Caving 2026 – A van As, D Cumming-Potvin & J Wesseloo (eds)
© 2026 Australian Centre for Geomechanics, Perth, ISBN 978-1-7636842-3-2
doi:10.36487/ACG_repo/2645_105

Applying a risk management approach to mass underground mining

Craig Stegman [a,*]

[a] *Stegman Advisory Services, Australia*

Abstract

Recent incidents highlight the inherently high-risk nature of mass underground mining. The consequences of these risks include multiple loss of life, loss of production, reduced reserves and mine life, increased operating and capital costs, loss of reputation/social licence, and increased legislative and compliance requirements.

The management of major hazard risks requires organisations to implement effective enterprise risk management (ERM) practices to systematically manage both the threats and opportunities. A key element of ERM is the identification of the organisation's risk capacity and risk appetite. In simple terms, an organisation should not take on risks that it does not have the capacity to withstand nor risks that exceed its risk appetite. When a risk exceeds a company's risk appetite, the company should consciously assess whether it can eliminate or mitigate the risk to as low as reasonably practicable (ALARP) and then decide if the residual risk can be accepted based on the company's risk appetite.

The underground major hazard incidents that occurred during 2025 raise the question of the adequacy of the industry's risk management approach, both in terms of understanding the nature of the risks involved and the effectiveness of the controls applied to the risks. The incidents also raise serious questions about the risk appetite of the industry and whether that appetite is aligned to stakeholder risk tolerances. The industry must improve its ability to manage inherent risks to a level that satisfies multiple stakeholders' expectations. The specific challenge posed to the underground mass mining industry by recent incidents is: How can (and should) it effectively manage the risk of major hazard events? Any answer to this question will likely require substantial changes to the way risks are evaluated and underground mines are designed, constructed and operated.

The global response to major tailings storage facility failures, which drove the adoption of the Global Industry Standard for Tailings Management (GISTM) (Global Tailings Management Institute 2020) across the mining industry, serves as a pertinent case study for underground mining. It demonstrates how coordinated pressure from stakeholders can drive a major shift in industry risk management practices, resulting in lower risk tolerance, more stringent controls and a requirement for more transparent corporate risk governance.

The ultimate question for the mining industry is: How can the industry establish, maintain and, in instances, regain the trust of the many industry stakeholder interest groups such that mass underground mining can be undertaken with acceptable levels of risk for all participants?

Keywords: *risk management, risk appetite, to as low as reasonably practicable, Global Industry Standard for Tailings Management, seismicity, rockburst, pillar failure, inrush*

1 Introduction

The operational risks associated with large-scale underground mining are well known and, unfortunately, all too commonly manifested. Recent incidents like the fatal seismic event at the El Teniente block cave in Chile, the fatal inrush event at the Gasberg block cave in Indonesia and the mine collapse at the Kakula underground

*Corresponding author Email address: craig.lance.stegman@gmail.com

mine in the Democratic Republic of the Congo highlight the inherently high-risk nature of large-scale underground mining. The potential consequences of such risks include multiple loss of life, loss of production, reduced reserves and mine life, increased operating and capital costs, loss of reputation/social licence, and increased legislative and compliance requirements. The risks are therefore strategic, financial, operational, compliance/regulatory and reputational in nature. Further, the increasing scale and complexity of underground mines is arguably contributing to an increase in both the likelihood and consequence of the risks, irrespective of the many improved controls adopted by the industry.

The materiality of mass underground mining risk dictates that the industry implements effective enterprise risk management (ERM) to systematically manage both the threats and opportunities. Whilst risk management practices have been widely adopted across the mining industry, the status of underground major hazard risk management is less mature than other industries with significant risk profiles (e.g. chemicals, nuclear, and oil and gas) (Brady 2019; Hopkins 2022; Wilkinson 2022).

2 Recent underground major hazard incidents

The mining industry witnessed 3 serious major hazard events associated with large-scale underground mines in the space of 5 months in 2025, 2 of which were at mature block cave mining operations. Whilst investigations into the root cause(s) of the incidents are continuing and, in some cases, information is limited, the implications for the underground mining industry are significant.

2.1 Kakula geotechnical event: 18 May 2025

A cascading collapse of mine pillars at the Kakula mine (jointly owned by Ivanhoe Mines, Zijin Mining Group, Crystal River Global Limited and the Government of the Democratic Republic of the Congo) resulted in loss of electrical infrastructure and flooding of the mine workings, triggering an evacuation of the mine. Mining operations subsequently resumed in lower-grade areas whilst new dewatering infrastructure was installed to recover access to higher grade parts of the deposit. Rehabilitation of underground workings has also been undertaken in parallel (Ivanhoe 2025).

The Kamoa-Kakula copper mine employs a large-scale mechanised drift and fill mining method with paste backfill to recover a shallow, gently dipping stratiform orebody. Preliminary investigations indicate secondary pillars in the eastern more mature part of the Kakula mine began to yield in a cascading fashion, resulting in stress redistribution to regional pillars, which then began to yield. Backfill placed in the primary stopes did not prevent loading of the regional pillars and regional pillar stability may have also been compromised by regional geological features. A comprehensive mine redesign is being undertaken that “prioritises long-term operational stability over short-term production recovery” (Ivanhoe 2025), including increasing pillar dimensions and changes to the mining sequence to improve stress redistribution and overall mine stability. In addition, upgrades to geotechnical monitoring in the mine are being undertaken (Ivanhoe 2025; Webb 2025).

The Kakula incident bears many similarities to the mine collapse in the 1990s at the nearby Kamoto mine, which resulted in the closure of the mine. Mining at Komoto restarted in 2007 utilising a system of pillars and a staged mining sequence to shape deformation, manage stress and control mine stability (Shiels et al. 2023). The most infamous precedent example of cascading pillar failure is the Coalbrook mine collapse in 1960 in South Africa that killed 437 workers (van der Merwe 2006).

2.2 El Teniente seismic event: 31 July 2025

A major mining-induced seismic event occurred at the El Teniente block cave mine (owned by Codelco 2025) in Chile, triggering widespread rockbursts that killed 6 and injured a further 36 employees. The event, measuring 4.3 magnitude, occurred beneath the northern mining blocks and caused significant damage to mine workings. Mining operations were initially suspended but have since resumed, although at reduced levels, whilst mine workings are rehabilitated (Codelco 2025).

A preliminary investigation (Codelco 2025) concluded that:

> "*…the earthquake (seismic event) was a larger and more complex phenomenon than those that have occurred in the last 35 years.*"

and

> "*The most likely cause of the rockburst was identified as a vertical stress release process resulting from geometric changes and the interaction of cavities in the northwestern area of the deposit, i.e., the shape of the ground has changed, affecting how the rock mass is supported within the mine.*"

The El Teniente mine has a long history (from the 1970s) of rockbursts related to seismic activity, including previous fatal events, reflecting high stress-to-strength ratios and a strong rock mass with brittle behaviour. The intensity and frequency of events have increased over time as the mine becomes deeper and larger and there is more interaction between mining areas (Rojas et al. 2023).

2.3 Grasberg inrush event: 8 September 2025

Approximately 0.8 Mt of wet material flooded the extraction level and associated mine workings in the Grasberg block cave mine in Indonesia (jointly owned by Freeport-McMoRan and Government of Indonesia), entrapping and fatally injuring 7 workers. Mining operations were suspended in the immediate aftermath of the incident but have since resumed at reduced rates whilst the mine workings are rehabilitated.

The inrush material was a mixture of water and fine rock that had collected in the bottom of the overlying open cut mine. The block cave had broken through into the open cut, creating a connection between the material in the open cut and the underground mine workings. Freeport noted the incident:

> "*…was unprecedented in PTFI's multi-decade history of block cave mining in the Grasberg minerals district.*" *(Freeport 2025)*

Inrushes are relatively common in the block cave mines at Grasberg once they have broken through to the surface, owing to the area receiving an average of 5 metres of rainfall per annum. A fatal inrush had previously occurred at the Deep Ore Zone mine on 18 April 2011 (Stegman, pers comm, 2011).

2.4 Lessons from the incidents

Whilst the consequence of each of the major hazard events may have been unprecedented, the underlying risks are well known in the underground mining industry, that is:

1. uncontrolled ground movement risk
2. seismicity and rockburst risk
3. inrush risk.

This suggests the severity of the risks, in terms of both consequence and likelihood, have been underestimated. Likewise, controls to manage the risks were ineffective and/or insufficient, potentially because of underestimating the risk severity or the failure to identify specific causal pathways. For example, the controls that were in place at the time of the incident were possibly sufficient to manage a less severe incident (the collapse of few pillars, a smaller seismic event or a smaller inrush). This clearly points to the need for strengthened and additional controls and a more dynamic approach to risk management to eliminate or mitigate the higher severity incidents, which will inevitably require substantial changes to the way underground mines are designed, constructed and operated.

The incidents therefore raise serious questions about the ability of the mining industry to correctly identify and assess major hazard risk and its ability to manage those risks to an acceptable level. They raise questions about the risk appetite or tolerance of the mining industry and the quality of the industry's risk management, governance and oversight. Ultimately though, they potentially trigger a loss of confidence and trust in the industry.

3 Tailings storage incidents and the Global Industry Standard for Tailings Management case study

Two catastrophic failures of tailings storage facilities (TSFs) in Brazil have reshaped the mining industry's approach to managing the risks associated with the storage of mine waste. On 5 November 2015 the Mariana dam (Vale-BHP) failed, releasing 43 million cubic metres of mine waste, killing 19 people, destroying nearby towns and contaminating 668 kilometres of river systems. A second failure occurred on 25 January 2019 when the Brumadinho dam (Vale) failed and released 9–10 million cubic metres of mine waste, killing 270 people (Luiz et al. 2020). In addition to the impact on human life and the environment, the owners of the TSFs have suffered substantial adverse legal, financial and reputational consequences.

In response, the United Nations Environment Programme, the Principles for Responsible Investment and the International Council on Mining and Metals (ICMM) co-convened the Global Tailings Review. Civil society and investors strongly supported the review, including the Church of England Pensions Board, which had significant influence over the review[†]. The review resulted in the development of the Global Industry Standard for Tailings Management (GISTM), which was officially launched in August 2020. All ICMM members were required to implement the GISTM. By January 2022, a total of 79 companies had committed to implementing the standard (Dhawan & Davey 2022) and over half of the industry by market capitalisation had committed to the GISTM by January 2024 (Church of England 2024).

The GISTM established 15 principles and 77 auditable requirements, including:

1. an ambition of zero harm to people and the environment from tailings facilities
2. appointing an accountable executive and a responsible tailings facility engineer for all TSFs
3. public disclosure of information on each TSF (e.g. risk assessments, including run-out analysis of dam failure), which takes the form of self-reporting on member websites
4. a commitment to community engagement
5. mandatory, independent, third-party audits and certifications.

The adoption of the GISTM required mining companies to implement the standard for facilities with 'extreme' or 'very high' failure consequences by August 2023, and all other facilities by 5 August 2025. The Global Tailings Management Institute was launched in January 2025 as an independent body to oversee the auditing and certification of companies to the GISTM.

Certain investors, including the Church of England Pensions Board, have stated they will vote against the chairs of companies that have not committed to the GISTM. It is also claimed companies that can credibly demonstrate comprehensive implementation are more likely to attract more favourable terms for insurance and lower capital costs (Dhawan & Davey 2022).

Clearly, it should not have taken events like the Mariana and Brumadinho TSF failures to improve the management of a recognised major hazard risk with significant precedent. Ultimately, a wide range of stakeholders (communities, government, investors and regulators) worked together to compel the mining industry to adopt more stringent controls, be more transparent with stakeholders about the inherent risks, engage and consult with relevant stakeholders about those risks, and commit to mandatory independent audit and certification. Fundamentally, the mining industry now operates with a much lower risk tolerance for TSF failures than less than a decade ago.

[†] The Church of England Pensions Board was a major institutional investor in the mining industry and felt a moral and financial obligation to act following the catastrophic tailings disaster at Brumadinho, Brazil. The Investor Mining and Tailings Initiative (IMTSI) was founded in 2019 and was led by the Church of England Pensions Board and the Swedish Council on Ethics. It is a coalition of more than 100 investors with more than USD 25 trillion of assets under management (Church of England 2024).

Today, the choice the mining industry faces in relation to the recent underground major hazard events is whether it can demonstrate it has learnt from the events and established comprehensive controls that prevent their recurrence, thereby pre-empting stakeholders responding in a similar way as they did to the TSF failures.

4 The way forward: applying a risk management approach

The effective management of risk compels the mining industry to implement an ERM approach to its risks. An ERM is an integrated, continuous and structured business process for managing enterprise risks so that an organisation minimises unexpected performance variance and maximises the intrinsic value of the business (Lam 2017). ERM is defined in a range of international standards (e.g. ISO 31000:2018 and COSO, 2018 ERM Framework) and many jurisdictions around the world have established legal standards and guidelines describing how organisations shall implement effective ERM. Critically, risk management must be integrated into the way an organisation makes decisions and is a key dimension of the organisation's culture (International Organisation for Standardisation [ISO] 2018).

4.1 Key principles of enterprise risk management

Whilst many risk management concepts are well understood and practiced by the mining industry, it is worth exploring some of the key underlying principles:

1. Risk is "*the effect of uncertainty on objectives*." (ISO 2018)
2. A key element of ERM is the identification of the organisation's risk capacity or risk tolerance (its actual ability to absorb risk based on its financial and operational resources) and its risk appetite (the level of risk it is willing to take on within that capacity to generate a return on investment). In simple terms, an organisation's risk appetite should be less than its risk capacity, given an organisation should not take on risks that it does not have the capacity to absorb (Institute of Risk Management [IRM] 2011; Figure 1).
3. Risk appetite is defined by both internal and external factors that vary with time, including:
    a. the organisation's strategic goals (how much risk is necessary to achieve its goals), its financial capacity to absorb loss, and its culture and attitude to risk (from risk-adverse to risk-seeking)
    b. the industrial and regulatory environment in which it operates and the expectations of stakeholders, including investors, regulators, customers and communities.
4. When a risk exceeds an organisation's risk appetite, the company should consciously assess whether it can eliminate or mitigate the risk to be as low as reasonably practicable (ALARP). It is then necessary to assess the residual risk against the risk appetite to confirm it is now acceptable.
5. Risk severity is estimated by assessing the consequence and likelihood of a risk. This is often a subjective process where the consequence is determined as the maximum reasonable consequence (MRC), which is the worst-case scenario that is realistic and plausible, and the likelihood is an estimate of how likely the MRC is to occur.
6. Risk control effectiveness measures how well controls reduce either the consequence or likelihood of a risk, both in terms of the design of the controls (if they are fit for purpose) and their implementation (if they are implemented as designed and intended).

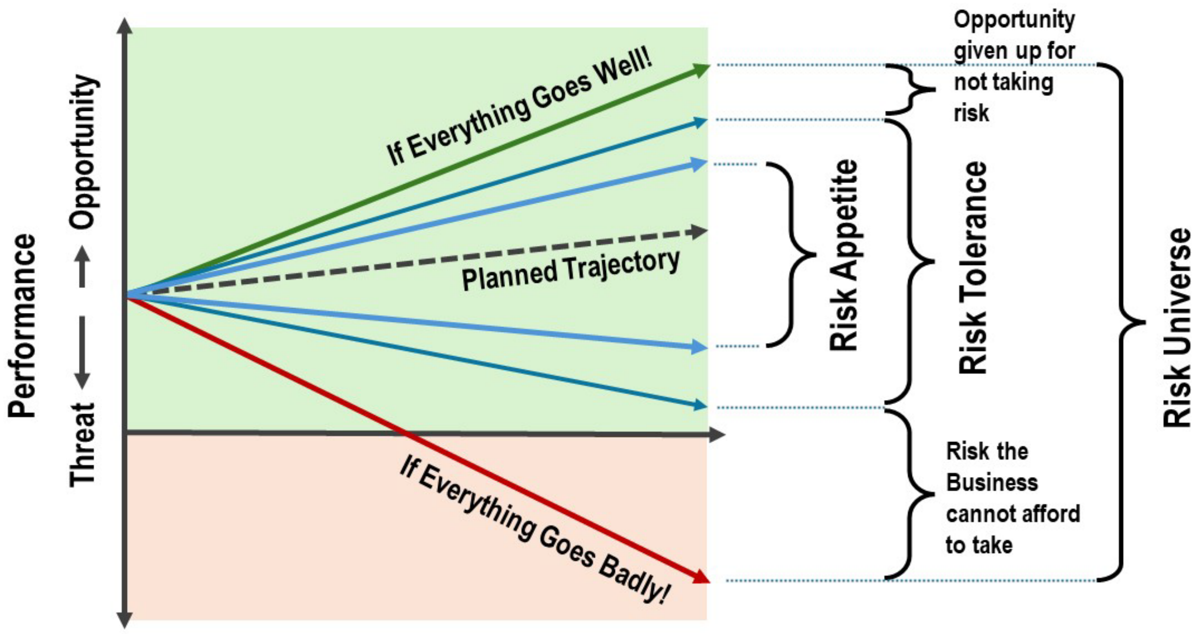

Figure 1 Concepts of risk tolerance and appetite (IRM 2011)

4.2 The practicalities of enterprise risk management implementation

In practice, assessing risk severity and control effectiveness is subjective. The determination of both MRC and likelihood is prone to under- and over-estimation because 'realistic' and 'plausible' very much depend on the experience, understanding and cognitive biases of the people undertaking the risk assessment. The mining industry is increasingly applying semi-quantitative risk assessment tools to improve the objectivity of the assessment of ALARP risk and has also adopted layers of protection analysis to assess control effectiveness, including control dependency and redundancy (Summer 2003).

Many safety professionals strongly argue that effective ERM must be underpinned by an enabling and complementary organisational culture and structure. In terms of organisational culture, there is consistent advocacy for the mining industry to adopt the principles of high reliability organisations (HROs) to manage catastrophic risk (Hopkins 2009, 2022; Brady 2019; Wilkinson 2016, 2022; Howe et al. 2023). The concept of HROs stems from analysing the characteristics of organisations that safely and successfully operate in risk-intensive industries, which include the mindset, culture and organisational design attributes.

Hopkins (2022) has advocated for the organisational separation of technical authority from operational leadership to ensure the 'voice of the process' is not over-ridden by production and financial imperatives, based on the 'technical authority' model adopted in process-intensive industries. In essence, application of the 3 lines of defence (or assurance) model (Institute of Independent Auditors 2024) seeks to ensure clear and separate organisational accountabilities between the risk owner (first line operations), the standard setter (second line) and the independent audit (third line).

5 Applying a risk management approach to current challenges in mass underground mining

The recent major hazard events at the Kakula, El Teniente and Grasberg mines require the mining industry to reassess its risk management approach and the way it thinks about underground mass mining risks.

5.1 The importance of risk knowledge and understanding

The foundation of a risk management approach to mass underground mining is knowledge and understanding of the underlying risks, especially of their dynamic nature. Some of the risk phenomena the industry is seeking to control are evolving and only partially understood, and there are known unknowns. The mining industry is also continuing to push the boundaries on large-scale mass underground mining in terms of increasing scale, depth and speed to production, with complexity raising the potential for unknown unknowns (unprecedented events). The increasing adoption of mass mining methods across the mining industry raises the potential for blind spots across the industry where critical knowledge is known to only some organisations. Cave mining has historically been the preserve of only a small number of organisations that had built up significant internal knowledge and capability, verging on intellectual property. This asymmetry of knowledge is a challenge for the mining industry.

5.2 Increasing risk severity

The El Teniente and Grasberg incidents establish new precedents for known and established hazards that require an upward revision of both MRC and likelihood rankings for the underlying risks. Using a generic risk matrix scheme like those used by most major mining companies (Figure 2) the safety consequence of seismicity and inrush risks have increased from a single fatality (moderate) or several operator fatalities (major) to multiple fatalities (catastrophic). Some classification schemes distinguish between operator and community member loss of life and are less tolerant of community member loss of life, which may mean both risks may not be at the maximum MRC because of the absence of community member loss of life (cf. Mariana and Brumindho TSF failures). The financial consequences of each event, whilst only partly disclosed in these instances, are likely to be more than USD 1–2 billion, based on production interruption/loss, increased operating and capital costs, and loss of reserves. However, a financial consequence ranking will vary by organisation, with larger organisations likely to have higher thresholds than smaller organisations. The impact on reputation is less tangible but significant, and a repeat incident would inevitably trigger a far greater loss of reputation consequence (e.g. the 2 tailings storage facility failures in Brazil). Likelihood has also increased, potentially from 'rare – not known to have occurred' to at least 'unlikely – known to have occurred but < 1 event/30 years' or even higher in the case of the mines involved. The changes in severity for the risks are shown in Figure 2.

RISK MATRIX		CONSEQUENCE				
	Consequence Type:	Insignificant	Minor	Moderate	Major	Catastrophic
	Safety	First Aid Case	Medical Treatment Case or Lost Time Injury	Permanent Disability or single fatality	Several permanent disabilities or operator fatalities	Several fatalities of members of the public or multiple operator fatalities
	Operational/ Financial	No disruption to operation	Brief disruption to operation	Partial shutdown of operation	Partial loss of operation	Substantial or total loss of operation
	Reputation	Awareness/ concern from specific individuals	Concern/ complaints from certain groups/ organisations	Public concern/ adverse publicity within neighbouring communities	Suspected reputational damage; local/ regional public concern and reaction	Noticeable reputational damage; national and international public attention and repercussions
LIKLELIHOOD: **Almost Certain** (1/year)	One or more events per year	2	3	4	4	4
Likely (3 years)	One event every 1-3 years	2	2	3	4	4
Possible (10 years)	One event every 3-10 years	1	2	3	4	B 4
Unlikely (30 years)	One event could happen within 30 years	1	1	2	3	4
Rare (>30 years)	Event has not occurred before and is unlikely within 30 years	1	1	2	A 3	3

Figure 2 Generic risk matrix showing trends in risk severity for the mentioned recent underground major hazard risks

5.3 Reassessing risk appetite

A reassessment of the underground major hazard risks against an organisation's risk appetite is a 2-part process, starting with a reassessment of the organisation's risk appetite to ensure the risk tolerance thresholds are appropriate for the organisation and then assessing if the relevant risk has fallen into the unacceptable or intolerable level (Figure 3). It is usually the company's board that sets the risk appetite and management's role to manage to it. Risk appetite can be expected to change with time in response to internal and external factors; some organisations will want to adopt a lower risk appetite (a more conservative approach) considering the recent major hazard incidents. It may also be appropriate to reassess the threshold and whether the distinction between operator and community member loss of life is logical (and ethically sound) considering the industry's stated goals of 'zero harm'.

The second part of the process requires the explicit linkage of risk appetite to the organisation's risk matrix (Figure 2). Whilst it is self-evident that certain risks are intolerable, it is not always clear from the risk matrix which risks will not be tolerated under any circumstances. The ALARP framework (Figure 3) clarifies the threshold for risks that must be mitigated and the level of mitigation that is acceptable) A risk that is determined to be 'catastrophic' (e.g. multiple fatality outcome) should clearly be 'intolerable' and requires significant mitigation (Point A – Figure 3). The intent should be to mitigate the risk to 'tolerable if ALARP' (Point B – Figure 3). The obvious question that ultimately must be addressed from this process is 'what happens when the residual risk (after mitigation) remains in the intolerable range (Point C – Figure 3)?'

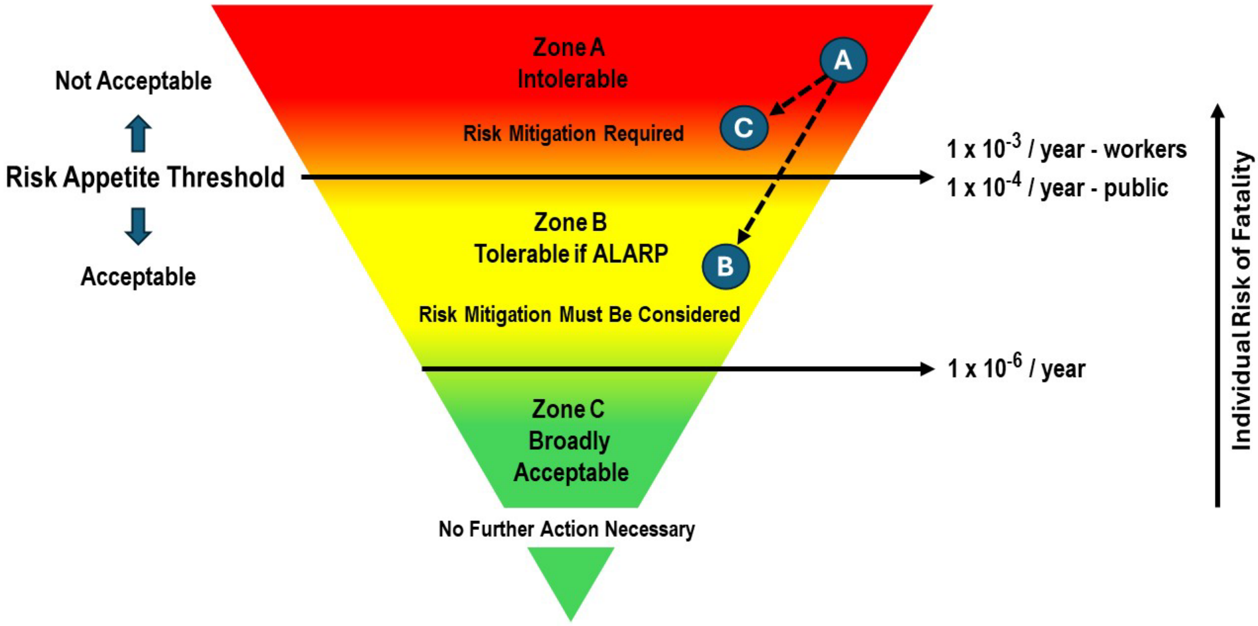

Figure 3 Risk severity criteria and the application of the as low as reasonably practicable (ALARP) framework (modified from Stanley et al. 2018)

5.4 Improving risk controls

In the immediate aftermath of the recent major hazard events outlined above, the involved organisations have recognised the pressing need to implement stronger controls to better manage their major hazard risks (some of the proposed controls are listed in Table 1). This includes both improving existing controls and developing new and additional controls to those already implemented.

Table 1 Proposed additional controls

Mine	Risk	Previous controls	Additional controls
Kakula (Ivanhoe 2025)	Uncontrolled ground movement	Regional pillars, mining sequence, primary and secondary pillar sizing	Increased pillar widths for additional structural support, changed mining sequence to improve stress distribution and overall stability (mine redesign) and enhanced geotechnical monitoring
El Teniente (Codelco 2025)	Seismicity and rockburst	Extensive preconditioning, dynamic ground support, managing size and geometry of the mining blocks and mining sequence, undercutting methodology and geometry, seismic monitoring, autonomous mining operations	Whole-of-mine modelling, improved seismic monitoring, mine redesign, increased automation
Grasberg (Freeport 2025)	Inrush	Dewatering, active drawpoint monitoring, autonomous mining operations	Improved cave management and draw control, improved monitoring (seismic and cave back), improved pit dewatering and water management, and increased automation and remote mining operations

5.4.1 Existing controls

Many of the existing controls were developed over decades and track the increasing complexity of the underground mining operations at both El Teniente and Grasberg. There has been a strong history of innovation in the mining industry, reflecting the truism that necessity drives innovation. For example, Codelco successfully pioneered the application of dynamic ground support (Rojas et al. 2023) and rock mass preconditioning (Morales et al. 2007; Gonzalez et al. 2022; Rojas et al. 2023) at El Teniente to manage the impact of seismicity on mine openings. Likewise, the industry has developed comprehensive management systems for inrush risk (Saepulloh et al. 2022; Ghadirianniari et al. 2024). However, those controls by themselves have proved to be insufficient for extreme events. In the case of seismic risk, for example, it is unlikely that dynamic ground support and/or preconditioning can mitigate the impact of large seismic events of the magnitude observed at El Teniente in July 2025 (Louchnikov & Sandy 2017; Morisette & Hadjigeorgiou 2019).

There has also been a strong reliance upon anticipating major hazard events, both in time and space. Although imperfect, a range of warning signs or weak signals has been used to indicate an increasing risk trend (Table 2). For example, precursor events are used in trigger action response plans to direct changes in the way a mine is operated to mitigate the risk of an unwanted event. However, Codelco noted there were no indications of seismic activity prior to the fatal seismic event (Codelco 2025) and Freeport indicated there were no warnings for the fatal inrush that occurred in September 2025 (Freeport 2025). This is a serious concern because it undermines the assumption that major hazard events can be anticipated and mitigated by removing operators from at-risk areas in an underground mine in a timely manner. This raises the question of what additional information is required to help to identify an impending major hazard event in time to materially mitigate its severity, if indeed such information exists.

Table 2 Weak signals for underground major hazard events

Risk	Causes	Precursor events
Uncontrolled ground movement	Uncontrolled stress accumulation around mine workings	Increased stress in mine pillars, deformation of mine openings, damage to ground support, small falls of ground, increased seismicity
Seismicity and rockburst	Uncontrolled stress accumulation around mine workings, high deviatoric stress	Increased stress in mine pillars, deformation of mine openings, damage to ground support, increased seismicity and small-scale rockbursts, a lack of seismicity where seismicity is expected
Inrush	Water and fines accumulation, connection between water/fines and underlying mine workings	Water accumulation above mine workings, increased water flows from drawpoints, increased fines in a drawpoint, minor 'pushes', negative water balance (water in >> water out)

5.4.2 A focus on mitigation

Most proposed controls focus on mitigating the consequence of an event rather than preventing the unwanted event from occurring, highlighting the difficulty of preventing unwanted events (like seismicity and inrush) from occurring, and particularly their reoccurrence, in existing mines. It is also because many major hazards are inherent in the mining method. For example, the block caving mining method utilises stress redistribution and concentration around the mining void to break up the rock and drive cave propagation to the surface. Seismicity is therefore a positive indicator of the caving process. However, it is a fundamental requirement in block cave mining to ensure people and critical infrastructure are not located in areas of significant stress concentration. Likewise, the ingress of water into a cave volume is the logical outcome of cave propagation to the surface, which is in turn often critical for orebody recovery and managing air blast risk.

In the first instance it makes absolute sense to seek to protect operators from the unwanted events and eliminate the risk of fatalities. However, the potential for significant business interruption and adverse financial and reputational impacts (greater than an organisation's risk appetite) remains. The challenge, therefore, is to mitigate the risk to within the bounds of an organisation's risk appetite.

5.4.3 Improving monitoring and additional data requirements

Both Codelco and Freeport have identified the need for a more holistic view of the mine operation based on the integration of key monitoring data. They have recognised the opportunity to integrate data from a wide range of monitoring systems, including historical information (e.g. drillcore logs, face mapping, rock quality measurements) and real-time data (e.g. seismicity, extensometer measurements, cave trackers and production draw) to allow greater insights into the state of the mine. The holistic cave monitoring and reporting system implemented at the Oyu Tolgoi block cave mine is an outcome of such considerations (Stegman et al. 2022; Ulziijargal et al. 2024).

The need for improved cave back and cave shape monitoring is well documented (Stegman et al. 2018) and there has been considerable innovation in the last decade with the development of remote imaging techniques (including seismic array mapping, tomography and the recent application of muon technology), and Cave Tracker and Networked Smart Marker systems (Bayar et al. 2024), to track material movement in the cave block and define cave boundaries. But there are still issues with the resolution of these systems and the need for considerable interpretation of multiple data sets to create useful insights.

In the context of the recent major hazard events described here, it would be extremely powerful if it were possible to identify water and fines accumulations inside the cave and the preferential flow pathways that may trigger an inrush event, and to be able to measure changing stress conditions throughout the mine in real-time, which, when coupled with dynamic modelling, could be used to predict increasing seismic risk.

5.4.4 Increasing automation and remote operations

Increased application of autonomous and remote mining operations is being prioritised at both El Teniente (Codelco 2025) and Grasberg (Freeport 2025) to remove people from high-risk work locations. Autonomous and remotely operated underground mining equipment are already widely used, and the technology is relatively mature. That said, there are still many tasks that require people to be underground, especially during the mine construction phase and those associated with maintenance activities. As such, it will take some time to be able to operate underground mines without putting people underground.

5.4.5 Improving the forecast of rock mass response to mining

Arguably the most important control for managing major hazard risk in large-scale underground mines is the ability to accurately forecast the rock mass response to mining at both local and global scales. Codelco reached a similar conclusion in its investigation into the fatal seismic event at El Teniente:

> "*…risk management practices had been applied separately across projects as they were developed, reinforcing the need to strengthen the integrated geomechanical monitoring and modelling system to incorporate new variables and anticipate broader underground behaviour.*" *(Codelco 2025)*

It is also a primary input into managing the broader risk of uncontrolled ground movement; for example, the Kakula mine incident.

Predictions of how a rock mass will react to mining is entirely dependent on the underlying geomechanical model being applied. The elements of an adequate fit-for-purpose geomechanical model are:

1. sufficient orebody knowledge to enable accurate rock mass characterisation at the scale of the design (e.g. local versus global)
2. ongoing monitoring to assess the quality of model inputs and assumptions (e.g. new or different orebody knowledge) and to identify differences between forecast and actual rock mass response as quickly as possible
3. ongoing calibration of the model against actual rock mass responses to mining.

Rock mass characterisation is an imprecise process that is heavily dependent on interpretations of the local geology (lithology, alteration, structure, rock mass domains) and routinely suffers from insufficient data (undersampling and/or non-representative sampling and measurement of rock properties). The resultant models, which underpin mine design, invariably oversimplify and smooth/average the orebody properties. A simple analogy to explain the inherent modelling challenge is 'a chain is only as strong as its weakest link'. A mine design may appear technically feasible based on a particular geomechanical model, but the model will likely under-represent the weakest rock, which is the weak link in the causal chain and the point of failure. At a minimum, understanding the inherent uncertainty of the geomechanical models is fundamental.

There are 2 ways this problem can be addressed:

1. by collecting more information at an increasing density, which allows much more detailed geomechanical models to be created that explicitly model the weakest zones, recognising that this adds cost and time to the mine design phase and reduces economic returns from the project
2. by creating mine designs that provide sufficient 'factors of safety' to address the known unknowns in the rock mass, recognising that conservative mine designs will also reduce economic returns from the project.

This risk-reward trade-off between allocating time and resources to collecting sufficient orebody knowledge and building fit-for-purpose geomechanical models as the basis for mine design and speed to development plays out on every underground project. In practice, 'sufficient' is very difficult, if not impossible, to define at the start of a project. Unfortunately, the consequences of an inadequate geomechanical model and poor mine design usually only become obvious in the production ramp-up and subsequent operations. The hypothesis that 'get into production as fast as possible and any problems can be sorted out afterwards' assumes that the consequences of a poor mine design are not catastrophic, which in the case of large, complex underground mining operations, is a big 'IF'.

Codelco's summary of its El Teniente incident investigation highlighted another extremely important aspect of stability analysis – the key role of global stability analysis; that is, 'whole of mine'-scale stability in addition to analysis at the scale of a single excavation or block cave (Codelco 2025). Global analysis must consider changes through time to analyse significant mining interactions (interaction between block caves, including diminishing pillars) but also, as highlighted by the El Teniente incident, the cumulative impact of rock mass extraction and its unweighting. For example, many decades of resource extraction at a mining location will slowly and gradually unweight the rock mass, triggering increasing differential stresses and creating the conditions for large-scale mine deformation.

5.4.6 Assessing control effectiveness

Assessing control effectiveness closes the loop in the risk assessment process by testing controls to ensure they are working as designed. For example, weak signals can be missed because monitoring systems are insufficient and/or poorly designed or are not working as designed, or the data is not being assessed in a timely manner. Typically, the process of control verification is performed by the front line operations teams and is then checked by second or third line assurance.

A more powerful process for reviewing control effectiveness is through a digital mine management system that brings of all the key underlying information required to be 'in control' into one place and integrates that data to allow insights to be shared across an organisation, including between front line and assurance teams. Moorcroft et al. 2022 describe the approach used at Oyu Tolgoi block cave operations to establish an operations platform that aggregates historical and real-time data and links the data to the mine's TARPs and cave management plan rules. Cave monitoring workflows are used to improve day-to-day and long-term management of caving operations for a variety of units, including operations, design, technical and senior leadership teams, and allows major hazard control verification to occur in real time. Importantly, the platform triggers warnings on the status of the underlying geotechnical monitoring systems; for example, when the data feed from a sensor is offline. The cave management system drives increased visibility and transparency of cave performance and a culture of open sharing of information, which helps break down silos between teams.

5.5 Towards a high reliability mindset

The effective management of underground major hazards in the mining industry requires a high level of rigour and systematisation to achieve effective ERM. It also requires a mindset and organisational culture that promotes a sense of 'chronic unease'. Fruhen et al. 2014 have defined "chronic unease" as maintaining "a state of constant wariness towards the management of risks." Fruhen & Flin 2015 then define the key attributes of "chronic unease" as "flexible thinking, pessimism, a propensity to worry, vigilance, requisite imagination and experience". These attributes, whilst somewhat abstract, are required if the mining industry is to anticipate 'unprecedented' major hazard incidents. The assumption that future incidents will be of a similar consequence or follow similar causal pathways to those of the past ignores the lessons from recent events and the increasing complexity of large-scale underground mining.

The concept of 'chronic unease' is synonymous with 'preoccupation with failure', one of the 5 principles of a high reliability organisation (Weick et al. 1999; Weick & Sutcliffe 2001; Hopkins 2009, 2021). Howe et al. 2023 provide a useful example of the application of an HRO mindset applied to the management of an environmental disaster in the mining industry (like a TSF failure) and this can be readily translated to major hazard management in the underground mining industry (Figure 4).

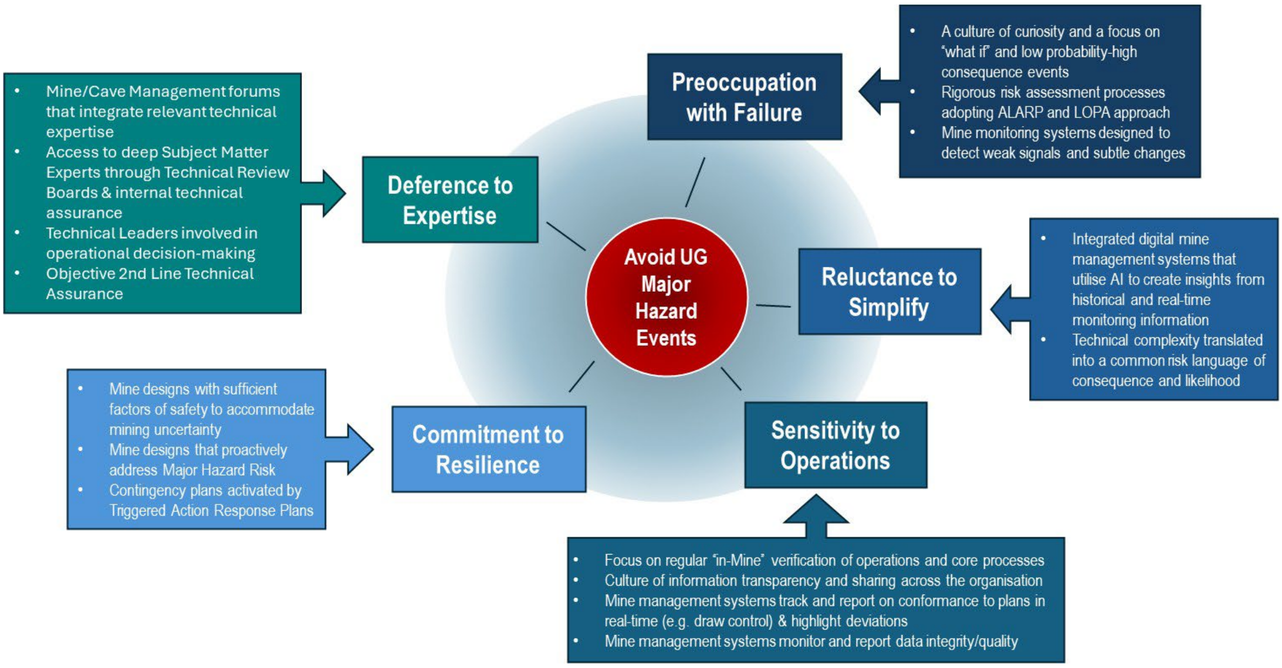

Figure 4 Application of the high reliability organisation mindset to the management of underground major hazard events (modified from Howe et al. 2023). As low as reasonably practicable (ALARP), layers of protection analysis (LOPA), artificial intelligence (AI)

6 Conclusion

Major hazard events like those experienced at Kakula, El Teniente and Grasberg are powerful reminders of the risks associated with large-scale underground mining. The consequences of these events have been multiple loss of life, material financial impacts, and loss of reputation for the organisations involved and for the broader mining industry. The incidents challenge the adequacy of the industry's risk management approach to major hazard management in terms of the how well the risks are understood, the willingness of both the industry and individual mine operators to accept the risks, and how the risks are effectively managed.

The mining industry stakeholder response to the 2 tailings storage facility failures in Brazil in 2015 and 2019, which resulted in significant loss of life and catastrophic impacts on the environment, provide a very relevant example of the industry's stakeholders resetting the industry's risk appetite and instituting a more rigorous and far more transparent approach to the management of major hazard risk. The challenge for the mining industry is how it can establish, maintain and, in instances, regain the trust of the many stakeholder interests in that mass underground mining can be undertaken with acceptable levels of risk for all participants.

The solution lies in the application of rigorous and transparent application of enterprise risk management processes, founded on a clear definition of risk appetite (what is acceptable to the industry but also, ultimately, to the industry's stakeholders) and the creation of comprehensive controls that mitigate the consequences of major hazard events to a level that is within the industry's risk appetite. Current controls have repeatedly been shown to be inadequate. As an unavoidable consequence, the mining industry must accept the responsibility that it must not only develop stronger and more effective controls, which likely requires substantial changes to the way underground mines are designed, constructed and operated, but also ensures that all associated major hazard risks are fully anticipated and consciously accepted. The appropriate and dynamic management of underground mining risk requires a 'whole of industry' approach and the adoption of a high reliability organisation mindset.

The ultimate question for the mining industry is: How can the industry establish, maintain and, in instances, regain the trust of the many industry stakeholder interest groups such that mass underground mining can be undertaken with acceptable levels of risk?

Acknowledgement

Thank you to Roland Burgman, Alex Campbell and David Collopy for their input and critical review of this paper.

References

Bayar, E, Simanjuntak, K, Birch, D, Mardiansyah, F & Purwanto, H 2024, 'Seismological data and analysis for the early stages of block caving', in D Johansson & H Schunnesson (eds), *MassMin 2024: Proceedings of the 9th International Conference & Exhibition on Mass Mining*, Luleå University of Technology, Luleå, pp. 893–908, https://doi.org/10.36487/ACG_repo/2435_G-02

Brady, S 2019, *Review of All Fatal Accidents in Queensland Mines and Quarries from 2000 to 2019*, Queensland Department of Natural Resources Mines and Energy, Brisbane.

Church of England 2024, *The Investor Mining and Tailings Safety Initiative*, viewed 15 February 2026, https://www.churchofengland.org/about/leadership-and-governance/national-church-institutions/church-england-pensions-board/pensions#:~:text=The%20Investor%20Mining%20and%20Tailings%20Initiative%20(IMTSI)%20was%20founded%20in,has%20developed%20though%20three%20phases:

Codelco 2025, 'Codelco achieved 937,000 tons of its own production and US$4.159 billion in EBITDA in the third quarter' press release, viewed 15 February 2026, https://www.codelco.com/en/codelco-alcanzo-937-mil-toneladas-de-produccion-propia-y-us-4-159

Dhawan, R and Davy, A 2022, *7 Lessons from disaster – mining's journey to a safer mine*, viewed 15 February 2026, https://www.icmm.com/en-gb/comment/2022/lessons-from-disaster

Freeport 2025, *Freeport Update November 18, 2025*, presentation, viewed 20 February 2026, https://s22.q4cdn.com/529358580/files/doc_presentations/2025/FCX_3Q25_CC_update.pdf

Fruhen, L, Flin, R & Mcleod, R 2014, 'Chronic unease for safety in managers: a conceptualisation', *Journal of Risk Research*, vol. 17, no. 8, pp. 969–979.

Fruhen, L & Flin, R 2015, 'Chronic unease' for safety in senior managers: an interview study of its components, behaviours and consequences', *Journal of Risk Research*, vol. 19, pp. 1–19.

Ghadirianniari S, McDougall S, Eberhardt E, J, Varian, K Llewelyn, R Campbell, A Moss 2024, 'Wet inrush susceptibility assessment at the Deep Ore Zone mine using a random forest machine learning model', *Mining Technology: Transactions of the Institutions of Mining and Metallurgy*, vol. 133, no. 3, pp.276–288.

Global Tailings Management Institute 2020, 'Global Industry Standard on Tailings Management', International Council on Mining and Metals (ICMM), United Nations Environment Programme (UNEP) and Principles for Responsible Investment (PRI) https://thegtmi.org/gistm-implementation-documents/

Gonzalez, F, Vallejos, J, Rojas, E & Landeros, P 2022, 'Evaluation of the seismic rock mass response to mining and the impact of preconditioning using an epidemic-type aftershock model', *International Journal of Rock Mechanics and Mining Sciences*, vol. 150, https://doi.org/10.1016/j.ijrmms.2021.104975

Hopkins, A 2009, 'The problem of defining high reliability organisations', in A Hopkins (ed) *Learning from High Reliability Organisations*, CCH Publishing, Sydney, pp. 5–16.

Hopkins, A 2021, *A Practical Guide to Becoming a "High Reliability Organisation"*, Australian Institute of Health & Safety, Kensington.

Hopkins, A 2022, *Sacrificing Safety: Lessons for Chief Executives*, CCH Publishing, Sydney.

Howe, L, Johnston, S & Côte, C 2023, 'Mining-related environmental disasters: A High Reliability Organisation (HRO) perspective', *Journal of Cleaner Production*, vol. 417, https://www.sciencedirect.com/science/article/pii/S0959652623021236

Institute of Risk Management (IRM) 2011, 'Risk Guidance Paper - Appetite & Tolerance', London, viewed on 20 March 2026, https://www.theirm.org/media/7239/64355_riskapp_a4_web.pdf

International Organisation for Standardisation 2018, *Risk management — Guidelines (ISO 31000:2018)*, International Organisation for Standardisation, Geneva.

Ivanhoe Mines 2025, *Ivanhoe Mines Announces Restart of Underground Mining Operations on Western Side of Kakula Mine on June 7, 2025*, news release, viewed on 18 January 2026, https://www.ivanhoemines.com/news-stories/news-release/ivanhoe-mines-announces-restart-of-underground-mining-operations-on-western-side-of-kakula-mine-on-june-7-2025/

Lam, J 2017, *Implementing Enterprise Risk Management – From Methods to Applications*, Wiley, Hoboken.

Louchnikov, V & Sandy, MP 2017, 'Selecting an optimal ground support system for rockbursting conditions', in J Wesseloo (ed.), *Deep Mining 2017: Proceedings of the Eighth International Conference on Deep and High Stress Mining*, Australian Centre for Geomechanics, Perth, pp. 613–623, https://doi.org/10.36487/ACG_rep/1704_41_Louchnikov

Luiz, H, Enner, A, Park, E, Rogério, G, Yunung, N, Nariane, B, … Carlos, R 2020, 'The 2019 Brumadinho tailings dam collapse: Possible cause and impacts of the worst human and environmental disaster in Brazil', *International Journal of Applied Earth Observation and Geoinformation*, vol. 90, pp 1–12, https://www.sciencedirect.com/science/article/pii/S0303243420300192

Moorcroft, TH, Simanjuntak, K, Dorjsuren, O, Sanaakhorol, M, Enkhtaivan, E, Watt, … Zimmermann, T 2022, 'Oyu Tolgoi and Rio Tinto partnership with Palantir Technologies to provide effective geotechnical risk management', in Y Potvin (ed.), *Caving 2022:*

Proceedings of the Fifth International Conference on Block and Sublevel Caving, Australian Centre for Geomechanics, Perth, pp. 877–890, https://doi.org/10.36487/ACG_repo/2205_60

Morales, RF, Henriquez, JO, Molina, RE, Araneda, OA & Rojas, EG 2007, 'Rock Preconditioning Application in Virgin Caving Condition in a Panel Caving Mine, CODELCO Chile El Teniente Division', in Y Potvin (ed.), *Deep Mining 2007: Proceedings of the Fourth International Seminar on Deep and High Stress Mining*, Australian Centre for Geomechanics, Perth, pp. 111–120, https://doi.org/10.36487/ACG_repo/711_8

Morissette, P, and Hadjigeorgiou, J, 2019, 'Ground support design for dynamic loading conditions: A quantitative data-driven approach based on rockburst case studies', *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 11, no. 5, pp 909–919, https://doi.org/10.1016/j.jrmge.2019.03.002

Rojas, E, Muñoz, A & Landeros Córdova, P 2023, 'Evolution of dynamic rock support systems at the El Teniente mine', in J Wesseloo (ed.), *Ground Support 2023: Proceedings of the 10th International Conference on Ground Support in Mining*, Australian Centre for Geomechanics, Perth, pp. 129–140, https://doi.org/10.36487/ACG_repo/2325_08

Shiels, A, Mpoyo, M, Beck, D & Dehkhoda, S 2023, 'Simulating global deformation and assuring ongoing stability in a complex multi lode room and pillar mine' in Schubert & Kluckner (eds.), Poceedings of the 15th ISRM International Congress on Rock Mechanics & 72nd Geomechanics Colloquium, Austrian Society for Geomechanics, Salzburg, pp 87–92.

Saepulloh, D, Hassell, R & Albrecht, J 2022, 'Managing the risk of uncontrolled flow of material (mudrush) at Argyle Diamond Mine', in Y Potvin (ed.), *Caving 2022: Proceedings of the Fifth International Conference on Block and Sublevel Caving*, Australian Centre for Geomechanics, Perth, pp. 583–596, https://doi.org/10.36487/ACG_repo/2205_40

Stanley, A, Nicholls, C, Burnup, B & Smith, J, 2018, 'Risk tolerability targets; misconceived, misunderstood and misapplied', *Symposium Series No 163 Hazards 28*, Institute of Chemical Engineering, Rugby https://www.icheme.org/media/16956/hazards-28-paper-50.pdf

Stegman, C, van As, A & Peebles, E 2018, 'Past learnings focus innovative solutions to future cave mining', in Y Potvin & J Jakubec (eds), *Caving 2018: Proceedings of the Fourth International Symposium on Block and Sublevel Caving*, Australian Centre for Geomechanics, Perth, pp. 37–42, https://doi.org/10.36487/ACG_rep/1815_0.3_Stegman

Stegman, CL, Togtokhbayar, O, Herselman, S & Altankhuu, B 2022, 'Oyu Tolgoi: engineering a Mongolian caving dynasty', in Y Potvin (ed.), *Caving 2022: Proceedings of the Fifth International Conference on Block and Sublevel Caving*, Australian Centre for Geomechanics, Perth, pp. 625–634, https://doi.org/10.36487/ACG_repo/2205_43

Summer, A 2003, 'Introduction to layers of protection analysis', *Journal of Hazardous Materials*, vol. 104, no. 1–3, pp. 163–168. https://doi.org/10.1016/S0304-3894(03)00242-5

The Committee of Sponsoring Organizations (COSO), World Business Council for Sustainable Development (WBCSD) 2018, *Enterprise Risk Management, Applying enterprise risk management to environmental, social and governance-related risks*, viewed on 15 February 2026, https://www.coso.org/_files/ugd/3059fc_671ed4466c0e423b93a9ef3d2e30b786.pdf

The Institute of Internal Auditors (IIA), 2024, *Statement of Position Three Lines Model - An Update of the Three Lines of Defense*, viewed 25 March 2016, https://www.theiia.org/globalassets/site/resources/statements-of-position/tlm_assurance_advice_support_effective_gov_en.pdf

Ulziijargal, M, Enkhtaivan, E, Purevdorj, M, Purwanto, H, Simanjuntak, K & Moorcroft, T 2024, 'Oyu Tolgoi geotechnical monitoring system', in D Johansson & H Schunnesson (eds), *MassMin 2024: Proceedings of the 9th International Conference & Exhibition on Mass Mining*, Luleå University of Technology, Luleå, pp. 383–397, https://doi.org/10.36487/ACG_repo/2435_C-07

van der Merwe, N 2006, 'Beyond Coalbrook: What did we really learn?', *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 106. pp. 857–868.

Webb, M 2025, Ivanhoe cuts 2025 guidance, withdraws 2026 forecast as DRC copper mine restarts', *Creamer Media's Mining Weekly*, viewed 15 February 2026, https://www.miningweekly.com/article/ivanhoe-cuts-2025-guidance-withdraws-2026-forecast-as-drc-copper-mine-restarts-2025-06-12

Weick K, Sutcliffe, K & Obstfeld, D 1999, 'Organising for high reliability: processes of collective mindfulness', *Research in Organisational Behaviour*, vol. 21, pp. 81–123.

Weick, K & Sutcliffe, K 2001, *Managing the Unexpected: Resilient Performance in an Age of Uncertainty*, John Wiley & Sons, Hoboken.

Wilkinson, P 2016, 'Can HRO Theory and Practices be Applied in Practice? A Case Study', *Proceedings of the SPE Asia Pacific Oil & Gas Conference and Exhibition*, Society of Petroleum Engineers, Perth.

Wilkinson, P 2022, *DISCUSSION PAPER - Process Safety Management Application and relevance to mining*, Queensland Commissioner for Resources Safety and Health, Brisbane, https://www.publications.qld.gov.au/ckan-publications-attachments-prod/resources/2dcf46e9-1a16-48ce-a11c-edf3c8902031/noetic_psm-discussion-paper_30-june-2022.pdf?ETag=a4df5b898b41bdf057f0864ebe6339fc