The framework is supported by empirical benchmarking data and lessons learned from historic cases within PT Freeport Indonesia's operations and other caving operations. An overview of typical failure mechanisms, best practice monitoring, situation-dependent ground control strategies, and temporary and permanent closure measures (i.e., concrete filling) is provided. The strategies outlined herein offer underground operators a valuable resource for enhancing safety and operational reliability when developing strategies to manage potential high-closure events in critical production areas.

## 1 INTRODUCTION

Panel and block caving are mass mining methods often applied to large, low-grade ore bodies due to their low production cost and substantial capacity (Pourrahimian & Askari-Nasab, 2010). Caving projects entail significant capital investment, primarily due to the necessity of extensive infrastructure to accommodate the high mining rates associated with caving operations (Stewart & Butcher, 2016). The layout of these excavations involves an intricate network of drifts, access tunnels, drawbells, drawpoints, and other excavations. Ensuring the stability and operational reliability of these excavations during the undercutting process, subsequent cave production, and throughout the life of mine is key to the success of a caving project (Hormazabal, Alvarez, & Valderrama, 2020).

High-closure events in caving operations present significant challenges and threats to safety and

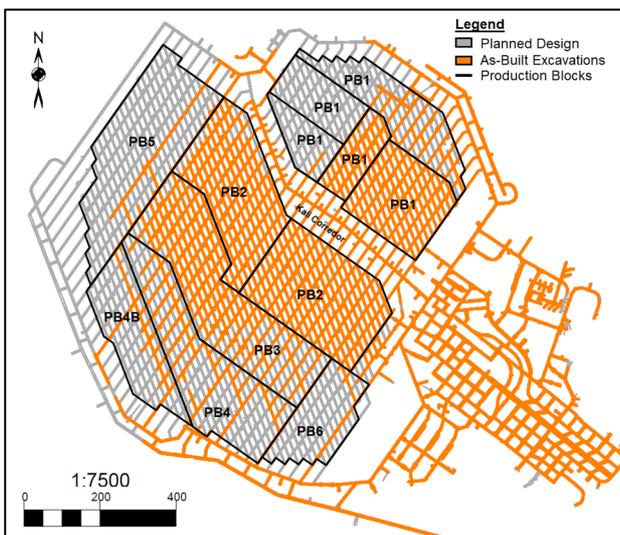
productivity. Such events are characterized by extreme convergence (and commonly rapid rates), which cannot be managed by conventional ground control procedures. Given their potential to impact the extraction level, it becomes imperative to adopt a comprehensive management strategy to effectively address this risk.

This paper outlines the problem faced at the Grasberg Block Cave (GBC) mine, the framework developed to address this problem, and its applicability to other mines or caving projects facing similar challenges. Note that the framework described herein focuses on non-violent deformation (e.g., bulking, squeezing) and does not consider discrete kinematic or dynamic ground deformation (e.g., strain-bursting, and remote fault slip events).

## 2 PROBLEM

As the footprint size of caving operations continues to increase, so does the range of rock mass quality conditions likely to be encountered and the potential for high-closure events (Campbell, Banda, Fajar, & Brannon, 2018). These trends pose significant challenges to excavation stability hazard identification and resource allocation to manage the associated risks effectively.

The GBC mine is a prime example, with its expansive footprint comprising 1,896 drawpoints covering approximately 790,540 m<sup>2</sup>. With a drawpoint sequence encompassing numerous production blocks, some subdivided into subblocks, the mine currently has 864 drawpoints opened with 56,070 linear meters developed in the extraction level (Figure 1). Future plans include opening an additional 372 drawpoints over the next five years, further reflecting the high expansion rate of the mining operation.



**Figure 1** GBC mine as-built excavations and planned design as of March 2024.

The scale of the operation, combined with the heterogeneous geological elements, brings in varied rock mass responses across the mine footprint, underscoring the complexity of the challenge (Campbell, et al., 2020). (Campbell, Banda, Fajar, & Brannon, 2018). Traditional ground control strategies, such as the regular

practice of Preventive Ground Support Maintenance (PSM), have proven ineffective in addressing failure mechanisms in certain areas of the production footprint where more aggressive closure has occurred.

Experience in the GBC, as well as other surveyed operations, indicate that high-closure events often manifest as gradual instability, characterized by the complete or near-complete convergence of excavations within the caving operation. Such events may arise from the individual or cluster failure of the pillars supporting the extraction level in the affected area.

These non-dynamic, high-strain events commonly result from a combination of contributing factors. Geological conditions, such as weak ground, unfavorable geological structure orientation and contact zones, play a significant role. The unique demands arising from abutment and cave loading cycles are also strong contributors to these events. Some excavation geometries can worsen the situation by concentrating induced stresses in small pillars across wide spans, particularly in areas where grizzlies and ore passes are located. Adverse loading conditions, including long abutment residency times, excessive lead-lags, excessively long cave fronts, uneven draw, high tonnages (resulting in brow degradation), improperly formed major apices (from undercut blasting), remnant pillars, incomplete drawbell firing, and high hang-ups, further compound the instability risk. Furthermore, atmospheric, and aqueous degradation (such as corrosion and weathering) result in progressive weakening of the rock mass and ground support systems over time. Mechanical damage from blasting or equipment damage also contributes to the loss of system capacity. In short, locating high-hazard areas spatially and temporally is not a straightforward task, given the combination of contributing factors.

While the likelihood of high-closure events in GBC is not considered high, the potential consequences of such events are significant. These consequences range from the most crucial asset in the mine, the personnel, to critical

infrastructure damage or loss (i.e., access, egress, production pathways, and ventilation services), equipment subjected to obstruction, disruptions in production schedules, and inability to recover ore. For Instance, in the case of high-closure events that occurred in GBC (See Figure 2) in 1H 2023, the disruption in production stands at approximately 1,900 Ktons. Therefore, identifying and risk mitigating areas susceptible to high-closure events is essential for ensuring the safety and sustainability of mining operations.



**Figure 2** GBC area that experienced high-closure at P19.

### 3 FRAMEWORK

PTFI has developed a framework that offers a strategy for effectively managing risks associated with high-strain events within cave mine extraction levels. The main objective of the framework is to understand and proactively manage the impact of high-strain events. Given the resource challenges inherent in large-scale caving operations, the strategy helps reducing the problem to a manageable level using the following approach:

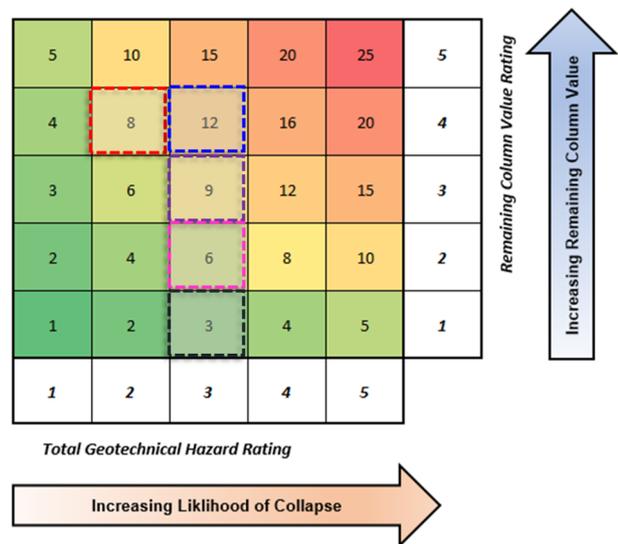
- quantifiably assess and rank the relative risk-of-loss value for extraction level assets (e.g., drawpoints, grizzlies, etc.),
- establish a systematic approach to track the performance assets having the greatest risk of loss value
- define a stratified response plan to proactively address stages of closure if and where they develop.

Details related to each of these three main components are outlined in the following subsections.

#### 3.1 Assessing the Risk of Loss Value

The risk of loss value for specific extraction level assets or groups of assets is assessed in terms of the likelihood of a high-closure event and the value of reserve associated with a given asset (i.e., the consequence). High-closure likelihood is defined based on the local geotechnical hazard while the reserve value is defined based on net smelter return (NSR) from the resource model attributed to a given asset.

The overall risk of loss value is then quantified based on the product of ratings applied to each of these two components through a typical risk assessment matrix approach; see an example in Figure 3. The individual component ratings and resultant risk of loss value ratings are assessed spatially using a node-based map of the extraction level footprint. The ratings are also assessed temporally to provide a useful indication of the likely timing of peak risk of high-closure events and the associated value of reserve at risk of loss. Figure 3 Risk of loss rating matrix.

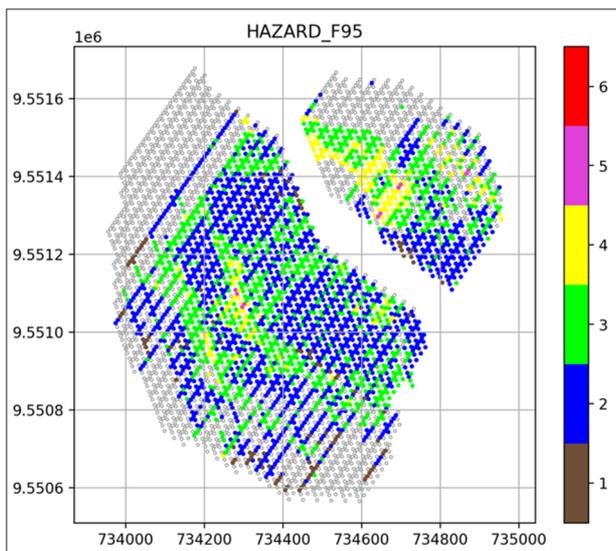


**Figure 3** Risk of loss rating matrix.

This risk of loss assessment approach injects valuable information into the framework by incorporating core performance forecast confidence indicators (i.e., geotechnical hazards) with corresponding value (i.e., NSR)

through the production life of the drawpoint or panel. When compiled and compared on a panel-by-panel basis, the approach provides an indication of the relative risk profiles (dynamically through time) between panels already developed and mined to those that have yet to be developed.

Assessing the geotechnical hazard and relative likelihood of high-closure events for a given asset at a given time is based on a comprehensive, node-based geotechnical hazard map of the extraction level. The factors considered in the development of individual ratings include parameters such as cave height (as a proxy for loading conditions), abutment residency time (derived from development schedule data), forecasted corrosion, forecast convergence (utilizing the global stress model and rock mass character), distance to faults, overbreak, and more. The forecast is a blend of observational and forecasted inputs, employing a variable weighting system to calculate the hazard index. The calibration of this tool is achieved through the incorporation of damage data, PSM requirements in the past and convergence data, ensuring accuracy and reliability in hazard assessment. The legend for the hazard map, as depicted in Figure 4, indicates that lower hazards are shown in cooler colors, while higher hazard levels are represented in red; axis indicate Northing and Easting in meters.



**Figure 4** Asset-based hazard map for GBC extraction level by 2024Q02(F95).

In addition to providing a relative rating of the geotechnical hazard and likelihood for a high-closure event, this tool empowers geoengineering teams to plan for monitoring frequencies based on hazard levels and provides guidance to engineering and operations on ground support recommendations for future developments and PSM requirements. The tool also allows production planners to visualize geotechnical hazard levels spatially and temporally in the context of the remaining in-column reserves.

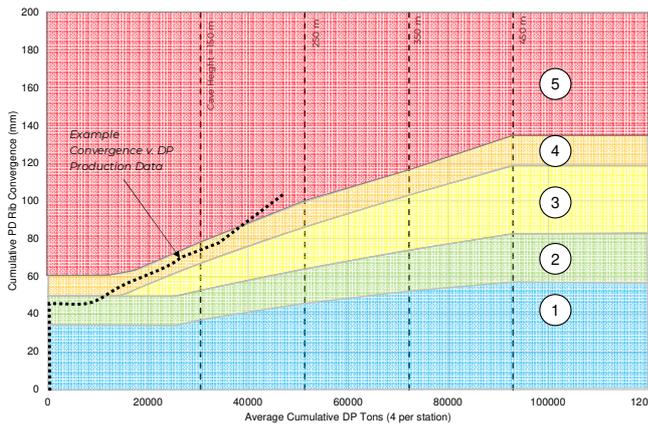
### 3.2 Tracking Performance of High Risk of Loss Value Assets

The hazard map provides a means of identifying areas most prone to high-closure and prioritizing these based on the (local) value of ore at risk of loss. For those areas of both high hazard and high consequence (i.e., risk of loss) a focused observational method is applied. This method establishes a systematic process to evaluate confidence in the expected performance of individual assets/areas and reliably recover the included ore columns based on observations from the performance of adjacent areas.

One of the primary components considered in this method is how the actual excavation convergence compares to the current forecast. Figure 5 presents an example of the approach for tracking the divergence of the actual versus forecast convergence. The cave load demand forecasts adopted for the chart are based on recorded production tonnage, interpreted cave height, and previously developed Monte-Carlo simulations that account for gravity loading of caved material, ground arching, and draw factors on average cave load (WSP, 2023). The magnitude and trends of the actual relative to the forecast are categorized into ranges that correspond to varying levels of confidence in the forecasted behavior and indicate the scale and type of additional information that may be needed to improve confidence.

Through this approach to tracking performance, it is also possible to assess our confidence in forecasting future responses. This is significant in that the efficacy of any applied response plan requires that we have appropriate resources and

tools in place to identify the early indications of a developing high-closure event. If our confidence in being able to forecast a future state is low, there is a greater potential that we would be unprepared to identify early indications and would need to take corrective actions to improve our forecast confidence. The dashed line in Figure 5 presents the conceptual convergence response relative to forecast confidence regions.



**Figure 5 Pillar response tracking tool using cumulative convergence against cumulative production tonnage.**

#### 4 RESPONSE PLANNING BENCHMARKING AND LESSONS LEARNED

Benchmarking has been undertaken to better understand high-closure events and associated responses at other caving operations. This information supported the development of the proposed framework in three (3) important areas:

1. Understanding the geologic, geotechnical, and mining factors that are likely to be most important to consider in the development of the comprehensive geotechnical hazard (i.e., high-closure events likelihood).
2. Establishing appropriate monitoring threshold criteria for response plans, and
3. Developing effective response actions to minimize the potential for lost value where and when high-closure events occur.

Details related to these components of the benchmarking are outlined in following sub-sections.

#### 4.1 Contributing Factors

Drawing insights from derived from the benchmarking exercise, it is evident that high-closure events in caving operations often result from a combination of contributing factors rather than a singular root cause (Shea, Sinclair, & Welsh, 2018). Through an analysis of various cases and studies, Table 1 summarizes contributing factors that have been identified to have the potential to lead to non-dynamic, high-strain events in caving.

Examining convergence rates before high-closure events, as shown in Table 2, across different mining cases provides potential risk indicators, which helps inform proactive monitoring and response strategies. It is crucial to consider both rates and magnitude in assessing deformation stages and associated response strategies. Identifying discernible deformation stages allows for the implementation of appropriate responses.

**Table 1 Contributing factors to closure events**

Category	Description of Contributing Factors
Geological Conditions	Poor ground (Define either from low intact strengths, presence of clays, fracturing, seeping water, alterations, shear zones. etc.)
	Foliated Rock types
	Major Faults Intersecting
	Contact Zones
Pillar Geometry	Small pillars across wide spans and high extraction ratios (i.e., Grizzly chambers)
Demand	Abutment Loading
	Cave Loading
	Consolidated Ground
Cave Geometry and Sequence	Long abutment residency times
	Excessive lead-lags
	Adverse cave fronts
	Sequencing (Drawbelling)
Mucking	Cave Boundary Interaction
	Paused Draw
	Uneven Draw
Blasting	High Hang-Ups
	Poor blast continuity (stubs/remnant pillars)
	Incomplete drawbell firing
	Improperly formed major apices
Degradation	Overbreak
	Ground Support Corrosion
	Ground Support Deficiency (loss of capacity)
	Chemical Ground Degradation (microdefects/water interaction)
Others	Non-Chemical Ground Degradation (i.e., blasting damage, equipment damage)
	Inadequate ground support installation

**Table 2 Convergence rates observed before the onset of high-closure**

Operation	Pre-Warning Rate [mm/days]	Warning Rate [mm/day]	High-closure Rate [mm/days]
Henderson P75 (Ribs)	0	4.4	32.05
GBC P19 (Ribs)	0.3	1.3	15.3
GBC P19 (Back)	0	4.5	10.8
GBC P21 (Ribs)	0.1	0.9	21.2
GBC P21 (Back)	0.1	1.1	21.6
New Afton	0-1.0	1.0-4.0	>4.0

#### 4.2 Lessons learned on Response Strategies

A review of high-closure event cases and literature reveals a range of strategies to respond effectively to high-closure events.

#### Use Analytical Methods

Use analytical methods to understand the ground response and support interaction. The ground reaction curve method offers valuable insights into ground behavior. However, it is essential to understand its limitations, particularly due to the assumptions of circular excavations in continuous, homogeneous, isotropic, and linear elastic rock masses (Barla, 2001). Additional empirical methods have been presented by (Hoek & Marinos, 2000) to understand the potential for squeezing problems in deep tunnels.

#### Apply Numerical Modelling

Numerical modelling allows for more detailed design analysis of stress-induced damage around complex excavations considering the support system (Sandy, Gibson, & Gaudreau, 2007) (Barla, 2001). Additionally, (Beck & Villaescusa, 2012) covers the appropriate modelling methods for large deformations, understanding the rock mass behavior, and support system response to demands.

#### Have a Toolkit

In order to implement strategies effectively, it is crucial, from an operational standpoint, to have a readily available toolkit of ground support elements on site that align with the findings from previous assessments. These findings, derived from both analytical and numerical analyses, inform the selection and deployment of appropriate ground support elements. This toolkit may comprise a range of elements, including high-capacity cables, hybrid bolts, MAI bolts, heavy welded mesh, OSRO straps, and grouts/resins among others. Having such a toolkit readily accessible ensures timely and efficient implementation of ground support strategies.

#### Strategic Planning for Drawpoints and Grizzlies

Decide whether or not to mine certain drawpoints or grizzlies within areas characterized by very poor to poor ground conditions. Evaluating the ground quality and potential risks associated with mining in these

areas allows for informed decision-making to mitigate the likelihood of high-closure events.

#### *Respond in a Timely Manner.*

Due to the dynamic and time-sensitive nature of high-strain events in caving operations, timely strategies are crucial for mitigating risks and maintaining operational safety. However, resource constraints often pose challenges to implementing these strategies.

#### *Boost Support Intensity*

When deformation arises, a common response in many operations has been to increase the intensity of support by enhancing bolt density and length (Sandy, Gibson, & Gaudreau, 2007).

#### *Create Artificial Pillars with Backfill*

Another strategy to prevent excessive closure while providing a controlled environment for repairs is to include backfill, such as muck, concrete, or a mixture of both, to create stiff artificial pillars.

#### *Consider Unconventional Bolts*

The benefits and limitations of using yielding support for their capacity in terms of deformations has been summarized by (Sandy, Gibson, & Gaudreau, 2007). Other mines have adopted hybrid bolts comprising resin bars and friction bolts, as observed in LaRonde and New Afton (Mercier-Langevin & Turcotte, 2007) (Kamp, 2022). Additionally, high-capacity bolts are employed as part of bolt strategies to enhance support effectiveness.

#### *Stiff Monolithic Support Implementation*

The adoption of monolithic support systems such as universal beam sets (Beck & Villaescusa, 2012), presents an innovative approach to enhancing ground support effectiveness in high-closure events.

#### *Support System Integration*

Ensure that support elements function as a cohesive system connecting bolts and aerial support. Weakness in the system, often observed at the collar, is addressed using welded mesh and heavy gauge mesh straps. These help distribute the loads across several bolts, contributing to the

overall stability of the excavation (Kamp, 2022) (Sandy, Gibson, & Gaudreau, 2007).

#### *Probe Holes Before Advancing.*

Applying probe holes to determine the ground conditions during development becomes necessary as part of a strategy to predict ground reaction early and prepare the action plan for advancing and proper ground support installations.

#### *Short Rounds*

Implementing short advances, coupled with the installation of complete support systems, allows for confirmation of support effectiveness. This approach has proven successful in operations such as New Afton and the Henderson Mine (Kamp, 2022) (Shea, Sinclair, & Welsh, 2018).

#### *Ground-Penetrating Radar Technics*

Ground-Penetrating Radar (GPR) is a method used to confirm the ground conditions in areas where drilling could not be undertaken. GPR is particularly useful in cases where there is a need to consolidate the ground, as it is important to verify and confirm the ground conditions before and after consolidation.

#### *Material Stripping*

In cases when closure prevents equipment access for repairs, stripping out damaged material has been identified as a viable option in various caving operations.

#### *Continues Mucking Draw Strategies*

Employing draw strategies to ensure continuous mucking in the local area of convergence and its surroundings has been observed to potentially reduce convergence rates in some operations. Similar strategies have resulted in decreased convergence rates in other mines (Febrian, 2004; Millán & Quezada, 2012; Sahupala & Srikant, 2007 a, b).

#### *Continues Improvement and Learning*

Mining operators continuously strive to improve reactive strategies by learning from past experiences and benchmarking against industry best practices. By implementing lessons learned and adapting strategies based on observed

outcomes, mining operations can enhance resilience and effectiveness in responding to high-strain events.

## 5 RESPONSE PLANING

PTFI internal analyses, supported by industry benchmarks, clearly defined discernable stages of deformation marked by accelerated rates of

closure. It is clear that anticipating these stages is critical from a planning and response standpoint.

**At PTFI, a dedicated high-closure TARP was defined for use in addressing the risks of loss value associated with high-closure events (see**

Table 3). Triggers included in this plan were carefully selected based on insights from convergence rates observed during previous high-closure events at the GBC mine and other benchmarked cases (see Section 5). The overarching aim of this TARP is to provide clear guidance when convergence rates are high or when total displacement is met, empowering decision-making regarding the response actions.

**Table 3 PTFI Hight Closure TARP**

<b>Trigger Action Response Plan</b>	Response to Partial Panel Closure and High-closure Rates on Extraction Level		
<b>What is measured?</b>	Convergence and Single Wall Deformation measurements from start of Panel.		
<b>Responsibility for measurement(s):</b>	Geoengineering department is responsible for Convergence and Single Wall Deformation measurements and for recording PSM and rehabilitation events. Measurements to be carried out using pin to pin and backed up with Lidar scanning measurements.		
<b>Frequency of report(s):</b>	Geoengineering department shall report on weekly basis to the list as below.		
<b>Purpose and implication of measurement:</b>	The amount of panel closure could impact on safety and will impact production.		
<b>Owner</b>	<b>Geoengineering Department</b>		
	<b>Level 1: Acceptable Conditions</b>	<b>Level 2: Alarm Actions</b>	<b>Level 3: Urgent Action Required</b>
<b>Criteria</b>	-Convergence Rate:< 5 mm / week -Total Convergence +100 mm -Single Wall Deformation Rate < 2.5 mm / week -Total Single Wall Displacement +50 mm.	-Convergence Rate 5 - 15mm / week -Total Convergence +400 mm -Single Wall Deformation Rate 2.5 – 7.5mm / week -Total Single Wall Displacement +200mm.	-Convergence Rate >15 mm / week -Total Convergence +700 mm -Single Wall Deformation Rate +7.5 mm / week -Total Single Wall Displacement +350 mm.
GeoEngineering department	- Determine the level of hazard at current mining stage - Review 3D scan/convergence report and inspect area (s) where increased displacement was observed. - Maintain record of 3D scans/convergence using the frequency suggested by the hazard maps. - Prepare and distribute monitoring summary report and continue tracking result against forecast performance.	-1 to 3 times per week 3D scan/convergence at the area (s) of increased convergence. -Prepare and distribute summary reports 1 to 3 times per week to stakeholder. -Inspect area (s) where increased displacement was observed. -Prepare and distribute note summarizing contributing factors to closure. -Communicate with Engineering and Operation departments. -Develop ground control improvement corrective action plan (PSM 2)*, in cooperation with Engineering and Operations departments. -First warning to prepare for concrete fill.	-Barricade area and communicate with Engineering and Operation departments. -Final warning to concrete fill identified draw points. Provide excavation-ratio improvement corrective action plan to prevent full closure of panel. -Daily 3D scan/ convergence surrounded area (s) of high closure if safe monitoring is possible. -Prepare and distribute daily summary report to stakeholder.
UG Engineering	No action is required.	Develop and issue worksheets of approved ground control improvement corrective plan (PSM 2)*, in cooperation with GeoEngineering and Operation departments.	Develop excavation-ratio improvement corrective action plan, in cooperation with GeoEngineering and Operation departments.
UG Operation	No action is required.	Schedule and execute approved ground control improvement corrective plan (PSM 2)*, in cooperation with GeoEngineering and Operation departments.	Develop excavation-ratio improvement corrective action plan, in cooperation with GeoEngineering and Engineering departments.
UGSC	No action required.	Confirm the first warning to prepare for concrete filling of draw points.	Review and approve the excavation-ratio improvement corrective action plan

\*The response plans should prioritize assets based on their hierarchy of value, focusing on strategies for access, blocks, drifts, grizzlies, drawbells, and drawpoints respectively. This ensures efficient resource allocation, with a priority given to higher-value assets, such as grizzlies over drawpoints.

## 6 CONCLUSIONS

The developed framework offers a comprehensive strategy for managing the risk of high-closure events in caving operations. By focusing on monitoring, response procedures, and linking them to geotechnical hazards and reserve value, the framework provides a holistic approach for enhancing safety and operational reliability.

Proactive measures, such as identifying contributing factors, classifying high-hazard areas in the footprint, optimizing ground support systems, implementing observational methods for tracking rock mass response to mining against expected performance, are integral components of the frameworks. These proactive measures contribute to risk prevention and facilitate timely and effective response strategies.

The framework is supported by empirical benchmarking data and lessons learned from historic cases within PTFI and other caving operations. Drawing insights from real-world experiences enhances the effectiveness and applicability of the response strategies.

Moreover, in responding to high-strain events, the implementation of timely effective strategies becomes imperative for minimizing the impacts of this risk.

Continuous improvement is a cornerstone of effective risk management. By learning from past experiences and benchmarking against industry standards, caving operations can continuously enhance their ability to manage high-strain risks effectively.

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