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_97

Seismic hazard in deep hard rock mining: a brief comparison of stoping and caving experience

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Abstract

As global mineral resources become depleted near the surface, hard rock mining operations are progressing to depths exceeding 1 km metres and approaching ultra-depths of 2 to 3 km or greater, resulting in an escalating seismic hazard. This paper presents a comparative discussion of seismic mechanisms and risk management strategies between deep hard rock stoping and caving mines. First, common mining-induced seismic source mechanisms between these two mining methods are reviewed based on case studies that focus on strong rockburst events. Accordingly, their risk mitigation measures from a practical ground control perspective were compared and discussed. The goal of this paper is to identify first principles that can guide seismic risk management plans for both mining methods.

Keywords*:* *hard brittle rock, rockburst, seismic source mechanism, seismic risk management plan*

1 Introduction

As near-surface mineral deposits become progressively depleted, the global mining industry is undergoing a shift towards deep operations. This migration into the deep and high stress regime fundamentally alters the geomechanical environment. At these depths the primary driver of instability for hard rock mining shifts from gravity-driven falls of ground to mining-induced, stress-driven failures, increasing the seismic hazard and the potential for violent rockbursts. The management of seismic risk at depth is not a 'one-size-fits-all' engineering challenge. It is primarily dictated by the mining method, specifically the choice between stoping and caving. In stoping operations such as those at Agnico Eagle's LaRonde mine (Mercier-Langevin & Hudyma 2007) and Discovery Silver's Kidd mine (Disley 2014), both in Canada, seismic risk is often concentrated around discrete pillars and advancing stope faces. In massive caving operations like Codelco's El Teniente mine in Chile (Potvin et al. 2010) or LKAB's Kiirunavaara complex in Sweden (Joughin 2023), the seismic response tends to be wider (e.g. cave scale), involving the interaction of the large-scale cave void with regional geological structures and massive abutment zones. Despite these operational differences, the underlying physics of rock failure modes remain consistent, i.e. the sudden release of stored strain energy. Ultimately, as the common mining slang goes, 'rock is rock' and it obeys the similar ground control principles regardless of the extraction method employed.

This paper provides an analysis of rockburst mechanisms within the frameworks of rock mechanics theory and mining operations, adhering to the 'first principles' approach. This is followed by a comparative review of seismic mechanisms and risk management strategies in deep hard rock mining. By reviewing common large-scale seismic source mechanisms, specifically focusing on a range from localised pillar bursts to large-scale fault slip while excluding local strainbursts, the study examines how different mining conditions influence the dynamic rock mass response. Through case studies, risk mitigation measures are compared

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from a practical ground control perspective. This paper aims to identify the first principles of seismic risk management that are applicable across both stoping and caving environments at depth.

2 Rock mechanics principles for mining rockburst

2.1 Rock mechanics principles

Hard brittle rock is characterised by high peak strength followed by a rapid strength reduction once the applied load exceeds its peak capacity. Through the use of stiff testing machines, complete load deformation relations are recorded in laboratory settings and traditionally categorised into Class I and Class II post-peak behaviours. Recent research (Cai 2025) has demonstrated that Class II behaviour is often an artifact caused by the unloading of the actuator as the servo control system maintains a constant lateral strain rate, suggesting it may not represent an intrinsic property of hard rock (Hou & Cai 2022). Conversely, Class I failure represents the intrinsic strain softening behaviour of the rock. From a first principles perspective, violent rock failure in both the laboratory and the field, such as a rockburst, requires the external loading environment to provide energy in excess of what the rock can consume in a stable strain softening fashion. This instability criterion is simplified and defined by the relationship between the local mine stiffness (LMS) and the post-peak stiffness of the rock, as illustrated in Figure 1. The complete strain softening relations recorded in laboratory testing provide a valuable conceptual model for describing in situ rock mass deformation and the energetic drivers of violent failure. It is critical, however, to acknowledge that loading conditions in underground mining operations typically deviate from idealised quasistatic laboratory environments. While strain softening is commonly observed under constant low confinement and fixed strain increments, such conditions are rare in mining areas of engineering interest. For instance, following mass blasting, the stress field in the surrounding rock mass changes drastically within minutes or even seconds, resulting in dynamic loading conditions and simultaneous changes in confinement. Conversely, in areas remote from active production or development blasting, the rock mass and geological structures may continue to deform under static conditions for months or years through rock mass creep. These various loading regimes and their implications for stability are summarised in Figure 1.

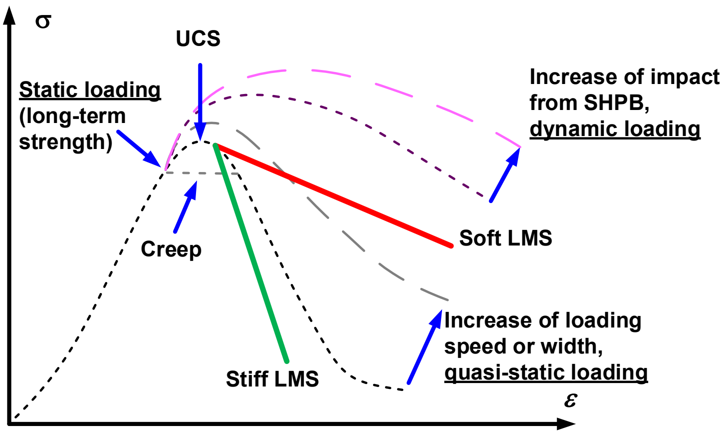


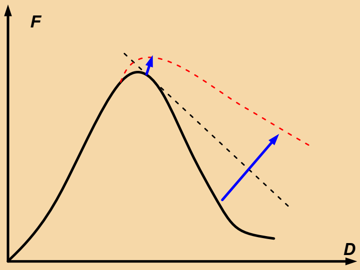
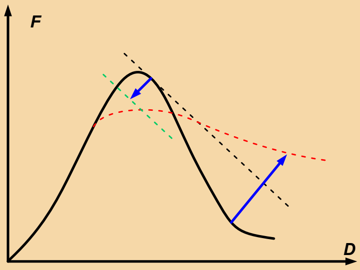
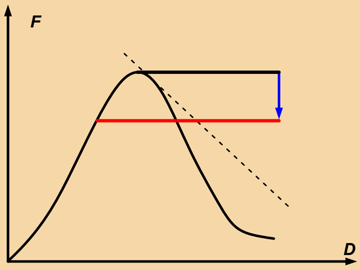
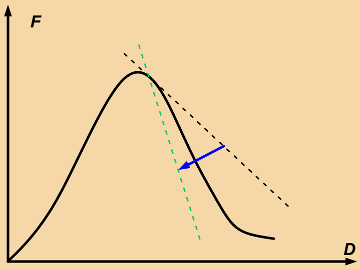
Figure 1 Impact of local mine stiffness (LMS) and loading conditions on rock failure modes

To improve engineering design it is plausible to test rock properties under loading conditions that simulate field environments. For example, static rock tests are preferred over quasistatic tests to estimate long-term rock strength and creep behaviour at a constant load level over several months. Similarly, dynamic rock testing provides insights into rock failure processes subjected to impacts lasting less than one second. Unfortunately, these tests are often time-consuming or cost-prohibitive for standard underground mining designs. Historically, the mining industry tends to accept lower testing standards than other disciplines, such as civil tunnelling or nuclear waste disposal, due to the relatively short service life of typical mine excavations where production life may only remain open for a few months. However, this design paradigm is increasingly challenged in high-risk environments. Mines subjected to rockburst hazards, especially those with mine-wide impacts and long service lives, like deep caving operations, require a more rigorous approach. For caving design, factors such as the impact of defects on rock block strength and the breakage of rock bridges during static shearing are critical for predicting cave propagation and ground control hazards. These complex rock mass properties remain difficult to capture through conventional rock testing techniques.

2.2 Mining rockburst and its prevention

The severity of a rockburst, initiated when induced stress exceeds rock mass strength, is primarily governed by the energy balance between the failing rock and the external loading system (as LMS). From a rock mechanics perspective, a violent rockburst can theoretically be avoided if any of the 4 quasistatic loading conditions illustrated in Table 1 are satisfied. Achieving conditions 1A and B generally requires tactical engineering measures, such as specialised ground support or localised de-stress blasting, to directly alter the deformation behaviour of the burst-prone ground. In contrast, fulfilling conditions 2A and B most often necessitates strategic measures, typically involving fundamental changes to mine design and sequencing, in an attempt to optimise the external loading environment from a stress management perspective surrounding the high-risk zones. These engineering measures will be revisited in Section 4, following a review of mining conditions that are conductive to seismic sources in both stoping and caving operations.

Table 1 Four loading conditions (arrow/s) and possible measures to control rockburst hazard

Conditions		**Possible engineering measures**
1A Strength enhancement		Increase confinement Apply/upgrade ground support Minimise blast damage to rock mass Backfill (through confinement) Compaction of muck piles
1B Ductility modification		Stress shadowing De-stress blasting or confined blasting Hydraulic fracturing Adjust mucking/draw rate
2A Stress reduction		Change mining method or mine layout Optimise mining sequence Change mining direction Manage extraction ratio Strategic pillar design (crush pillar, stabilising or regional pillars) Local mine design, such as just-in-time development
2B Stiffness optimisation		

2.3 Slip-type events

The movement of major geological structures is frequently the driver of large-magnitude seismic events in underground mining. These occurrences are typically classified as fault slip events and, in a geomechanical context, can include shear displacement along geological contacts such as dyke boundaries. Although these mechanisms are fundamentally similar to natural earthquakes, the direct triggers for mining-induced slip are governed by underground extraction activities rather than the regional tectonic setting. Generally, as the spatial extent of mining increases, such as during the late stages of bulk stoping or as a cave matures, the potential for triggering structural movement rises. Consequently, it is difficult to completely eliminate this risk during late-stage extraction. The severity of slip-type events can be conceptually estimated by the classic equation for seismic moment (*M*):

$$M = G \times A \times d \quad (1)$$

where:

G = shear modulus of the surrounding rock mass

A = area of the slip surface

d = average slip displacement.

Beyond the previously mentioned breakage of intact rock bridges, which is often a prerequisite for a slip-type event, the equation indicates that both the slip area and displacement can be related to the Mohr–Coulomb criterion (Labuz & Zang 2014). Under this criterion, slip occurs if shear stress exceeds the combination of cohesion and frictional resistance, the latter of which is governed by normal stress. Shear stress and normal stress are influenced by mining activities through two primary factors. Firstly, larger mining footprints often relates to more drastic stress redistribution within the surrounding rock mass. Regarding fault slip potential, mining expands the volume of rock subjected to increased deviatoric stress, thereby increasing the potential for the structure to reach its shear strength over a larger surface area with escalating stick-slip risk. Secondly, as mining progresses, more voids are created and subsequently relaxed. Whether these voids remain open or are backfilled afterwards, they reduce the confinement of surrounding rock mass via the unclamping effect. Unclamping offers structures greater freedom to displace and increases the likelihood that a structure can daylight into excavations. These two factors contribute to the breakdown of rock bridges and asperities through repeated seismic activity and fault creep, eventually allowing for more continuous and larger-scale slip events.

3 Mining geomechanical drivers for large seismic events

This section focuses on briefly reviewing large-magnitude seismic events and severe rockbursts that present significant ground control challenges, such as pillar bursts and fault slip events. While localised strainbursting is a common form of violent rock failure, it is typically associated with lower seismic magnitudes (e.g. $M \leq 1$) and released energy scales on the order of kJ/m^2. Proactive implementation of competent ground support systems and administrative controls is often sufficient to contain such localised hazards. In contrast, the energy released during a pillar burst or slip-type event can be several orders of magnitude greater, necessitating more robust management approaches.

3.1 Bulk stoping

Modern deep mechanised stoping operations routinely employ cemented backfill to enhance ground stability and maximise ore recovery. The use of consolidated fill increases scheduling flexibility, enabling multiple concurrent production faces or mining blocks. However, this operational flexibility often also results in complex mined-out geometries, particularly during late-stage extraction. The accumulation of stress within these geometries frequently relates to large seismic events occurring at converging mining fronts, sharp mining block corners or abutments, and various forms of remnants. The most common mining-related geomechanical drivers for large seismic events in stoping environments are summarised below.

3.1.1 Converging mining fronts

As mining blocks advance towards one another, the intervening rock mass is subjected to rapidly escalating stress concentrations. In addition to pillars (e.g. regional or dyke pillars, see below) formed by lateral converging fronts, flat sill pillars representing the final connection between 2 mining horizons are particularly vulnerable to high-strain energy accumulation and subsequent violent failure. This is often exacerbated by the fact that the major principal stress in deep mining environments is typically sub-horizontal. At the LaRonde mine, sill pillars were identified as one of the highest hazard areas, with historically large and damaging events occurring as these pillars thinned (Mercier-Langevin & Hudyma 2007).

3.1.2 Barren pillars

Low-grade or waste pillars are often left intact to maintain regional stability. Due to their typically large dimensions and squat shape, these pillars do not yield as readily. At Kidd mine, regional pillar failure and shear rupture planes are dominant seismic sources at depths approaching 2,900 m (Disley 2014). This risk is particularly pronounced where a sharp stiffness contrast exists. For instance, stiff geological features such as dykes, can act as stress channels that load up and yield suddenly, releasing massive amounts of stored energy. At the Young-Davidson mine in Cananda, the presence of stiff diabase (dolerite) dykes intersecting the thick orebody created highly burst-prone conditions (Xu et al. 2019).

3.1.3 Diminishing (transverse) stope pillars

During primary-secondary (or tertiary) extraction sequences, the secondary or tertiary pillars are progressively reduced in size. Under high stress condition, if the load-shedding from the primary stopes exceeds the capacity of the diminishing pillar before it can yield in an aseismic fashion, a violent pillar failure can occur. Experience at Nickel Rim South mine (Canada) and other mines has shown that the slenderness of the temporary ore pillars is critical to determine whether early yielding or stress and strain energy storage occurs (Jalbout & Simser 2014).

3.1.4 Remnants

In the final stages of a mine's life, pillars originally designed for infrastructure protection, such as shaft or rib pillars, are often recovered or subjected to extreme regional stresses. These remnants often represent the last stiff elements in a highly extracted environment. For instance, Mount Charlotte mine (Western Australia) historically experienced its largest seismic events, ranging from Richter local magnitude (ML) 2.5 to 3.0, during the failure of rib and crown pillars, leading to the adoption of large-scale preconditioning (Mikula et al. 1995).

3.1.5 Abutment

Stress concentration is common at the abutments of large mined-out areas, especially at sharp corners at depth. At the Westwood mine (Canada), a major Nuttli magnitude 3.7 seismic event prompted a geomechanical investigation that delineated this mechanism (Jalbout et al. 2024). The back-analysis concluded that a stiff, sub-vertical, east–west-trending porphyritic dyke acted as a rigid regional abutment. This tabular feature effectively channelled and concentrated high sub-horizontal regional stresses, acting as a severe stress raiser directly adjacent to active stoping horizons and intersecting the structural fabric.

3.1.6 Slip-type events

Large-scale fault slip events can be triggered by a combination of any of the aforementioned mining conditions or accelerated by the global stress redistribution near stoping abutments. At Creighton mine (Canada), while the majority of seismicity occurs close to mining, significant events occur hundreds of metres away along major geological shear zones (Malek et al. 2008). At Nickel Rim South, mine-scale geological structures become activated as the overall extraction rate increases, with oblique faults leading to larger-scale fault slip events due to the release of clamping (Simser et al. 2024).

3.2 Cave mining

Cave mining, encompassing block or panel caving and sublevel caving (SLC), including variants such as sublevel retreat caving), differs fundamentally from stoping in that the mining sequence, abutment and direction are generally fixed to achieve and sustain the caving process. The massive scale of these operations means that seismic responses can often be mine-wide or cave-wide, driven by the interaction of the growing cave void with regional stress fields and geological structures. The common mining-related geomechanical drivers for large seismic events in cave mining environments are discussed below.

3.2.1 Caving front

Rockbursts on the extraction level are a primary hazard, particularly near the caving front in post-undercutting configurations. The advancing undercut concentrates massive abutment loads onto the underlying production infrastructure. At the Deep Mill Level Zone in Indonesia, extreme abutment loading at depths exceeding 1,500 m has resulted in a single large seismic event that could evolve into cascading 'pillar-runs', resulting in high-energy failures over large extents of the extraction drifts (Simanjuntak et al. 2020). Incomplete undercutting blasts can further compound this risk by creating point loading on the remaining rock bridges. Stress-driven damages in abutments can also occur due to adverse cave shapes that funnel energy into competent rock units. In SLC at depth, the strict top-down mining sequence often results in rockbursts at the immediate production and footwall drifts near the cave bottom. As mining progresses deeper, the step-out zones and lower levels are subjected to increasing stress from the overlying cave and host rock convergence. At the Ernest Henry mine in Australia, the 45° inclination of the orebody creates a high stress abutment in the step-out zone of each level, where cave propagation has not yet initiated, resulting in intense seismic responses (Campbell et al. 2016).

3.2.2 Slip-type events

These are common when the cave approaches or intersects major geological structures. In the Reservas Norte sector of El Teniente mine, large seismic events are specifically linked to the reactivation of 4 major faults as the cave footprint expands (Potvin et al. 2010). Caving mines can also incur large-magnitude slip-type events on structures that do not intersect the cave but are due to changes to the in situ stress field. This usually manifests as an oblique- to strike-slip on steeply dipping structures on the sides of the cave, or reverse faulting on structures beneath the cave that become unclamped due to the unloading effect of the cave.

3.2.3 Regional pillars

Large seismic events can occur in regional pillars formed between adjacent caves. As multiple caves grow, the intervening rock mass is subjected to high stress loading, eventually exceeding the pillar's peak strength. At the Kiirunavaara mine, the interaction between different extraction blocks under a delayed sequence led to the formation of an unfavourable mine-scale remnant pillar that concentrated severe regional loading, ultimately contributing to the significant moment magnitude 4.2 event in 2020 (Boskovic 2022; Joughin 2023). Similarly, at the Leinster nickel operation in Western Australia, production was suspended following a major seismic event in the 11 Level Fold area where the SLC column interacted with regional shears, necessitating a transition to a block cave method to avoid high-activity zones (Hopkins et al. 2018).

3.2.4 Cave draw practices

Isolated or uneven draw, especially during cave propagation, can lead to irregular cave growth, localised stress concentrations and adverse cavity geometries. This may trigger or exacerbate the seismic risk.

3.3 A short summary of large seismic events

Reviewing the mining scenarios discussed above, the generic characteristics of mining-induced rockbursts can be summarised as follows: mining activities create stress-elevated conditions where a stress increase, often coupled with a confinement decrease, exceeds the local rock mass strength to cause a rockburst.

Alternatively, an increase in shear stress or a decrease in normal stress that exceeds the shear strength of a geological contact can trigger a stick-slip event. These high stress environments can be categorised into 3 primary types: highly stressed pillars, highly stressed abutments and structural movement.

3.3.1 Highly stressed pillars

Within an active mining area, high stress frequently accumulates in pillars. Examples include sill, regional or any form of diminishing pillars created by converging mining fronts. Diminishing pillars at a smaller scale also include secondary or tertiary stope extraction, rib pillar slabbing and late-stage remnants such as panel, barrier or shaft pillars. Adverse pillar loading can also result from isolated draw or incomplete undercutting blasting in block/panel caving mines.

3.3.2 Highly stressed abutments

Highly stressed abutments often develop adjacent to active mining areas, particularly where the abutment geometry forms a sharp angle perpendicular to the maximum induced principal stress. Examples include the extremities of a mining horizon or block in stoping and the extraction level of a cave where it converges with the caving front in a post-undercutting sequence. Similarly, the narrow bottom levels in top-down mining sequences, such as SLC, represent abutment hazards.

3.3.3 Structural movement-related events

Unlike pillar or abutment bursts, which are often localised, fault slip events involve the sudden slip along pre-existing geological discontinuities such as faults, dykes or lithological contacts. In caving mines, the massive expansion of the cave or footprint leads to global stress redistribution that unclamps regional structures.

3.3.4 Short summary

The 3 high stress mining environments described above are the primary geomechanical drivers of large seismic events and severe rockburst hazards. Pillars and abutments are similar and particularly hazardous because they represent large volumes of rock mass in close proximity to mine workings. This becomes increasingly critical during the late stages of mining as stresses are transferred to the final stiff elements (rather than backfill or muck) of the loading system. Therefore, ground control management at depth is essentially pillar management in the end. The proximity of major structures such as faults further influences the seismic hazard. Faults that daylight into large excavations have a greater potential for displacement and are thus more prone to slip. However, the overall risk level for fault slip is governed by the multiple factors defined in Equation 1. Furthermore, even if a slip-type event occurs remotely, the resulting seismic waves can propagate distances and trigger severe damage within highly stressed pillar or abutment zones.

4 Seismic risk mitigation measures

The possible engineering measures to mitigate large seismic risks listed in Table 1 are revisited here. While these measures are theoretically valid for rockburst prevention, the mining industry often prefers more practical and cost-effective measures compared to the civil rock engineering sector. This is primarily due to the relatively temporary service life of mine excavations and less-frequent personnel entry requirements. This section focuses on applying first principles to implement these measures in stoping and caving environments, including a discussion of the differences between these two mining methods.

4.1 Ground control principles in deep mining

In examining the 4 quasistatic loading conditions in Table 1, LMS is the external factor determining the trigger and severity of rockbursts, while the post-peak properties of the failing rock mass primarily affect the rockburst severity. Although LMS often appears to be an intangible term for producing operations, generally, a higher extraction ratio results in a softer LMS. In a simplified form, LMS can relate to the total released energy (E) involved in a rockburst process, expressed as:

$$E = F \times D \tag{2}$$

where:

F = applied force from surrounding rock masses

D = displacement of surrounding rock masses.

Mining activities, ranging from an adopted mining method to development blasts, impact the change in applied force or stress. Therefore stress is a more tangible and commonly controlled parameter than LMS. Compared to large-scale mining activities, immediate stress changes in a local area can be achieved through short-term activities such as blasting, mucking and backfilling within a relatively short time span. Accordingly, time or duration (t) is an often-overlooked controlling factor. The loading speed or input energy rate (E/t) determines whether the loading condition is quasistatic or violent, while the energy release duration can also affect the volume of the failing/ejected rock mass. From a mining geomechanics aspect, the time-dependent nature of rock failure means that rapid stress changes can bring rock to failure quickly and violently, whereas a chronic process of stress redistribution allows rock deformation to adjust slowly and dissipate energy gradually.

The rock deformation involved in energy release is largely affected by the elastic properties of the surrounding rock mass, such as the hanging wall, abutments or host rock surrounding faults. These host rock properties are less influenced by mining activities compared to the rock mass immediately adjacent to mine openings, such as the ore rock or ore pillar, which often serve as the source material for rockbursts. In contrast, activities such as preconditioning and excavation itself effectively change the properties of the rock mass near mine openings. The excavation process inherently degrades the properties of the near-opening rock mass and reduces local confinement (σ_3) through strain relaxation. This reduction in confinement decreases the rock mass strength (σ_{RM}), rendering the area burst-prone.

In summary, aside from LMS, the following variables can be practically influenced by mining activities and/or ground control to mitigate rockburst hazards:

- mining-induced stress (σ_1), representing the stress level of external loading conditions
- time (t), measuring the rate of change in σ_1 and LMS, which governs rockburst intensity
- rock mass strength (σ_{RM}), determining the capacity and volume of the rock mass near openings that may become burst-prone under specific stress levels or triggering conditions
- confinement (σ_3), a factor in controlling or maintaining rock strength and its failure modes.

Any strategic or tactical engineering measures that effectively control these variables are considered practical ground control measures. Strategic measures typically involve fundamental design choices and can impact multiple variables across broad spatial and temporal scales. However, strategic measures are not always preferred over tactical ones in practice. Because mining service lives are relatively short and mine designs often have limited flexibility once mines are in production, the choice between strategic and tactical measures depends on risk and cost assessments conducted by mine planners and operators.

4.2 Strategic measures

4.2.1 Overview

Strategic measures involve interventions that can exert a global impact on optimising the mining stress regime and consequently reducing mine-scale seismic hazard. The primary goals of these measures are to redistribute mining-induced stress evenly and gradually toward abutments or to establish a stress shadow over virgin ground to facilitate future extraction in a de-stressed environment. Consequently, strategic measures typically involve the optimisation or fundamental change of the mining method, mine layout or mining direction, provided such changes remain economically viable.

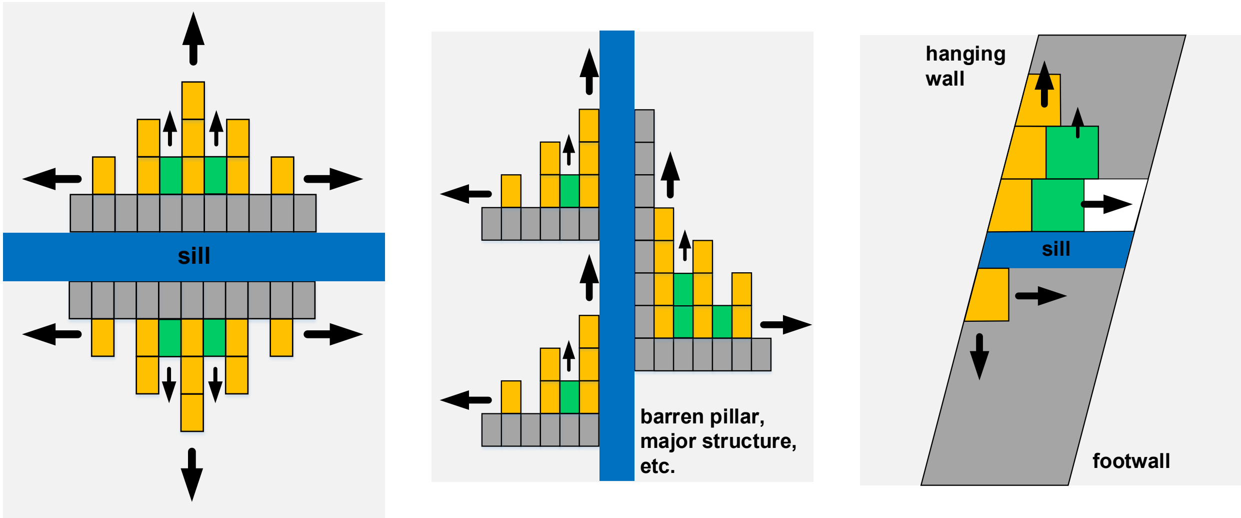
Arguably, it is difficult to implement drastic changes in mining layout or direction for established block/panel caving or SLC operations. In such instances, tactical design adjustments (Section 4.3) combined with robust operational controls (Section 4.4) are necessary to alleviate seismic risk. It should also be noted that due to the relatively fixed yet opposite mining directions of block/panel caving and SLC, block/panel caving inherently offers geomechanical advantages in terms of mining direction to a certain degree while SLC presents specific challenges from a global stress management perspective. These differences are elaborated upon following the discussion of stoping methods. Note that to tackle slip-type hazards, strategic measures such as mining sequence or layout should be adopted on a case-by-case basis, often supported with insights from well-calibrated 3D numerical modelling (see Sections 4.4 and 4.5.

Ultimately, not all mines can continue to operate safely and economically at depth as seismic hazards increase. Once engineering and operational measures are exhausted, limiting the overall extraction ratio or reducing mining rates can be effective ways to maintain LMS. As seen in the case of the Westwood mine following magnitude 3.0+ events, reducing extraction intensity was critical for resuming operations (Jalbout et al. 2024). If these measures fail to provide sufficient stability, a cessation of mining remains the final option.

4.2.2 Bulk stoping

Stoping and its variants are characterised by flexibility in mining direction and sequence to achieve high production. This flexibility is a double-edged sword; sequences or layouts that do not adhere to rigorous ground control principles often result in highly stressed ore pillars and remnants during the late stages of mining, particularly if stopes remain open or are backfilled with unconsolidated waste rock. This risk can be partially mitigated by transitioning to cemented backfill. Consolidated fill not only facilitates full extraction but also permits mining sequences that gradually push stresses towards the mining block abutments rather than concentrating stress within stope pillars. This stress redistribution process is often not immediate and is governed by factors such as sequence, fill curing rates, rock creep and regional field stress. During these periods, stress may concentrate on temporary remnants such as secondary or tertiary stopes, or on permanent features like dyke pillars. Nevertheless, when executed with a proper mining sequence, extracting ore adjacent to or underneath cured consolidated fill is considered a common measure for avoiding local high stress. Because engineered backfill possesses a lower stiffness than the host rock it cannot carry the same magnitude of load as a stiff rock pillar, thereby forcing the stress into the more distant and competent abutments.

Stoping, particularly when combined with cemented backfill, offers the ability to vary stope sequences and mining directions to rectify unfavourable stress environments. Figure 2 conceptually illustrates common sequence geometries for high stress environments. Figure 2a represents an early-stage mining strategy retreating from a barren sill pillar with an idealised chevron or diamond layout (note that simultaneous overhand and underhand mining away from a sill pillar is not common). This approach pushes stress toward the abutments while facilitating the gradual yielding of secondary ore pillars, thereby avoiding high stress accumulation in the sill pillar during the late stage of mining. Figure 2b represents retreating from a regional pillar or major geological structure, following the same principle as the barren sill pillar case in Figure 2a. The left side of Figure 2b illustrates the recovery of a sill pillar via a pinch-through sequence rather than creating a thick, flat sill pillar prior to final recovery. Figure 2c provides a section view perpendicular to the orebody strike, illustrating a sequence designed to avoid concave geometries or step-out abutments. Such sequences prevent the formation of sharp, high stress corner profiles on the footwall side when retreating from the hanging wall. There are other delicate sequences aimed at stress shadowing local scale pillars (e.g. secondaries) or sharp abutments, but these are not detailed here due to paper limitations.



(a) Diamond/chevron sequence to transfer stress

(b) Mining away from adverse structure or a pillar

(c) Retreating from a hanging wall

Figure 2 Section views of common sequence geometries for bulk mining, with stoping as an example

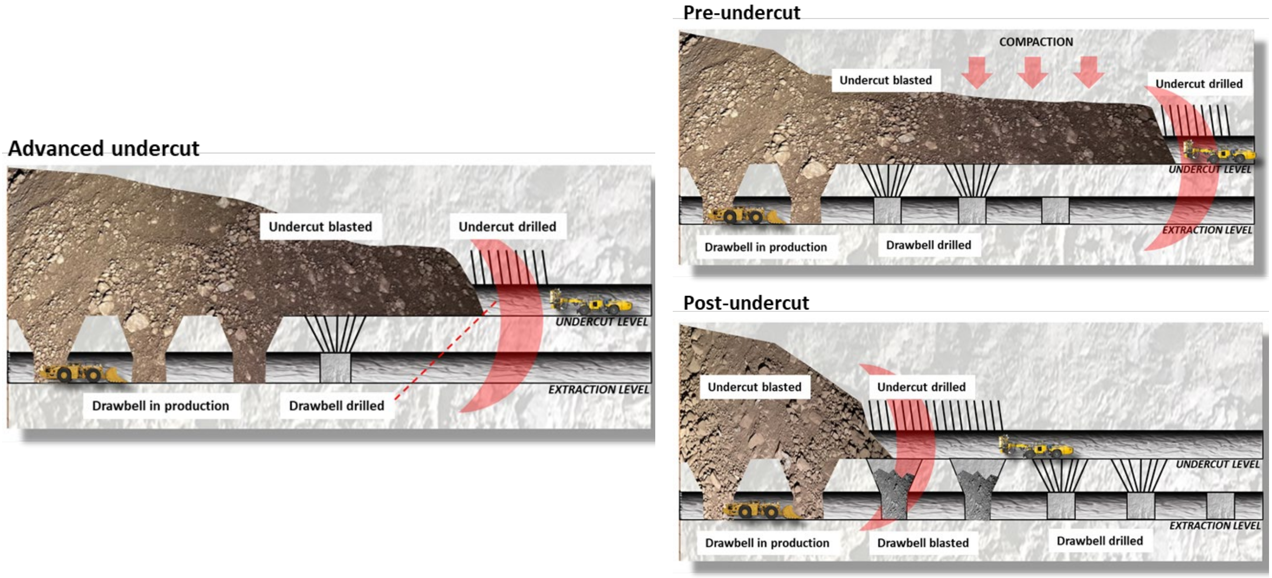
In general, a global mining sequence that drives the mining front along a single direction is favoured from a ground control perspective, although this inevitably compromises production flexibility. A global bottom-up sequence is often considered more ideal than top-down if not converging towards a sill pillar above, because it retreats towards shallower depths whereas top-down will always face an advancing front that is further clamped by gravity because of the downward loading of the gravity. However, this is often a luxury when extracting massive orebodies extending to depths. In reality, bottom-up sequences are often implemented at a mining block scale to minimise backfill costs. Top-down sequences are still advantageous to a certain degree because mining immediately under consolidated fill provides a stress-relaxed environment. However, following a top-down direction at great depth will eventually result in high stress concentrations on infrastructure located underneath the narrow, advancing front of the mining block at the bottom.

A bulk orebody is often divided into mining blocks by barren or ore pillars to improve production rates. To mine these blocks productively, primary-secondary or primary-secondary-tertiary sequences can be utilised to improve production flexibility and rates. If mining-induced stresses are increased to a certain level, sequence rules such as lead-lag distance or angle and pillar shape ratio should be adopted to avoid creating highly stressed stope pillars. In the late stages of mining at extreme depth, a transition to pillarless mining may be required to eliminate the risk of leaving high stress remnants within active mining areas.

4.2.3 Cave mining

Assuming an orebody is amenable to both stoping and caving, cave mining can be favoured from a stress management perspective at certain depths. Caving sequences are typically simpler, following either a top-down (SLC) or centre-out (block/panel caving) progression. Furthermore, caving is essentially a pillarless mining method that effectively pushes stresses toward the abutments, leaving no highly stressed large pillars within the production footprint. However, this geomechanical advantage relies on the strict execution of a robust cave management plan to ensure that no remnants are left behind. Note that the geomechanical factors contributing to high stress at these abutments differ between the 2 primary caving methods.

Once a cave is initiated in block/panel caving, the acute angles of the cave abutment, which ideally approach 90°, inevitably act as stress raisers. Abutment loading can be further exacerbated by sharper angles resulting from incomplete undercutting or adverse caveback profiles. In such cases, draw control is one of the few tactical measures available to improve the abutment angle and reduce seismic hazard. An effective strategic measure is the undercutting method as illustrated in Figure 3 (see Section 4.3.5 for further details). The implementation of advanced undercutting to de-stress the ground at the advancing caving front, thereby keeping most of the development activity away from the seismic hazard zones. Where possible, it is favourable to plan the cave initiation in locations containing adverse major structures or sharp footprint corners to mine away from the hazard early in the mine life.



(a) Advanced undercut (b) The other two undercut methods

Figure 1 Undercutting methods

SLC, with its characteristic top-down mining sequence, inherently drives stress concentrations and seismic hazards towards the bottom of the footprint and nearby infrastructure. Since most SLC operations, with the exception of vertical kimberlite pipes, are generally inclined, the design must account for the accumulation of stress at the lower extremities. Sharp step-out geometries and concave abutments (centre lagging) in both the plan and sublevel layout should be avoided in the design and sequencing to prevent trapping high stress in active mining areas.

As field stress and extraction ratios increase, LMS inevitably becomes softer and the highly stressed abutment becomes the primary seismic source in deep caving operations. Consequently, the premise that cave mining is superior to open stoping at certain depths can be challenged when transitioning into ultra-depth regimes. Given the scarcity of caving case histories at depths exceeding 2 to 3 km, it is envisioned that the seismic risk at ultra-depth can escalate to a new level where traditional options become limited. For instance, while increasing extraction level pillar dimensions can improve the overall stiffness of the system, it compromises draw interactions due to the increase in drawpoint spacing (refer to pillar design in Section 4.3.1.).

4.2.1 Slip-type events

While it is technically difficult to eliminate structural movement entirely, it is possible to influence the behaviour of structures through strategic mining. The primary objective is to reduce the shear potential of a target structure by either increasing the clamping force (normal stress) or reducing the shear stress acting along the slip surface. If a structure, such as a fault, does not daylight into excavations or runs parallel to active mining areas, the shear stress and clamping forces are difficult to estimate because they are mutually dependent. In such cases, a well-calibrated 3D numerical model incorporating detailed local mining sequences and structural characteristics can be helpful to guide the mine sequence. This modelling should be supported by verified seismic monitoring and field observations. General ground control rules of thumb also apply, such as mining away from problematic structures or avoiding mining along a structure.

It is important to note that large fault slip events resemble creep behaviour, where a period of rapid deformation follows a chronic, slower deformation phase. Intermittent microseismicity can occur in this slow creep period before a large event. With high-quality instrumentation, specifically a seismic system with adequate array density and bandwidth coverage, there should be typically accumulating evidence to suggest an increase in slip potential for a problematic structure. Drastic mining changes, such as the recovery of a high stress sill pillar or mass drawing in a high-loading cave abutment, are often the triggers for large-magnitude seismic events. In such cases, the timing of these activities must be reviewed carefully. In extreme scenarios, production activities should be halted if the risk of a large-magnitude event is deemed unacceptable, as slip-type events are difficult to decelerate once the acceleration phase begins.

4.3 Tactical measures

4.3.1 Pillar design

Pillars are ubiquitous across almost all underground mining methods and represent a primary source of high-magnitude seismicity in deep mining environments. Pillar stability is a critical design consideration in high stress settings, with the objective of either facilitating a yielding process to allow for aseismic or low-seismic failure (yielding or crush pillars) or ensuring long-term local and regional stability. Both pillar types are predominantly controlled by the confinement levels within the pillar core, which are governed by the pillar size and the width-to-height (W/H) ratio.

The yielding or crush pillar concept implies that a pillar can yield and transition to a stable, post-peak state, allowing for nearby mining to proceed safely. Based on field experiences from deep stoping mines (e.g. Sudbury, Timmins and Matachewan) in the Canadian Shield (Hedley 1992) and reef mining in South Africa (Ortlepp 1997), several W/H-based design rules seem to apply to generic hard rock environments:

- For W/H ratios between 1.5 and 2.0, squat hard rock pillars possess high peak strength and can exhibit significant seismic activity during the transition to a post-peak state. This implies that when the extraction ratio is high and LMS is soft, yielding pillars with such W/H ratios should be avoided.
- For W/H ratios less than 1.0, hard rock pillars can yield quickly, e.g., crush pillar.
- For W/H ratios greater than 3.0 there are few reported instances of sudden pillar failure. This implies that pillars in this range either remain stable or that the confinement within the core is sufficient to prevent rapid, violent yielding.
- For regional stability it is often prudent to design larger regional pillars with W/H ratios of at least 4.0 to 5.0 to ensure long-term integrity. An additional benefit of sufficient regional pillar width is the reduced probability of a major structure completely intersecting the pillar, which could otherwise facilitate large-scale instability.

These observations serve as a reference for pillar design, though it is essential to conduct routine pillar mapping to benchmark site-specific performance. Holistic pillar design should also consider factors such as dominant joint orientations, the dip of inclined pillars, overall pillar shape/size and local stress orientations. Additionally, proactive controls such as managing mucking and backfilling rates in stoping or draw rates in cave mining can assist in preventing violent failure by controlling the rate of confinement loss, as discussed further in Section 4.3.3.

In theory, permanent pillars left for local or regional stability should be designed to remain stable and aseismic. However, the ability to design large, squat pillars is often restricted by deposit shapes and operational constraints. In stoping there may be insufficient width available for large barren pillars, while in cave mining, excessively large pillars on the extraction level can result in wide drawpoint spacing that negatively impacts interactive draw. In these instances, proactive measures such as pillar reinforcement (e.g. strapping) should be considered in conjunction with the aforementioned operational rate controls.

4.3.2 Blasting

Blasting is one of the most timely and effective control measures when implemented appropriately, as outlined in the ground control principles in Section 4.1. Because a large volume of rock mass is relaxed suddenly during a blast, the surrounding stress redistribution occurs rapidly. The magnitude of this redistribution depends on the volume and location of the blast relative to the active mining area. Consequently, blasting can be utilised in short-term planning as a proactive measure to effectively reduce or remove high stress zones by pushing the stress further into the abutments, keeping the active workface remote from hazardous areas. However, the potential for blasting to trigger large-magnitude seismic events from a global stress management aspect was cautioned in Section 4.2.4. The specific application of blasting for de-stressing purposes is detailed further in Section 4.3.5.

4.3.3 Draw/mucking control

Mucking and draw rates can be monitored and controlled to respond to and mitigate seismic risk by manipulating the rate of energy release associated with confinement loss. In cave mining, production draw is the primary measure by which a cave management plan is regulated. Strategic draw control is fundamental in managing the propagation of the cave back and the redistribution of stress loads arising from undercut abutment stresses. By adjusting the draw rate across the footprint, engineers can influence the cave geometry to minimise adverse stress concentrations at the cave boundaries as well as airblast risk. For stope mucking, however, there is no universal rule for the ideal mucking strategy; a mine may choose to muck quickly to clear a stope before a sudden wall failure. Conversely, mucking may be slowed to allow the ground to settle and dissipate stored strain energy gradually through wall relaxation. These operational decisions are typically driven by site-specific ground conditions and real-time seismic monitoring.

4.3.4 Backfilling

Backfilling is a proactive measure used primarily in stoping to increase pillar strength by providing additional lateral confinement. While rockfill or hydraulic fill can provide confinement to the lower portions of a pillar, consolidated fill used in conjunction with barricades can provide full-height support to pillars, offering opportunities for later extraction such as secondary mining or pillar slashing. In cave mining, filling decommissioned crosscuts with concrete or high-strength backfill has been utilised to stabilise ground in high stress zones before resuming production or commencing rehabilitation.

4.3.5 De-stress blasting, undercutting execution and preconditioning

De-stress blasting, undercutting execution in block/panel caving and preconditioning all facilitate the de-stressing of ground by degrading rock mass strength and stiffness in areas prone to high stress accumulation. These measures aim to transform potentially burst-prone rock into a more yielded state.

In block/panel caving, the quality of undercut execution is a critical factor in managing stress changes and concentrations. Adhering to established undercutting guidelines and best practices is essential to mitigate undercut-induced stress hazards. It is strategically advantageous to maintain a relatively smooth or convex caving front (centre leading), following lead-lag rules. This geometry reduces stress concentrations at sharp corners and ensures a consistent advance of the caving front.

While hydraulic fracturing or confined blasting for preconditioning in caving operations are primarily intended to assist cave initiation and propagation, it is reported that they both provide a secondary benefit in seismic risk management. However, the authors caution against overstating the effectiveness of hydraulic fracturing for rockburst mitigation. For instance, cases we were involved with have led to inconclusive observations regarding the overall practicality and reliability of hydraulic fracturing when compared directly with confined blasting or targeted de-stress blasting for rockburst mitigation.

4.3.6 Ground support

Ground support systems designed to manage dynamic ground conditions represent an extensive field of study, with great progress made over the last 2 decades. Ground support remains an effective tactical measure for preserving local stability in both static, such as large squeezing ground, and dynamic ground conditions. The primary function of dynamic ground support is to absorb the kinetic energy of ejected rock and safely dissipate it through the deformation of support elements. It is important to note that for large slip-type seismic events, a robust ground support system combining dense yielding and stiff elements may dampen the seismic impact, but it does not necessarily eliminate seismic damage. Furthermore, the stress fronts manifested by a caving front passing through a production horizon are typically greater in stress change magnitude and far more repetitive than those experienced in stoping mines, e.g. stress changes experienced at a stope brow. As such, ground support capacity that is progressively consumed during these repeated loading cycles should be accounted for if it is critical infrastructure or highly exposed to rockburst.

4.4 Other operational measures

Seismic events are difficult to predict and must instead be managed through rigorous operational protocols. This challenge is particularly evident with large-magnitude events, including slip-type mechanisms, due to their chronic creep characteristics which are often difficult to detect or forecast with precision. Therefore, operational measures such as re-entry protocols and trigger action response plans serve as the final lines of defence, in conjunction with ground support systems.

4.5 Monitoring, back-analysis and optimisation

While large seismic events are difficult to predict, a mining area rarely becomes seismically active without prior indicators. A robust seismic risk management plan should evolve by iteratively integrating high-quality monitoring, field observations and detailed back-analysis to verify high seismic risk areas and the effectiveness of implemented mitigation measures.

5 Conclusion

This paper reviewed the geomechanical drivers and management strategies for seismic hazards in deep hard rock stoping and caving operations. While the extraction methods differ in implementation, the underlying physics governing rockburst hazards remains similar. Therefore, the principles of effective seismic risk mitigation measures between these 2 mining methods remain similar. Strategic measures, such as optimising mining sequences to drive stress towards barren abutments or implementing advanced undercutting in block caving, provide the greatest impact on mine-wide stability by managing the external loading environment. Tactical measures serve as essential controls to preserve local stability. The lack of experience in cave mines greater than 2 km depth poses some additional challenges that will need to be addressed. Increasing drawpoint pillar sizes may prevent interactive draw and influence the caving process. If the cave footprint is very large it may be necessary to implement large regional pillars, which will significantly reduce recoveries.

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