Ground Support 2026 - D Cumming-Potvin & J Wesseloo (eds.)
© 2026 Australian Centre for Geomechanics, Perth
doi:10.36487/ACG_repo/2625_37

Economic impact of ground control technologies in large-scale, deep underground caving mining

Allan Moss [a], Federico Scolari [b,*]

[a] *Sonal Mining Technology, Canada*

[b] *Sandvik, Germany*

Abstract

Deep large-scale cave mining methods play an increasingly important role in the copper industry. The quantity and complexity of these excavations demand, enhanced construction practices that reduce 'time-to-ore production' and ensure reliable access to drawpoints throughout the life of mine. Modern, integrated ground support systems, proactive excavation maintenance strategies, and comprehensive ground control management processes are central elements in delivering a safe, reliable, and productive mining system. Traditionally viewed as a cost and schedule constraint, effective ground support must be recognised as a strategic investment that directly enhances production reliability. Achieving this outcome requires a holistic approach that integrates multiple support elements into a cohesive system while accounting for installation quality, timing, and operational efficiency. 'Ground control' integrates advanced ground support, multi-layered monitoring systems, and rock mechanics algorithms with mine design and operations software. New features on bolting rigs can assess initial rockbolt capacity, while instrumented rockbolts monitor progressive deformation to evaluate residual capacity. Monitoring thus becomes an active design tool, enabling the timely installation of supplementary support essential to maintaining system safety and performance. This paper evaluates the value proposition of ground support across different stages of cave development and production, outlines the rationale for treating mine excavations as critical investments, and positions ground support as a strategic component fundamental to long-term operational success.

Keywords: *scheduling impact, asset management, ground control, monitoring, total cost of mining, preventive support maintenance*

1 Introduction

As near-surface deposits amenable to open pit mining become depleted, capital-intensive cave mines operating at depths greater than 1,000 m are expected to make a significant contribution to future copper supply. However, deep caving requires a prolonged pre-production period before revenue is generated, while operating at depth imposes stress and seismicity constraints. This increases the likelihood that excavation damage will disrupt production and create major safety concerns.

To mitigate these risks, the objective must be to deliver an achievable, resilient mine plan that safely and reliably meets target tonnages and grades. This is summed up by the industry mandates: 'plan the mine' and 'mine the plan'. Ground control is the process of assessing how the ground responds to mining and evaluating global and local support requirements to ensure stability, safety, and reliability. Historically viewed as an unavoidable operational cost and an irritant to schedulers, ground support represents a major financial and timeline factor:

- The initial investment: spending on ground support can be more than USD 1 billion in a large-scale caving mine. This exceeds the spending on mobile equipment used for drilling, loading, and

[*] Corresponding author. Email address: federico.scolari@sandvik.com

trucking. Both mobile equipment and ground support should be considered investments to be evaluated on performance and value to the operation (not on purchase price).

- Schedule impact: support installation accounts for roughly 35% of the schedule during the pre-production period, increasing to over 50% during the construction of the production footprint (from Sonal Mining and Sandvik benchmarks). The time required to complete critical-path excavations is influenced by the intensity of support required. Faster development rates can be unlocked simply by selecting appropriate support systems and optimising installation methods.
- Capex impact: deep caves require investments exceeding USD 5 billion to reach target production. Support consumes approximately 12–15% of pre-production capex, rising to 20–25% as the production footprint is developed. On a super-cave project, over USD 1.2 billion can be spent on installing support.

The value proposition for support ultimately centres on revenue generation. The impact of support on schedule during the pre-production (time to first ore) and the need to manage damage and support consumption during production ramp-up and ongoing operations underscores its strategic importance. Advances in ground support are required to enhance value by:

- improving design methods based on the realities of deep mining in brittle rock
- recognising the critical impact of constructability on schedule
- adopting a holistic approach that integrates multiple support elements into a cohesive system
- enhancing hazard forecasting and real-time measurement of installation quality
- better defining the role of support in the overall project value proposition.

2 Ground support: unavoidable cost or strategic investment?

Excavations are the major asset in an underground mine. Ground support is a critical control measure to ensure safe and functional excavations; however, it comes with significant cost and schedule impacts (see above).

If too little support is installed, deep mine excavations will sustain damage, curtailing revenue. Support is mandatory, and is a strategic investment required to protect value. Unfortunately, there is a mindset within the industry that support is simply an unavoidable cost and schedule impairment.

3 Cave mining: conceptually simple, technically challenging

Capital overruns are pervasive in the industry. Delays often occur due to ground conditions and construction constraints, increasing the time to the start of production and incurring significant financial penalties due to the time value of capital. According to Moss (2013), up to 70% of the capital is spent before commercial production and sustainable revenue generation.

Historically, few cave mines, whether greenfield or brownfield, have met the expectations of the plan approved at the time of the decision to commit, underscoring the fragility of caving projects and the unrealistic initial performance expectations. Typically, project evaluation includes a cash contingency as a percentage of the project cost, but seldom a time contingency or even an overt assessment of what late delivery might mean to the business. Insufficient attention is given to the impacts of delays when considering the timing of a pit ramp-down and an underground ramp-up or the transition underground from one production lift to the next. Frequently, the reluctance to commit capex sufficiently early is at the board level, often abetted by project teams anxious to obtain funding approval, who submit first-quartile project schedules but fail to communicate risk.

The probability that the ratio of actual to estimated capital cost for mining projects exceeds unity (i.e. a cost overrun) is approximately 74%. This result is based on mines built in the latter half of the 20th century, when the average ratio was approximately 1.25. The situation has not improved in the 21st century. A recent study

(McKinsey 2019) showed an average ratio of 1.6, with up to 60% schedule overruns. It is considered that larger, more remote operations have contributed to this increase in the ratio.

The technical challenges of caving are well known, if perhaps not necessarily well understood, and are documented (Flores-Gonzalez 2019; Edgar et al. 2020; Simanjuntak 2020; Casten 2020). There is a substantial focus on cave performance in the study phase, but less on construction performance.

The risk profile (Figure 1) transitions from schedule-driven risk (pre-production) to combined schedule/revenue risk (ramp-up) and finally to revenue reliability risk (steady-state operations). The primary threat to excavation functionality is stress and seismically induced damage.

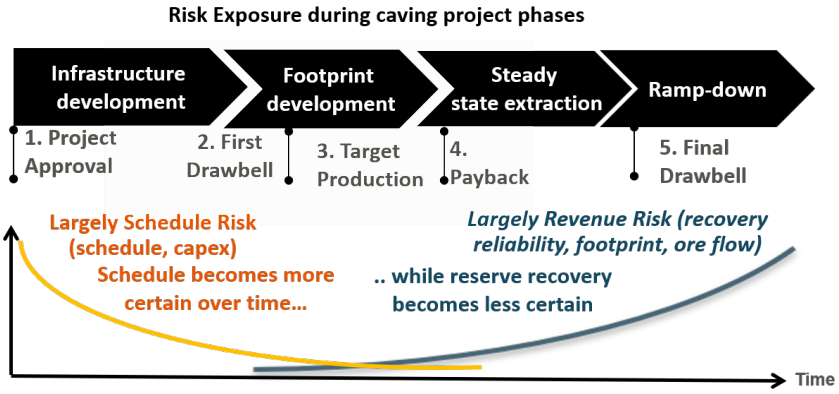


Figure 1 Project life cycle showing variation in risk profiles during the transition from pre-production to steady-state caving

A review by the authors of selected projects suggests that 70–80% of the delay is incurred during the pre-production construction period (Figure 2), with some 20–30% during the production ramp-up period. For example, one caving project experienced a 60% increase in capex, a significant portion of which can be attributed to a 40% increase in schedule from project start-up to target production. In turn, 80% of this schedule overrun is attributable to delays incurred during the pre-production period, and 20% to delays during the production ramp-up. Only 2 out of 11 mines completed pre-production in accordance with the plans. Many cases showed a delay of 1–3 years and, in 3 cases, delays exceeded 4 years. The average delay is 3 years. It is challenging to estimate the cost of the delays as each project has its own characteristics. It has been assumed that the cost of delay is around USD 50 million, resulting in a pre-production delay cost of USD 180 million per mine.

The delays are due to a variety of factors, including COVID, logistics, orebody knowledge, and planning effort. Ground support is certainly a factor. Even if it is only 10%, it still amounts to USD 18 million/mine, an incentive to invest more in an integrated design and planning process.

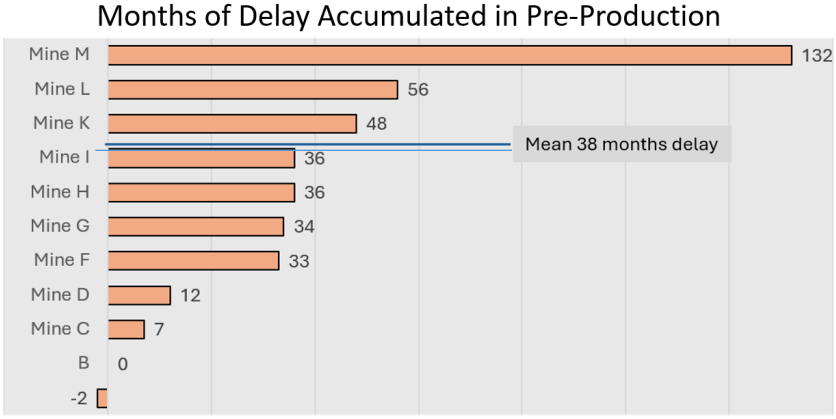


Figure 2 Pre-production time discrepancy between original plans and actual results from 11 deep mines

Construction delays are a significant contributor to cost overruns. For example, one caving project experienced a 60% increase in capex, a significant portion of which can be attributed to a 40% increase in schedule from project start-up to target production. There is a strong tendency for an asymmetric performance profile with limited upside and substantial downside (Figure 3).

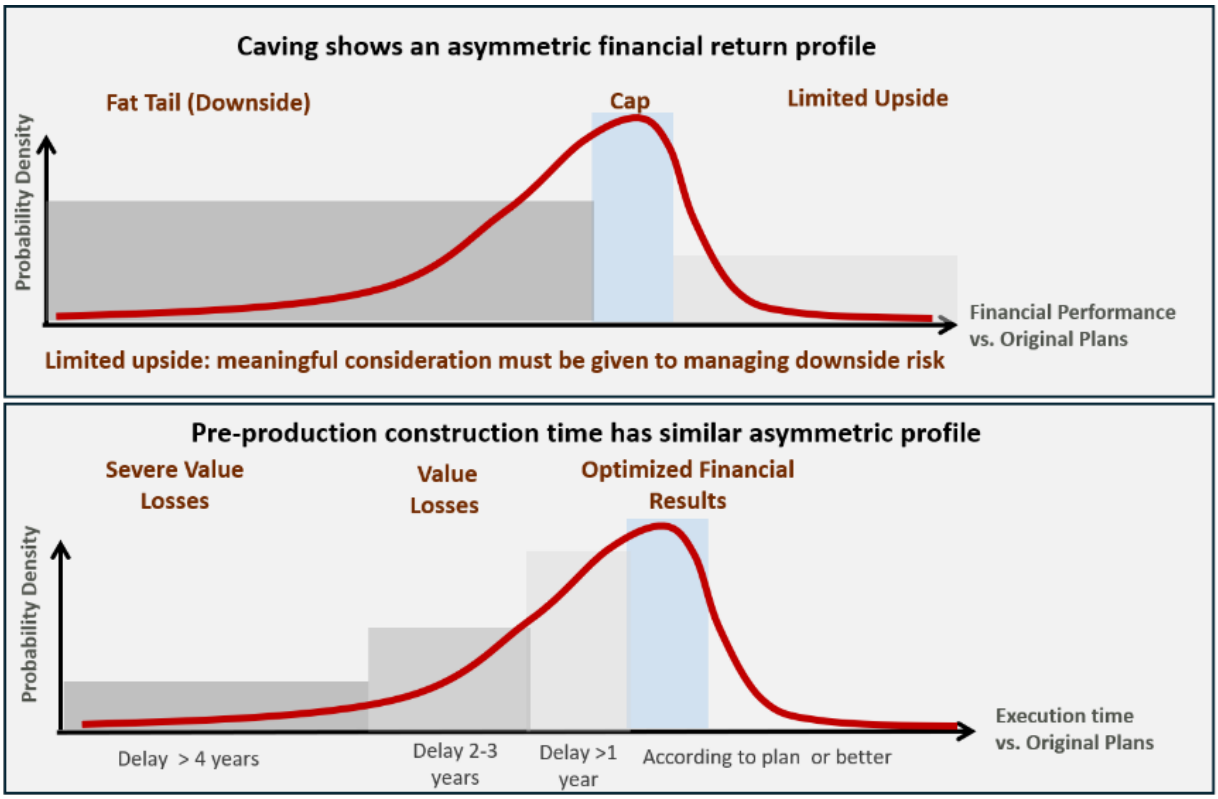


Figure 3 Asymmetric financial return profile of a large caving project resembles the effects of time discrepancies between planned pre-production construction and real execution

As a project progresses, operational optionality decreases while the asset risk profile shifts. Conversely, production delays during steady-state operations are accepted due to depth and must be managed as an integral part of operations.

4 Excavation (asset) management

Excavations represent the single largest investment in a caving project, far exceeding the cost of fixed and mobile equipment fleets. Development and infrastructure construction account for 60–70% of the entire mine construction schedule. Fully loaded development costs can exceed USD 12,000 per metre, with a substantial portion driven by ground support requirements.

Operating deep cave mines (>1,000 m) demands intense support both on and off the production footprint, constraining critical-path timelines. While long-term controls on stress and seismicity (layout, sequencing, draw strategy) are fixed years in advance, ground support and exclusion zones (both temporal and spatial) serve as the principal short-interval controls (Figure 4). Right-sizing support mitigates production interruptions without penalising advance schedules. As caving progresses, excavation damage correlates directly with proximity to the active cave front.

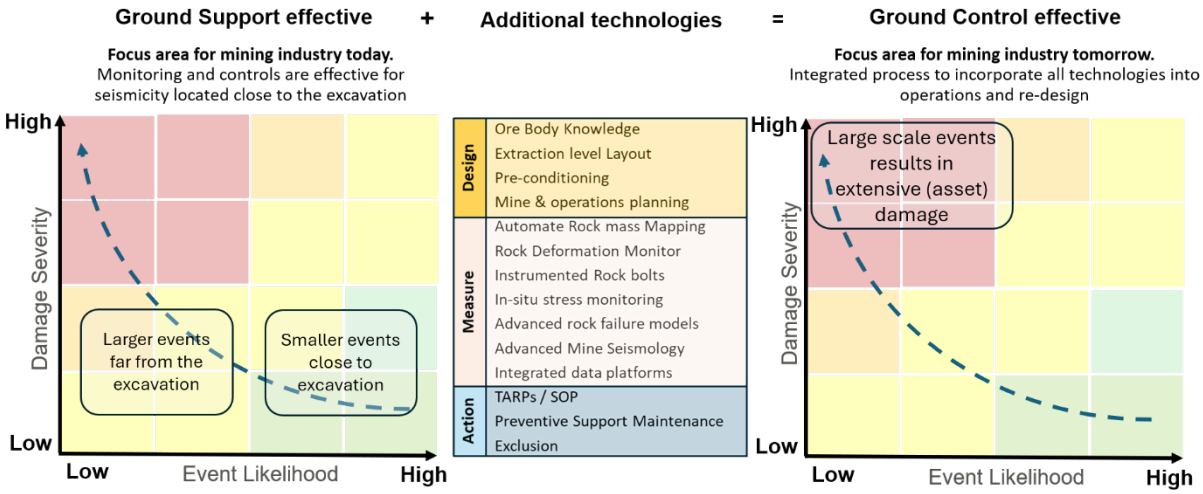


Figure 4 Consequence of event versus. likelihood matrix showing current industry controls for local damage and trend for future ground control challenges

Excavations are key assets and must be treated similarly to fixed and mobile equipment in the mine, with performance monitored and a planned maintenance regime implemented. The objective is to reduce production interruptions from unplanned repairs by implementing a drift-monitoring and maintenance program.

Standard measures used in asset management, such as availability, utilisation, and mean time to repair, must be developed to monitor excavation performance. This will ensure that any interventions are implemented in time to achieve the required operational effectiveness. Current practice is typically reactive, where little is done until damage occurs. Such an approach increases the likelihood of a safety interaction, resulting in production interruptions and revenue loss. However, too little attention is commonly paid to QA/QC during construction. Too often, poor-quality installations are accepted, resulting in reduced support capacity and shorter times to failure.

As induced stress levels increase, brittle rock masses become increasingly vulnerable to damage. At depth, drifts converge, support is consumed and must be replaced. Drifts need to be maintained, ideally in a planned manner, but at times, due to unexpected incidents (such as seismic events), in an unplanned manner. Shallow mine experience does not apply to mines operating under high-stress conditions. The industry must update the design process to meet the new challenges.

Figure 5 provides an example from an operating cave, showing the change in the percentage of temporary drawpoint closures for repair as a function of draw height. Four stages are highlighted. The first occurs early in the life of a drawpoint, in part because the support systems are not functioning at design capacity and in part because of unfavourable construction practices. The second involves repairs arising from a combination of damage caused by secondary breaking, equipment interactions, and cave-induced deformations that consume installed support capacity. A reduction in repairs is generally observed during the third stage as non-performing drawpoints are closed. A substantial increase in repairs eventually occurs with higher heights of draw in the fourth stage. This is associated with increased cave-induced deformations resulting from higher cave loads, production pressures, and draw practices.

Investigation into the causes of the damage revealed a skin of damaged rock in the walls of the production footprint varying in thickness from less than 200 mm to over 1 m. It was evident from drilling through the damaged skin that the rock had failed in a brittle manner and had bulked into the excavation. The condition of the walls of an excavation is a function of applied stress and intact strength (i.e. jointing intensity tends to decay with depth). Thus, intact rock strength can become the key measure of rock quality. It is suggested that operationally, an excavation moves from robust to fragile at the onset of moderate spalling and bulking

(Roy 2025). The increased bulking associated with spalling increases the demands on the installed support (consumption of capacity), making the system increasingly fragile.

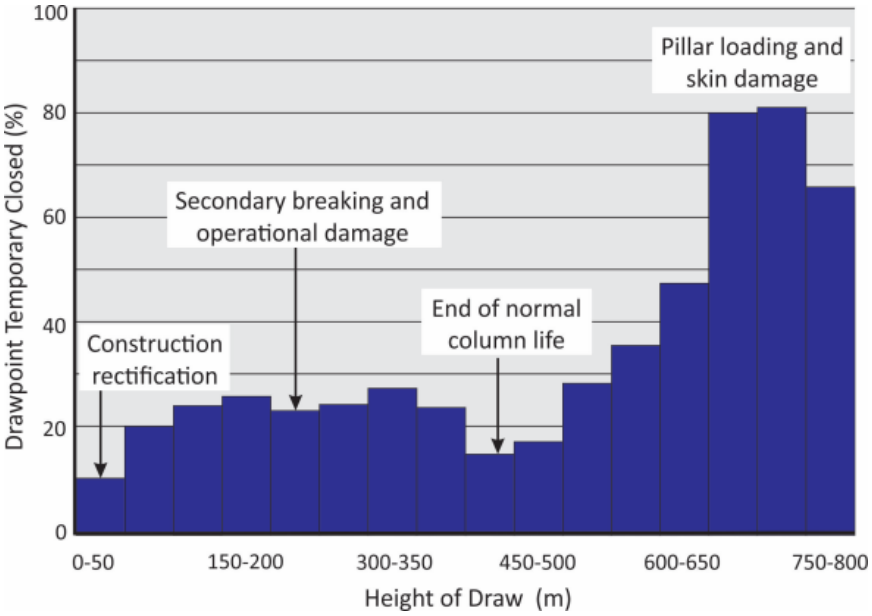


Figure 5 Example of percentage of temporary drawpoints closed for repair and upgrade of support as a function of height of draw (Moss & Kaiser 2022)

The transformation from a 'massive' to a 'damaged' rock mass is irreversible, fundamentally changing the excavation behaviour and its support requirements. The processes of brittle failure and bulking drive the need for deformation-based design Kaiser & Moss (2022) and Di Ciolli et al. (2022).

4.1 Time value of support

Upfront investments in high-quality support are routinely offset by the economic benefits of accelerated development. Figure 6 is a benchmark of single heading development rates. These determine the time to first ore and to revenue generation. The productivity of support installation has a significant impact on these rates.

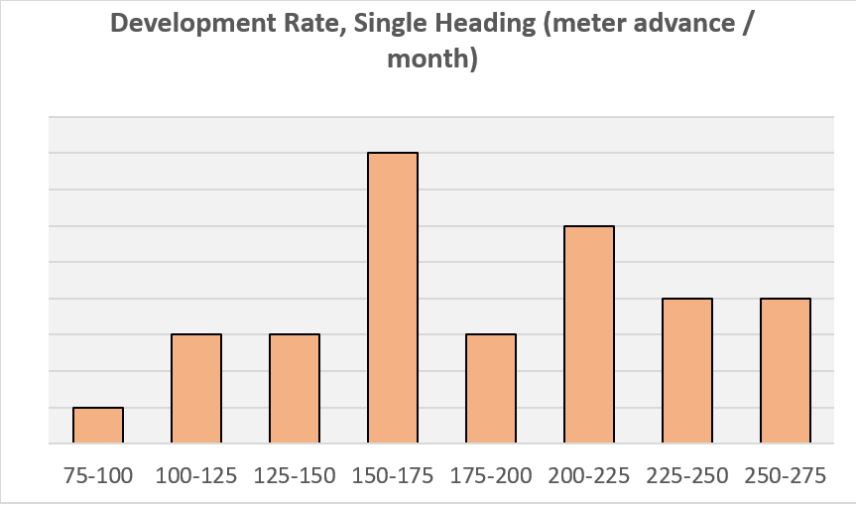


Figure 6 Distribution of 26 records of advance per month in a single heading, typically a 25–30 m^2 tunnel. (Sonal Mining Technology Database). Note the high variability of results

Table 1 Correlation between presumed value of development rate versus cost of development (USD [2025]), based on 6,000 total single heading metres

Unit cost (USD /m development)	USD 10,000/m	USD 15,000/m	USD 20,000/m
Metre/month (single heading)	125	150	175
Total months	48	40	34
Total costs	60 M	90 M	120 M
Time saved versus base case, months	–	8	14
Value of time saved (assumed 15 million/month)	–	90 M	150 M
Total value added	–	**30 M**	**90 M**

As shown in Table 1, project value is driven primarily by development speed rather than unit cost.

4.2 Costs, support systems and operational cycles

Support designs vary by mine-specific ground responses. A key observation is that support systems in deeper caves typically deal with brittle failure mechanisms and the impacts of cave-induced seismicity.

Figure 7 compares 2 seismically active cave mines producing more than 25 Mtpa. Though total support costs were within 5% over the period examined, the allocation of costs among bolting, surface support (mainly shotcrete), and cable bolts differed. Mine A (weaker rock mass) spent more on shotcrete support, while Mine B invested more in rockbolts to manage skin damage (fracture control) and cable bolts (retention) than shotcrete (surface control). It is critical to note that in both case the support acted as an integrated system.

Bolts and cable bolts account for about 75% of the investment in ground support. In a large deep caving operation, this investment could be close to USD 1 billion over the operating life of the mine.

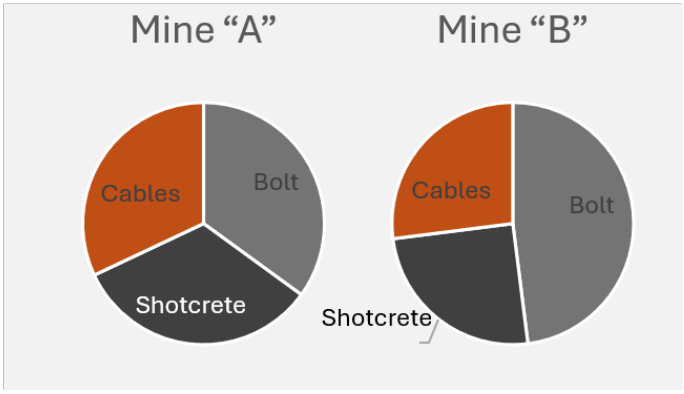


Figure 7 Comparison of support cost between 2 operating caves (Mine A, weaker rock versus Mine B, brittle rock)

A further breakdown of the cost in Mine B shows that primary support costs for the undercut level (UCL) were forecasted to be 75% of the extraction level (EL) costs, driven predominantly by differing shotcrete requirements (Figure 8).

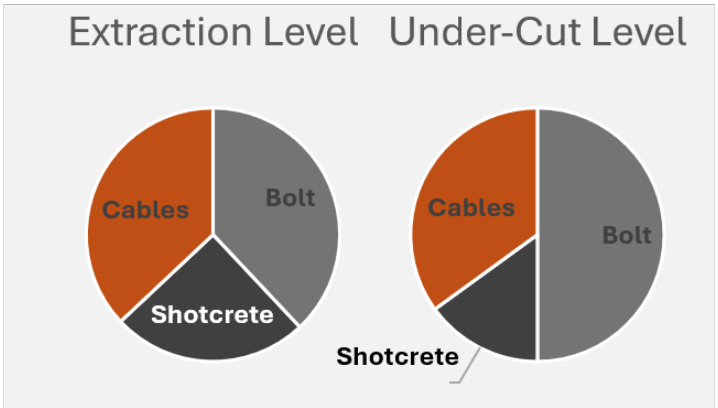


Figure 8 Comparison of actual primary support costs between extraction level and undercut level at Mine B

4.3 Support consumables and selection criteria

The chosen support element dictates the minimum achievable installation cycle time:

- **Friction bolts (split sets*/dynamic hybrid):** fast mechanical installation (1.5–2.5 mins/bolt); maximum benchmark rates of 15 bolts/hour. Material costs: USD 17.5 (Split Sets) to USD 52.2 (MDX).
- **Resin-anchored rebar/dynamic bolts (e.g. D-Bolts):** slower installation (3.5–6.0 mins/bolt) due to resin mixing and chemical set times; up to 10 bolts/hour. Cartridge resin can suffer from poor encapsulation quality (sometimes as low as 30% at the collar). Material costs: USD 30–40; installed costs: ~USD 100/bolt.
- **Self-drilling anchors (SDA)/hollow bars and pumpable resin bolts:** highly efficient in collapsing holes as drilling and placement occur simultaneously. Pumpable resin bolts achieve 12–13 bolts/hour, combining high speed with verified encapsulation.
- **Skin support:** fibre-reinforced shotcrete combined with either standard weld mesh or high-tensile woven steel mesh.

The correct selection of the various elements to combine into a support system is an obvious imperative based on an analysis of deformation, load and energy demand. Equally important are assessments of constructability and schedule impacts.

4.4 The operational bolting cycle

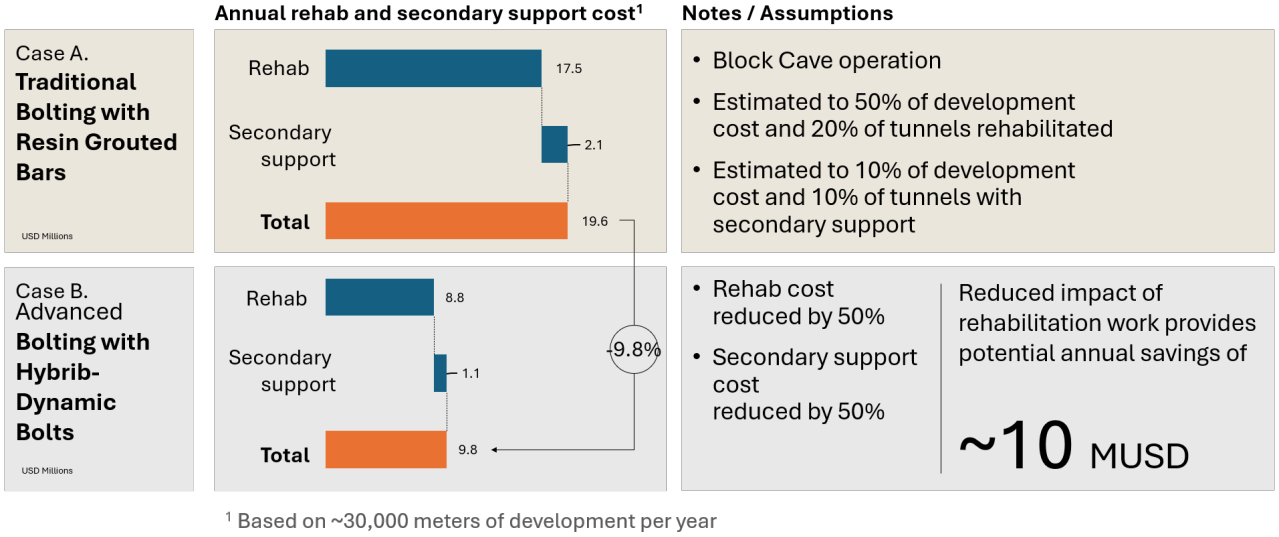
A standard mechanised bolting cycle spans 3.0–6.0 minutes per bolt, broken down as follows:

- Positioning and feed alignment: 0.5–1.0 min
- Drilling the hole: 1.0–2.0 min
- Media injection (resin/grout): 0.5–1.0 min
- Bolt insertion and mixing/tensioning: 1.0–2.0 min

Manual mesh handling can be an operational bottleneck. Rig-mounted mesh manipulators improve safety and face utilisation.

(*) SPLIT SET is a globally recognised registered trademark originally developed by Ingersoll-Rand. Here the name is used to indicate a standard friction rock stabilizer used in mining since decades. Dynamic friction bolts are an evolution of traditional friction stabilizers with enhanced static and dynamic performance. Sandvik MD/MDX are examples of this new category of rock bolts.

Benchmarking by the authors indicates that 8–10 bolts per hour are achievable for 2.4 m-long bolts using cartridge resins, rates increase to about 12 bolts per hour with pumpable resins, and to 15 bolts per hour with hybrid dynamic friction bolts. Deploying advanced dynamic hybrid friction bolts over traditional grouted rebars in ground that has been damaged and is difficult to drill can lead to a ~9.8% reduction in annual rehab and secondary support costs, yielding potential savings of ~USD 10 million per year based on a 30,000 m annual development baseline (Figure 9).



[1] Based on ~30,000 meters of development per year

Figure 9 In a large caving operation, replacing traditional rockbolts with advanced, dynamic solutions can generate substantial savings in direct secondary and rehabilitation costs. Improved access to orebody with relative increased production not included

Experience suggests that the requirement for long bolts at intersections is a bottleneck due to cement cure times and the need to plate and tension the bolts. The use of pumpable resins with extendable rockbolts is an alternate approach.

The adage that you can't manage what you don't measure is important. Sensing technologies have advanced over recent years. These need to be applied to the development cycle to better specific tasks, but, more importantly, to the logistics that support development and to the need to improve efficiency (i.e. reduce waste). An example from the mine access development is shown in Figure 10, where support accounted for about 40% of the cycle time, with bolts installed at a rate of 6–8 bolts per hour. The waiting time in the overall cycle is a critical element in achieving development rates, underscoring the need for real-time measurement.

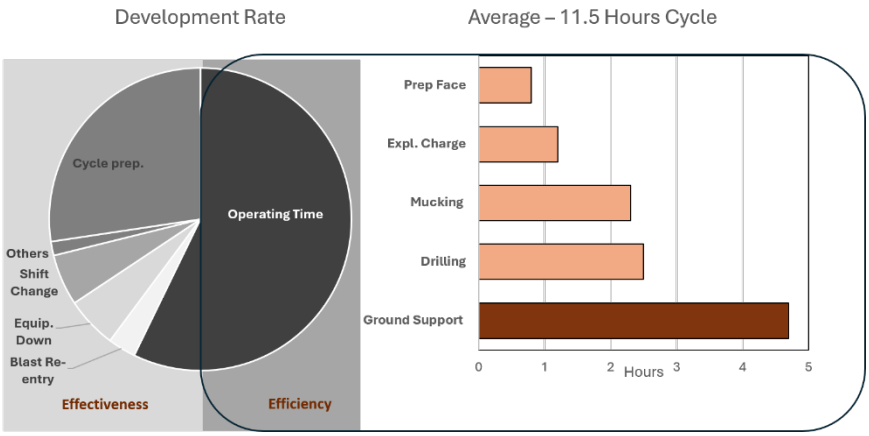


Figure 10 Breakdown of development schedule and effective cycle times

The premise is that by integrating technologically advanced bolts with appropriate installation equipment, the realities of installation productivity, construction logistics, and a ground control measuring system, the effectiveness of the support system can be increased by at least 10%, while improving efficiency, with the objective of achieving a target single heading development rate of 200 m/month.

5 Ground control management process

Figure 11 illustrates the ground/cave control management process as an integrated loop of theory (e.g. design and numerical modelling), practical operational decisions (e.g. mine sequencing and extraction speed), monitoring (e.g. seismic and geotechnical instrumentation), response (e.g. scheduled preventive support maintenance [PSM]), and redesign. The target is continuous improvement of theory and practice, with decisions based on physical measurements and data (less on tradition and previous experience).



Figure 11 Ground/cave control management process (courtesy of Dundee Precious Metal, redesigned/modified)

Excavation failure and large seismic events cannot be mitigated by any bolt, advanced chemical, dynamic mesh, or fibre-reinforced shotcrete. Ground control can be defined as the technology (science + practice) of maintaining the stability of excavations by managing the risks of ground movement and collapse. The goal is to design and maintain safe, stable mine openings through a combination of proper mine planning, ground support, and continuous monitoring by:

- Assessing in situ stresses and seismic response to excavation
- Applying ground support techniques
- Understanding (monitoring) rock mechanics during the entire life of mine.

The process requires reliable monitoring, as does effective asset management and PSM. Fixed and mobile 3D LiDAR scanning, radar, total stations, photogrammetry, borehole cameras and even underground radars provide deformation profiles and rates, together with the depth of bulked ground (Figures 12 and 13).

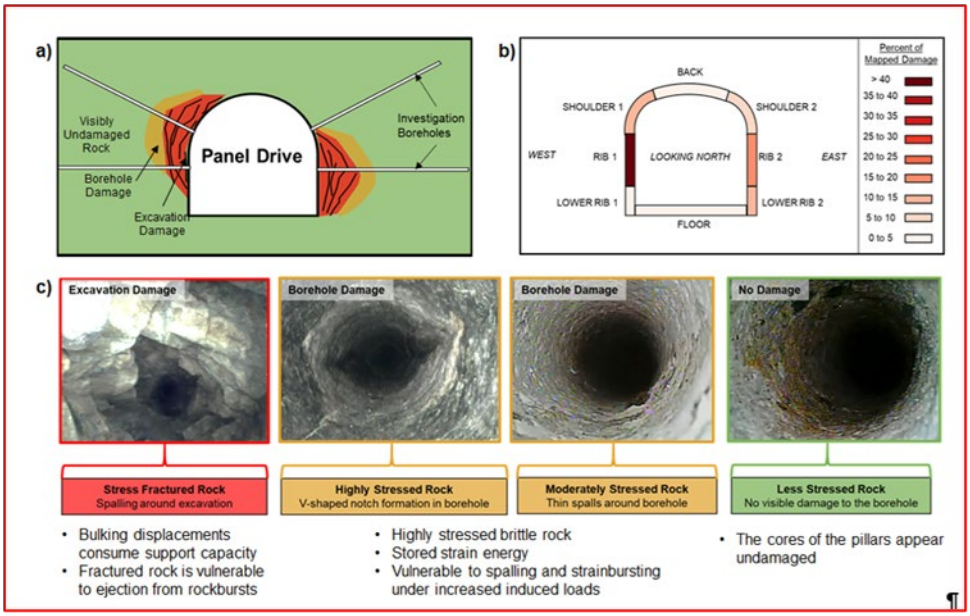
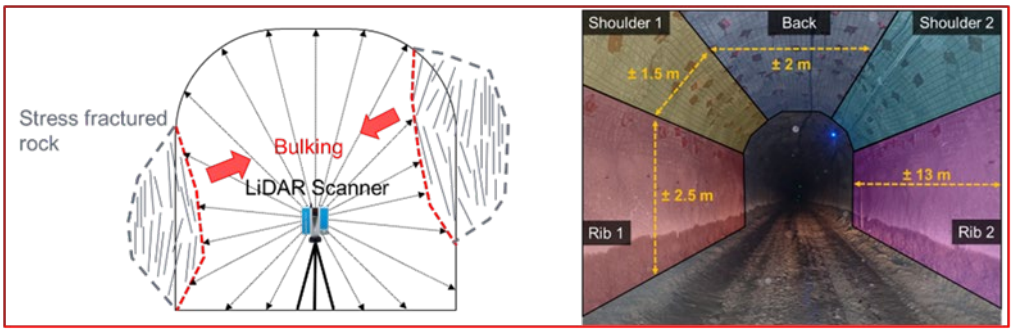


Figure 12 (a) Schematic of borehole camera surveys; (b) Stress damage 'heat map'; (c) Interpretation of borehole camera surveys showing progression of stress damage (modified from (Primadiansyah2023)



(a) (b)

Figure 13 (a) Static LiDAR scan monitoring setup at an EL drift; (b) Monitored structural segments at each location (Primadiansyah 2023)

This continuous data feed enables engineering teams to dynamically adjust support rules based on actual rock mass responses. Key performance indicators must drive real-time process control, Pareto assessments, and step-changes in process capability.

Civil tunnelling operations utilise dedicated QA/QC personnel at ~5% of the total workforce; mining operations have historically under-allocated this function. Under schedule pressures, poor drill-and-blast control results in excessive overbreak, inflating haulage costs, increasing shotcrete consumption, and degrading the integrity of footprint pillars. Furthermore, as the undercut advances beyond the EL, stress relaxation can cause unplated cable bolts to lose surface holding capacity, resulting in premature failure.

6 Integrated monitoring for data-driven ground control

Support design is all too often a siloed process. Integration based on the adoption and adaptation of emerging technologies (Figure 14) consists of:

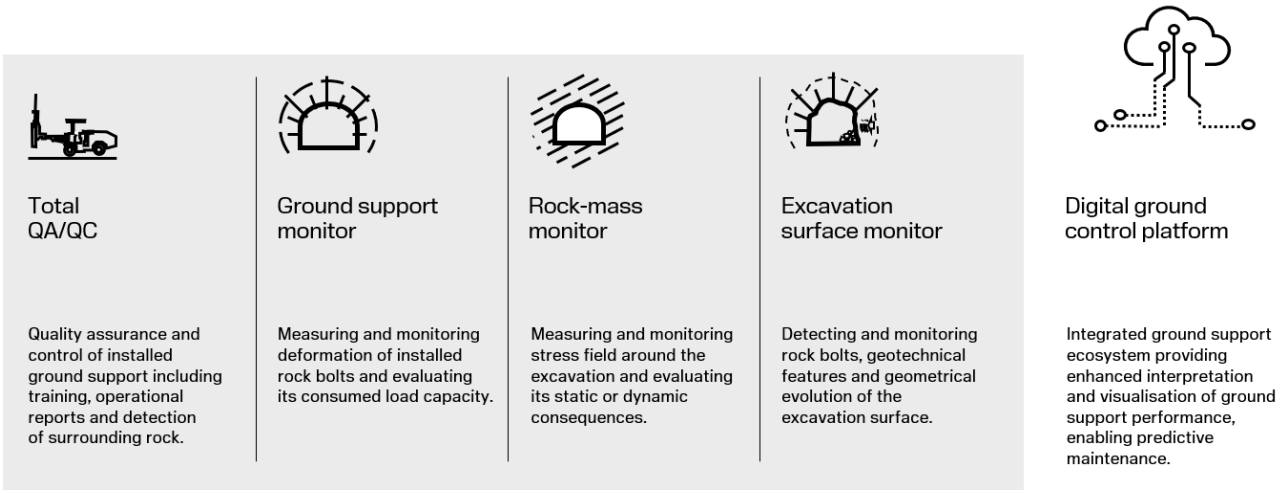


Figure 14 Modern approach to integrated monitoring strategy fit for data-driven ground control

- Real-time monitoring: rockbolt location and installation quality for reliable assessment of 'real' initial loading capacity
    - Automated bolting rigs capable of single-pass, remote execution. Switching from manual resin bolting to mechanised systems reduces support installation time per round from 4.5 to 2.7 hours (a 40% reduction), facilitating a 50% increase in monthly development rates (from 200 to 300 m/month).
    - Jumbo bolting with integrated pumpable resin for high installation speed and long service life.
    - Rock surface deformations and rockbolt elongation leading to an estimate of their residual capacity.
    - Instrumented rockbolts to evaluate ground conditions in the vicinity of the excavation.
- Software integration: integrating data streams into primary mine design and planning software to achieve real-time risk management.
    - Seismic data + Geotech sensors + LiDAR + Instrumented rockbolts + Ai-assisted geo-mapping
- Dynamic support elements: yielding rock and cable bolts engineered for high-velocity, large deformations, and loads (tensile and shear) to survive strain bursts and shakedowns,

7 Strategic project planning and risk execution

To secure production reliability, there is a transition from qualitative hazard assessments to reliability metrics:

- Production reliability: the probability that an excavation or mechanical system will perform its intended function for a specified duration without failure.
- Excavation vulnerability: the localised physical exposure of a drive to yielding or structural damage from environmental stressors, independent of operational severity.
- System fragility: the tendency of an interdependent network to suffer irreversible loss of functionality from external disorder. Deep caving operations behave as zero-redundancy systems, in which total operational fragility is dictated by the weakest link.

To increase reliability and reduce system fragility, operations must abandon customised, bespoke layouts ('the uniqueness trap') that introduce non-standard infrastructure and manual support methods. Instead, deep mines should adopt a modular native architecture (Flyvbjerg et al. 2026), turning the underground environment into a standardised, repeatable factory floor characterised by:

- Manage excavations as critical assets with appropriate levels of maintenance rather than temporary operational openings that require firefighting.
- Measure using performance metrics identical to those applied to mechanical assets.
- Integration of performance data into digital twins to manage support logistics.
- Damage will occur: the traditional approach has been reactive, waiting until damage occurs and then repairing it. This approach is time-consuming and costly. Experience has shown that repair costs can exceed 200% of the original development baseline.
- PSM with scheduled support maintenance reduces production interruptions, with costs limited to 25 to 50% of the original development costs.
- Time savings: reactive rehabilitation of a collapsed drift can drop advance rates from 70 m/month down to 15 m/month due to logistical constraints and production interference.
- Real-time QA/QC reporting via semi-autonomous jumbos that track bolt positioning and installation quality.
- Pumpable resins: increased use of pumpable resins to guarantee full bolt encapsulation and potentially to replace cable bolting of intersections.

Operations must categorise assets into zones of resolvable and radical uncertainty to manage downside risks effectively. Implementing a structured, data-driven support and development program transitions the mine away from reactive 'firefighting'. When digital monitoring indicates a drift has consumed a critical percentage of its displacement capacity, supplementary elements (ductile bolts, mesh straps, cable bolts) can be installed to restore system capacity before failure occurs.

Stability first, recovery next: the primary mandate is to build a robust mine that functions safely under credible load scenarios, adhering to the ALARP (as low as reasonably practicable) principle. 'Stability first, recovery next' exerts the single largest influence on ultimate ore recovery. Aggressive, overly optimistic feasibility studies create unrealistic corporate expectations, forcing site teams to compromise operational rules to meet unachievable targets. To ensure flexibility, designs must build in contingency infrastructure:

Strategic decisions must look beyond purely financial ratios to evaluate qualitative dimensions, including project schedule-delay risks and workforce exposure. The primary objective is to bring the mine into operation in a stable, controlled state first; true optimisation occurs once the system is proven resilient.

Forecasting damage and scenario planning: long-term 3D numerical models show that regional abutment loads increase as a cave front advances, driving static closure and pillar wall damage. Mine seismology must focus tightly on local geology—specifically stiffness contrasts where rigid, brittle rock mass lies directly adjacent to soft, yielding zones. Rather than relying on deterministic planning ('base cases'), deep operations must utilise a scenario planning framework (Rigby et al. 2026) to stress-test project economics, define ground support triggers, and maintain resilience across diverse geotechnical futures (Figure 15).

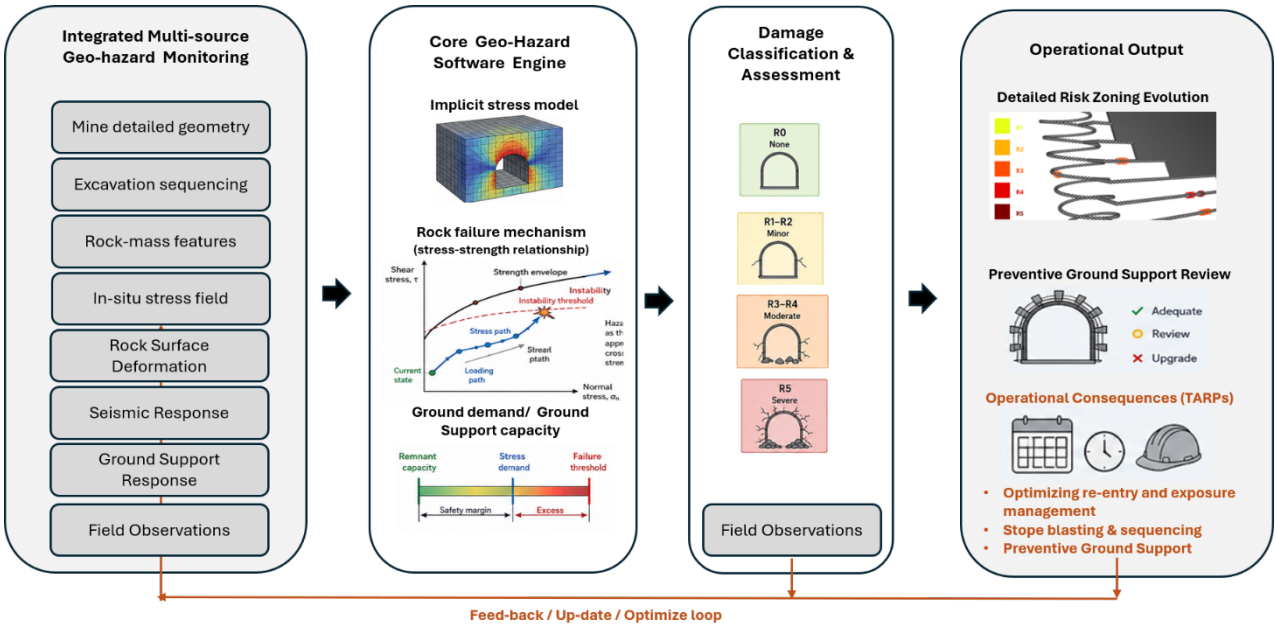


Figure 15 Proactive strainburst hazard assessment framework. Integrated sensors and monitoring systems drive a central hazard engine that quantifies the potential for instability. Classifies damage severity and supports operational decisions. The hazard engine iterates multiple data sources and embedded mechanisms (such as instrumented rockbolts) to deliver assessments on the ratio between support demand and actual residual capacity (generated with assistance of AI)

8 Conclusions

Deep caving operations represent the future of copper extraction, but success demands a fundamental paradigm shift in risk management. The large capital investments and irreversible physical pathways of these operations leave zero margin for error under traditional deterministic planning.

Excavations represent the single largest investment in a caving project, far exceeding the cost of fixed and mobile equipment fleets. Development and infrastructure construction account for 60–70% of the mine construction schedule. Fully loaded development costs can exceed USD 12,000 per metre, with a substantial portion driven by ground support requirements. As a project progresses, operational optionality systematically decreases while the asset risk profile shifts.

Investment in support exceeds USD 1 billion for deep caving operations. During the pre-production period, support is between 12 and 15% of capex, increasing to 25% upon commencement of the production ramp-up. Some 75 % of the support investment is attributable to the installation of bolts and cable bolts. Rock support is expensive. Payback comes from production efficiency and reliability.

The value proposition for support ultimately centres on revenue generation. The impact of support on schedule during the pre-production (time to first ore) and the need to manage damage during production ramp-up and ongoing operations underscores the strategic importance of support. Advances in ground support are required to enhance the value proposition by:

1. improving design methods based on the realities of deep mining in brittle rock
2. enhancing hazard forecasting and real-time measurement of installation quality
3. recognising the critical impact of constructability on schedule
4. adopting a holistic approach that integrates multiple support elements into a cohesive system
5. better defining the role of support in the overall project value proposition.

By adopting a rigorous, technically grounded scenario planning framework, mining companies can systematically map geotechnical uncertainties, evaluate financial consequences using real options, and deploy responsive engineering mitigations before risks manifest as operational catastrophes. Advanced ground support technologies are not an operational cost centre, but an investment fully integrated into an optimised 'end-to-end' process, driving data-driven decisions that enhance safety and ensure predictable, long-term economic performance.

Use of artificial intelligence disclosure statement

In the preparation of this work, the authors used Gemini to assist in the preparation of Figure 15. The authors have reviewed the content and edited it where required and take full responsibility for said content

References

Casten, T, Johnson, M, Zimmer, C & Mahayasa, M 2020, 'The transition to underground production', *Proceedings of MassMin 2020*, Gecamin, Santiago.

Di Ciolli, M, Campbell, R, Taylor, K, Primadiansyah, A & Kaiser, PK 2022, 'Practical application of deformation-based support design', in Y Potvin (ed.), *Caving 2022: Proceedings of the Fifth International Conference on Block and Sublevel Caving*, Australian Centre for Geomechanics, Perth, pp. 213–226, https://doi.org/10.36487/ACG_repo/2205_13

Edgar, I, Prasetyo, R & Wilkinson, M 2020, 'Deep ore zone mine wet ore mining empirical learnings, mining process evolution and development pathway', *Proceedings of MassMin 2020*, Gecamin, Santiago.

Flyvbjerg, B, Budzier, A & Christodoulou, MD 2026, *Towards a Theory of Modular Natives: Explaining Superscaling, China's Greatest Innovation Yet*, The University of Oxford, Oxford.

Flores-Gonzalez, G 2019, 'Major hazards associated with cave mining: Are they manageable?', in J Wesseloo (ed.), *MGR 2019: Proceedings of the First International Conference on Mining Geomechanical Risk*, Australian Centre for Geomechanics, Perth, pp. 31–46, https://doi.org/10.36487/ACG_rep/1905_0.3_Flores-Gonzalez

Kaiser, PK & Moss, A 2022, 'Deformation-based support design for highly stressed ground with a focus on rockburst damage mitigation', *Journal of Rock Mechanics and Geotechnical Engineering,* vol. 14, no. 1, pp. 50–66, https://doi.org/10.1016/j.jrmge.2021.05.007

McKinsey 2019, *Optimising Mining Feasibility Studies: The $100 Billion Opportunity*, https://www.mckinsey.com/industries/metals-and-mining/our-insights/optimizing-mining-feasibility-studies-the-100-billion-opportunity

Moss, A & Kaiser, PK 2022, 'An operational approach to ground control in deep mines', *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 14, no. 1, pp. 67–81.

Moss, A 2013, *Back to Basics*, presentation to Caving Knowledge Workshop, Santiago.

Primadiansyah, A 2023, *Evaluating Rock Mass Deformation and Support Capacity Consumption in High Stress Caving Environments*, MSc Thesis, University of British Columbia, Vancouver.

Rigby, A, Malovichko, D & Kaiser, PK 2026, 'A rockburst hazards assessment framework for strainbursting', *Journal Rock Mechanics and Rock Engineering*, https://doi.org/10.1007/s00603-026-05461-8

Roy, I 2025, *Spalling and Strainbursting in Deep Mine Tunnels – Data Driven and Numerical Analyses to Improve Ground Support Design and Reliability*, PhD thesis, The University of British Columbia, Vancouver.

Simanjuntak, K, Primadiansyah, A, Soumilena, N & Teweng, W 2020, 'Driving and managing stress in the Deep Mill Level Zone caving mine', *Proceedings of MassMin 2020*, Gecamin, Santiago.