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Prioritizing the mitigation of legacy geomechanical mine hazards using a risk-based approach

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ABSTRACT: Mining companies and governments are managing an increasing number of legacy assets in various states of closure, and these assets often include potential geomechanical hazards such as crown pillars, slopes, raises, and portals. Mitigating these hazards may require significant time and resources, and it may not be practical or economical to implement rehabilitation measures for all of the identified hazards in the short-term. This paper outlines a method for identifying and prioritizing hazards using a risk-based approach. The approach has been used successfully at numerous mine sites across North America and includes compiling the available data, identifying potential hazards, ground truthing and verifying expectations, assessing the likelihoods and consequences of failures, assigning risk ratings, and evaluating mitigation and rehabilitation measures.

1. INTRODUCTION

There are hundreds of thousands of legacy mine sites in North America with an estimated 500,000 in the United States (MSHA, 2015) and 10,000 in Canada (NRCan, 2010). Relatively few of these sites have been closed completely. For example, in Ontario only 50 of the more than 6,000 sites identified are classified as closed (MNDM, 2024). Legacy mine sites are typically complex, with rehabilitation efforts often hindered by uncertainty. As a result, comprehensive rehabilitation of the associated hazards is time consuming and expensive. Companies and governments must decide how to best allocate their available resources to rehabilitate the hazards in line with regulations and organizational targets. This paper describes a risk-based process to mitigate and manage legacy geomechanical mine hazards to help guide the allocation of resources.

2. OVERVIEW OF PROCESS

The objective of the geomechanical hazard mitigation and management process is to achieve an acceptable level of residual risk in a reasonable timeframe while limiting unnecessary expenditure. The process consists of four generalized stages:

- Identifying and initially categorizing the hazards. Key uncertainties in the understanding of the hazards are also identified during this stage.
- Investigating the hazards to confirm their presence and to reduce the identified uncertainties.
- Completing detailed stability analyses and a risk assessment for each hazard.
- Identifying, selecting, and implementing mitigation and management measures, as required.

This process has been used successfully at numerous legacy mine sites in Canada and the United States. The benefits of the process are that it is objective, transparent, actionable, and easy to communicate to all stakeholders.

3. IDENTIFICATION AND INITIAL CATEGORIZATION OF HAZARDS

3.1. Hazard Identification

The first step in the process is to identify potential hazards, compile the information readily available for each hazard, and identify any key gaps or uncertainties.

Geomechanical hazards at legacy mine sites include crown pillars between underground openings and the surface (including both stopes and development), unstable slopes in surface excavations (including open pits, glory holes, exploration trenches, etc.), and underground mine openings that have been excavated to the surface (i.e., shafts and raises).

Often some of the hazards are known in advance. However, a detailed review of the available information often identifies additional hazards or changes the understanding of the known hazards. Important sources of information for the review process include site visits, historical mine records, drillhole databases, reports, and historic site photos. An adequate understanding of the mining methods used and the mine history is essential to this process. The mining of pillars or the slashing (enlarging) of ore drives at the end of mine life is a common practice, and these activities are often not well documented, if at all. An understanding of the geological context and interviews with former mine personnel can help identify areas where undocumented mining likely occurred and assess how conditions may have changed over time. For projects with complex geometries, the construction of a 3D mine geometry model may be necessary to consolidate the available information and to adequately identify and assess potential hazards.

Each hazard should be listed, noting its type, position, available sources of information, and any key deficiencies or uncertainties in the understanding of the hazard. The list of potential hazards should be a living document and updated as the understanding of the site improves.

If hazards are identified at this stage that plausibly represent an immediate and significant risk to health and safety or the environment, action should be taken to limit the consequences of a failure (e.g., by limiting access to the area likely to be affected).

3.2. Hazard Screening

Once an initial list of hazards has been developed, a screening assessment is performed to identify the hazards that are likely to pose the greatest risk. The screening is completed as a qualitative or semi-quantitative risk assessment based on the understanding of the hazards at the time. A risk rating is determined based on the perceived or estimated likelihood of a failure and the plausible maximum consequence if the failure were to occur. The inputs may be qualitative or based on simple analyses, such as an empirical stability assessment. A simplified risk matrix (Fig. 1) is most effective at this stage.

The screening process must also consider the uncertainty in the understanding of each potential hazard. In cases where key parameters are uncertain, highly variable, or may have changed over time, the plausible worst-case scenario should be included in the screening assessment.

Once the risk has been estimated for each hazard, the resulting database can be sorted to identify the potential hazards with the greatest risk. From this, a work plan can be developed that focuses on the hazards with the highest risk. The final work plan typically accounts for regulatory expectations, as well as corporate and stakeholder risk tolerance and priorities.

The following example is based on experience at a legacy North American mine site with an open pit and a crown pillar. The open pit is now flooded; however, the as-built geometry was documented, and slope monitoring reports are available. A perimeter berm was constructed around the crest during operations and is still intact. The crown pillar is above a stope that underlies an access road that is still used for inspections. The underground mine is also flooded and, as such, access is no longer possible. The available documentation on the pillar is limited to the planned dimensions. The screening assessment could be ranked as follows:

- *Crown Pillar* – The probability of failure was estimated using the scaled span method (Carter, 2014) to be between 5% and 10% based on the planned stope dimensions. This may have been acceptable during operations but is not suitable for long-term closure. The consequences of a failure could be injury or death (high consequence of failure), as the pillar underlies the road. Additionally, there is a high degree of uncertainty in the available data as the mining records are incomplete. As a result, the crown pillar is classified as high risk.
- *Open Pit* – The available reports indicated that the overall slopes were designed with a relatively conservative factor of safety of 1.5 and that only a few bench-scale slope instabilities have occurred over the life of the pit. The consequences of a failure are low as access into and around the pit is prevented by berms. There is a low degree of uncertainty in the available data as design and monitoring reports are available, and the current condition of the slopes can be assessed visually. As a result, the open pit is classified as low risk.

The screening assessment for the open pit and crown pillar is represented on the basic risk matrix on Fig. 1. If there are relatively few potential hazards, a simplified risk assessment may not be required.

		Consequence of Failure		
		Low	Moderate	High
Likelihood of Failure	Low	Open Pit **Low**	**Moderate**	**Moderate**
	Moderate	**Moderate**	**Moderate**	Crown Pillar **High**
	High	**Moderate**	**High**	**High**

Fig. 1. Example basic risk matrix.

4. INVESTIGATION OF HAZARDS

Site investigations are almost always required to confirm the presence and condition of the identified hazards and to address key knowledge gaps or uncertainties. The methods used will vary based on the identified hazards, the understanding of the hazards, the results of the preliminary hazard screening, and the likely mitigation methods. Hazards with a higher risk rating will justify a more detailed investigation and vice versa. In some cases, it may be more cost effective to simply mitigate the hazard than investigate it. For example, a 5 m deep exploration trench can likely be backfilled without further consideration. Common investigation methods include:

- *Visual Inspections* – Inspections by trained personnel are a key component of the investigations. The intent is to locate and document the condition of the hazards and any existing mitigation measures (e.g., shaft caps) as well as to better understand the general site conditions and land use. In-person inspections also offer an opportunity to complete initial assessments of the rock mass characteristics. The use of an Unmanned Aerial Vehicle (UAV) during the inspection can be particularly helpful for surface features that are difficult or unsafe to access.
- *Photogrammetry and LiDAR Surveys* – A low-cost method for confirming the geometry of surface excavations. The collected data can also be used to measure the orientations of discontinuities in the rock mass. UAV-based LiDAR can be used to scan surface excavations as well as accessible underground excavations.
- *Bathymetric Surveys* – Used to better define the geometry of flooded surface excavations. The surveys are best completed using sonar, but a weighted sounding line can be used for a preliminary estimate in some cases.
- *Destructive and Non-Destructive Structural Testing* – Used to confirm the construction details of reinforced concrete caps for shafts and raises. Includes cutting, chipping, and/or coring to determine the type and configuration of steel reinforcement and the strength of the concrete. Repairs are required to the damaged areas following inspection and testing. If the cap is relatively thin, non-destructive methods such as a handheld radar scanner can be used.
- *Drilling and Geomechanical Logging* – Used to confirm the presence and geometry of underground excavations and to characterize the sub-surface rock mass. The presence and characteristics of backfill in underground excavations can also be confirmed. Rock and backfill samples are often collected and sent for laboratory strength testing. The drillholes can be used for downhole surveys and can be left open to allow for future downhole monitoring or the installation of sub-surface instrumentation (e.g., a multi-point borehole extensometer; MPBX).
- *Downhole Surveys* – Borehole cameras, Cavity Monitoring Systems (CMSs), or sonar tools are used to scan underground voids. These tools are typically deployed through drillholes but can be lowered into existing openings (e.g., shafts or raises). Cameras can be useful for visually assessing rock mass quality, the presence and characteristics of backfill, obstacles (e.g., rails or timbers), etc. The CMS and sonar scans allow underground voids to be defined with much less drilling. These tools work on a line-of-sight basis, and care is required to not allow obscured zones or artifacts to influence the interpretation of the scans. A CMS can only be completed in a dry opening, while sonar requires a flooded opening. The presence of dust and humidity can impact a CMS.
- *Geophysics* – Used to help define underground hazards. These methods are typically used to help extrapolate drillhole data or to generate potential targets for drilling if the understanding of the underground mine geometry is poor. Examples include Ground-Penetrating Radar (GPR), seismic surveys, and resistivity surveys.

Unexpected conditions are often encountered during the investigation of legacy mine hazards, and it is important that programs are designed with budget and schedule contingencies in order to adapt to the encountered conditions.

The data collected for each hazard should be reviewed and compiled. The current condition of the hazard should be compared to historic reports and photos to assess whether the hazard has changed over time. Any additional hazards identified during the investigations should be included in the hazard list.

5. REFINED RISK ASSESSMENT

5.1. Updated Stability Analyses

The stability and likelihood of failure of each hazard is re-assessed based on the improved understanding resulting from the site investigations. The analysis methods employed and the level of effort required to complete the analyses will vary based on the risk associated with each hazard. Example methods for different hazards include:

- *Crown Pillars* – Analyses may include bulking/raveling calculations (Pigott and Eynon, 1978), empirical stability methods (e.g., Carter, 2014), limit-equilibrium analyses, and/or numerical modelling.
- *Open Pits* – Analyses may include rockfall analyses, limit-equilibrium analyses, cave angle estimates, and/or numerical modeling.

- *Reinforced Concrete or Steel Caps and Plugs* – Capacity assessments are typically completed using standard structural calculations, but numerical models may be used in specific circumstances.

In cases where uncertainty remains, parametric or sensitivity analyses should be completed to better understand the potential impact of uncertainty on the likelihood of failure.

5.2. *Risk Assessment*

The risk assessment can then be updated to reflect the improved understanding of the likelihood of a failure. At this stage, a more comprehensive assessment of the potential consequences of a failure is also typically completed. For example, rather than focusing solely on health and safety and environmental considerations, it may be appropriate to consider financial, legal, and reputational factors. Many mining companies have their own consequence rating schemes that can be used or adapted to a particular site. An example consequence rating is shown in Fig. 2.

Updated risk ratings can then be calculated using a more refined risk matrix. An example is shown in Fig. 3, although alternatives can be used. It is important to note that the calculated ratings represent a snapshot in time based on the current condition of the hazard, land use, and existing mitigation measures. The risk assessment should be updated if any of these factors are expected to change. In some cases, it may be necessary to complete multiple risk assessments to capture a range of plausible scenarios.

Probability of Failure (PoF) Rating (%)	Consequence Rating: Very Low	Low	Moderate	High	Very High
< 1.5 %	1	2	3	4	5
1.5 - 5 %	2	4	6	8	10
5 - 10 %	3	6	9	Crown Pillar 12	15
10 - 20 %	4	8	12	16	20
> 20%	5	10	15	20	25

Risk Rating = Probability of Failure Rating x Consequence Rating

RISK RATINGS:
Very Low
Low
Moderate
High
Very High

Fig. 3. Example risk matrix for crown pillars.

To continue the example from Section 3.2, investigations of the crown pillar have allowed for a more reliable evaluation of the long-term stability of the pillar. The revised stability analysis estimates the likelihood of failure to be 8%. In addition to underlying the site access road, a site visit identified that the crown pillar is close to a pipeline that carries strongly acidic water requiring treatment. A failure of the pillar could result in injury (or possibly death) if someone is present at the time of the failure. It may also result in a breach of the pipeline

Category	Health and Safety	Environmental	Financial	Reputational	Legal
Very Low	First Aid injury	Low environmental impact	<$1,000,000	Negligible media interest	Regulation breaches without fine or litigation
Low	Medical treatment or multiple First Aid injuries	Minor environmental impact	$1,000,000 to $3,000,000	Crown Pillar Negative local media coverage or stakeholder complaint	Regulation breaches, possibly resulting in fines or litigation
Moderate	Lost Time injury (LTI) or multiple medical treatments	Moderate environmental impact recoverable in 1 to 3 years	Crown Pillar $3,000,000 to $5,000,000	Negative national media coverage over more than one day or stakeholder action resulting in national societal scrutiny	Crown Pillar Minor litigation / prosecution at operations level
High	Crown Pillar Single fatality or multiple LTIs	Crown Pillar Major environmental image with >3 years recovery period	$5,000,000 to $10,000,000	Sustained negative national media coverage; negative international media coverage; or topic of broad societal concern and criticism	Major litigation / prosecution at operations level
Very High	Multiple fatalities	Severe environmental impact with long recovery time	>$10,000,000	Physical impact on the assets; loss of ability to operate; or formal expression of significant dissatisfaction by government	Major litigation / prosecution at company level or loss of license to operate

Fig. 2. Example consequence rating scheme.

causing a spill into the nearby creek. Both consequences would have secondary reputational and legal impacts. Using the consequence rating scheme in Fig. 2, a high consequence rating is assigned and the risk updated on Fig. 3.

Once the risk assessment has been refined, there should be a clear understanding of the risks posed by the hazards identified at the site and which hazards pose the greatest risk. The focus can then shift to the mitigation and management of these risks.

6. IDENTIFICATION AND SELECTION OF MITIGATION AND MANAGEMENT MEASURES

The ultimate goal of mine rehabilitation is to eliminate unacceptable health and safety hazards and restore the site to its former condition or a condition that is compatible with the adjacent land use. This requires the elimination, rehabilitation, or mitigation of the identified hazards to achieve an acceptable level of residual risk.

The elimination or rehabilitation of geomechanical mine hazards at legacy sites often requires a significant investment in time and resources due to the nature of the hazards. Unlike most modern mines, these sites were not typically developed with closure in mind. As a result, it is often not feasible to achieve final closure in the short-term and the risks need to be managed in the interim, sometimes for extended periods. In cases where there is an ongoing site presence (e.g., for water treatment), it may also be desirable from a corporate risk management perspective to manage rather than eliminate the hazards so that resources can instead be used to address higher risk hazards at other sites.

Common methods for eliminating or rehabilitating hazards include:

- Collapsing crown pillars using controlled blasting.
- Recontouring the slopes of surface excavations.
- Backfilling stopes underlying crown pillars, open pits, or raises. The material used should be non-acid generating and selected to resist erosion and migration.
- Capping shafts, raises, or portals.
- Flooding surface excavations.

Common methods of eliminating or reducing the consequences of a failure include:

- Installing fences and signage around hazards. These measures will need to be inspected and repaired regularly. While these were acceptable for final closure in the past, stakeholders are increasingly unwilling to allow this.
- Constructing rockfall berms to protect people and equipment (e.g., along an open pit ramp required for periodic water quality monitoring or pump maintenance). The berms need to be cleaned out periodically.
- Implementing monitoring programs to identify changing conditions and allow site activities to be modified in response. This can include visual inspections, surface instrumentation (e.g., survey prisms or crack meters), sub-surface instrumentation (e.g., MPBXs, Time Domain Reflectometry cables, inclinometers, etc.), and remote monitoring such as InSAR. Monitoring programs require the ongoing involvement of trained personnel and clearly defined trigger limits and responses.

An important part of managing hazards is ensuring personnel accessing or working at the site are aware of the hazards and the controls in place to manage them.

An acceptable residual risk threshold should be established in consultation with the site owner and other stakeholders. The ability of the different mitigation measures to achieve this threshold can then be assessed. Fig. 4 illustrates the impact of different mitigation strategies on the example crown pillar. Backfilling the underlying stope will reduce both the likelihood and the consequences of the failure and effectively eliminate the hazard. In all cases, eliminating the hazard rather than managing the consequences should be the ultimate goal. If a managed solution is required in the interim, restricting access above the crown pillar with fencing will reduce the consequences of a failure and may meet the residual risk threshold. Monitoring and instrumentation without any other controls may not achieve the threshold on its own but could be deployed as part of an overall strategy that includes fencing.

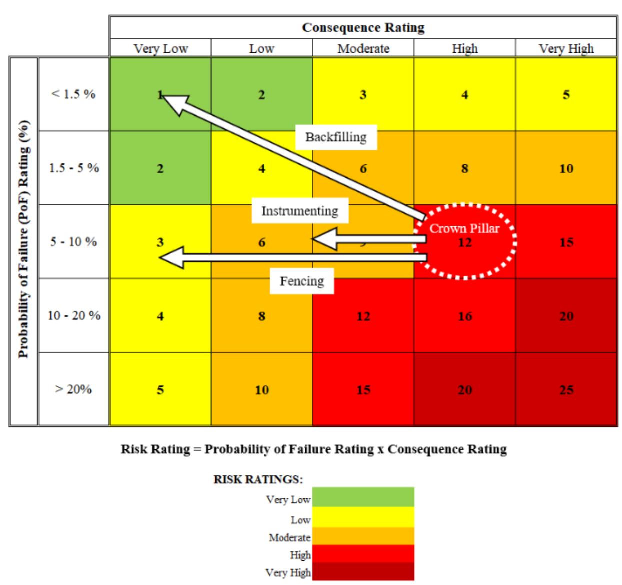

Fig. 4. Example effect of management and mitigation measures on risk.

Once practical and effective mitigation methods have been identified, a Multiple Accounts Analysis (MAA) can be used to help select the preferred strategy. This allows other factors to be considered, including:

- *Closure/Regulatory* – Considers whether the approach is suitable for final closure within the local regulatory environment or is instead an interim management strategy.
- *Health and Safety* – Considers potential hazards to workers or the public during the implementation of the mitigation measures.
- *Financial* – Considers the initial costs and any sustaining costs (e.g., for monitoring, repairing fencing, etc.).
- *Environmental* – Considers potential impacts on the land, wildlife, waterbodies, etc.
- *Social* – Considers whether the method is acceptable to local stakeholders.
- *Operational* – Considers the complexity of the method as well as factors such as schedule, access constraints, water management, etc.
- *Uncertainty* – Considers potential sources of uncertainty that remain after the investigation phase.

Once the options assessment is complete, the preferred mitigation strategy can be implemented.

7. SUMMARY

The risk-based approach for managing legacy geomechanical hazards presented in this paper has been successfully implemented at numerous mine sites across North America. The process consists of the identification and initial classification of mine hazards, the investigation of the hazards, a refinement of the initial risk assessment, and ultimately the selection and implementation of mitigation measures. The process is outlined in Fig. 5. While the ultimate goal is to achieve final rehabilitation of the sites, the approach incorporates the use of interim risk management measures to achieve acceptable levels of residual risk until longer-term solutions are implemented. The intent of the process is to allow mining companies and governments to optimize the use of their resources while managing and ultimately rehabilitating geomechanical hazards at legacy mine sites.

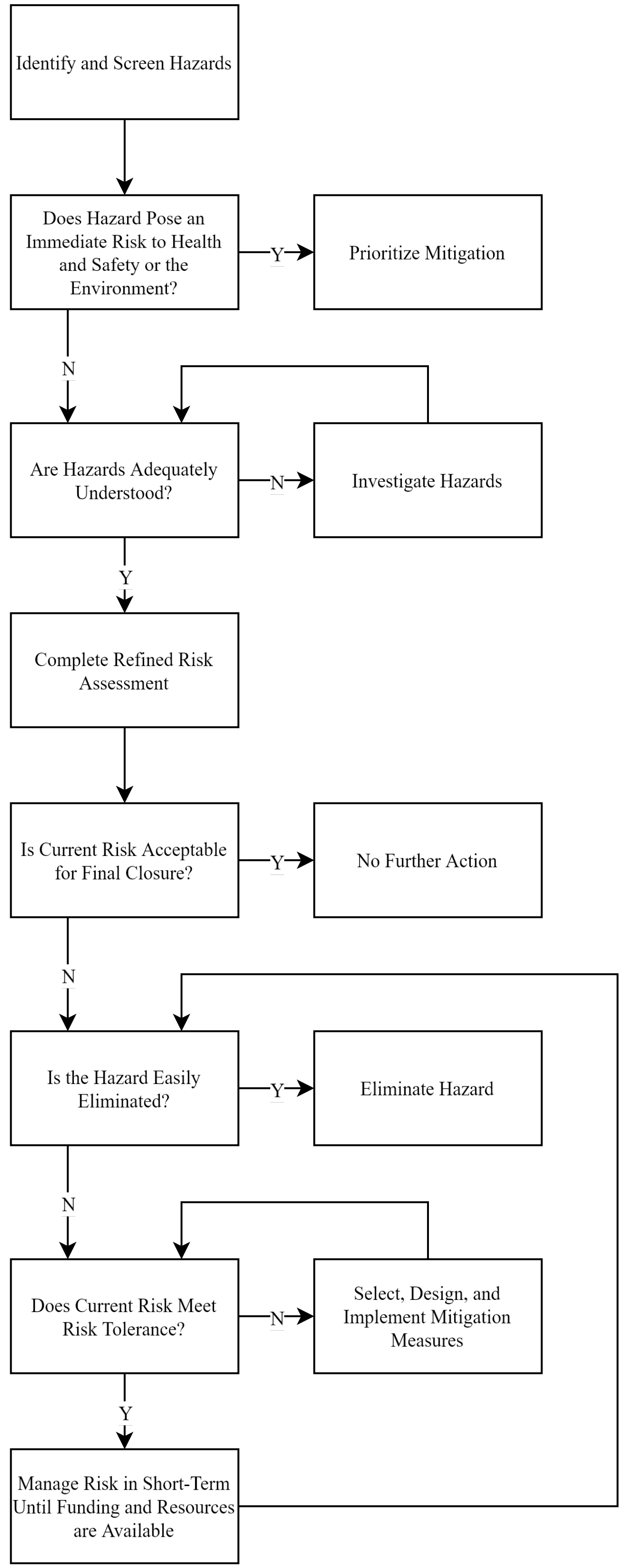

Fig. 5. Risk-based approach for hazard management.

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