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Towards a deformation-based probabilistic framework for rockburst hazard forecasting in cave mining

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Abstract

Rockburst hazard forecasting in cave mining is complicated by the evolving interaction between mining-induced stress redistribution, seismicity and progressive rock mass degradation. Conventional forecasting approaches have largely relied on seismic event metrics, energy-based demand or deterministic numerical modelling, none of which directly represent excavation-scale damage mechanisms or the uncertainty governing damage realisation. This paper presents a deformation-based, probabilistic framework for rockburst hazard forecasting tailored to cave mining environments and grounded in deformation-based support design (DBSD) principles. The approach reframes hazard in terms of the probability of exceeding damage-related deformation thresholds, recognising that pre-existing stress fracturing consumes support capacity prior to dynamic loading. Numerical stress modelling is used to define the evolving stress environment, while Monte Carlo simulation is employed to capture key sources of variability, including rock mass heterogeneity, rupture depth, bulking time, remnant support capacity and seismic efficiency. Application to cave mining case studies demonstrates that damage occurrence correlates with deformation demand exceedance rather than event size. Ultimately, probabilistic forecasting combined with robust operational governance provides a defensible basis for tracking hazard migration and managing strainburst risks as cave geometry and stress conditions evolve.

Keywords: *rockburst hazard forecasting, deformation-based support design, strainburst, Monte Carlo simulation, cave mining, remnant support capacity*

1 Introduction

The transition of block and panel caving operations to greater depths is invariably accompanied by high in situ stresses and complex geomechanical challenges. As outlined by Cuello & Newcombe (2018), securing the geotechnical knowledge required to navigate the life cycle of a deep block cave necessitates highly practical, forward-looking mine planning guidelines. As the cave footprint expands, the active undercut and extraction levels are subjected to a highly transient and punishing stress path. This continuous stress redistribution drives progressive rock mass degradation, structural unravelling and the generation of mining-induced seismicity (Jarufe 2024). Consequently, development excavations and extraction level pillars are exposed to an elevated risk of dynamically driven failures.

Historically, rockburst hazard forecasting has relied heavily on probabilistic seismic hazard assessment derived from seismic event metrics (e.g. local magnitude, radiated energy) or deterministic numerical modelling outputs. While these methods provide a macro-scale understanding of seismic source potential, they frequently fail to capture excavation-scale damage mechanisms. Traditional energy-based approaches often rely on blanket ejection velocity assumptions and fail to account for the displacement demands imposed on ground support systems during an event. As Kaiser & Malovichko (2022) demonstrate, these

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conventional methods often fail to capture the excavation-scale damage mechanisms that ultimately lead to support failure as they do not adequately represent the displacement demands imposed on the rock mass.

To address these limitations, this paper proposes a paradigm shift from deterministic, energy-centric hazard assessments to a probabilistic, deformation-based framework. Rooted in deformation-based support design (DBSD) principles (Kaiser & Moss 2022; Moss & Kaiser 2022), this approach regards all stress-driven damaging events at the excavation as strainbursts, regardless of magnitude. It quantifies hazard as the probability of exceeding specific deformation thresholds. By integrating advanced numerical stress modelling (Jarufe et al. 2020) with robust Monte Carlo simulations (Lowther et al. 2022; Li et al. 2025), the proposed framework explicitly accounts for the variability in rock mass parameters and dynamic demand, and the progressive degradation of ground support capacity over the life of the drawpoint.

2 Mechanics of rockburst damage in cave mining

2.1 Strainburst mechanisms, progressive degradation and discrete element method simulation

In highly stressed environments, rockburst damage is predominantly governed by strainburst mechanisms. Strainbursts occur when the tangential stresses near the excavation boundary exceed the local rock mass strength, leading to violent, self-initiated fracturing. To better understand these mechanics beyond pseudo-static assumptions, Gao et al. (2019) utilised a distinct-element bonded block method to simulate strainbursts. Their numerical investigations demonstrated that the self-initiated fracturing process is highly dependent on the stiffness of the surrounding rock mass, highlighting that rock mass degradation alters the boundary conditions long before a dynamic failure is triggered. These strainburst initiation and loading mechanics are illustrated in Figure 1.

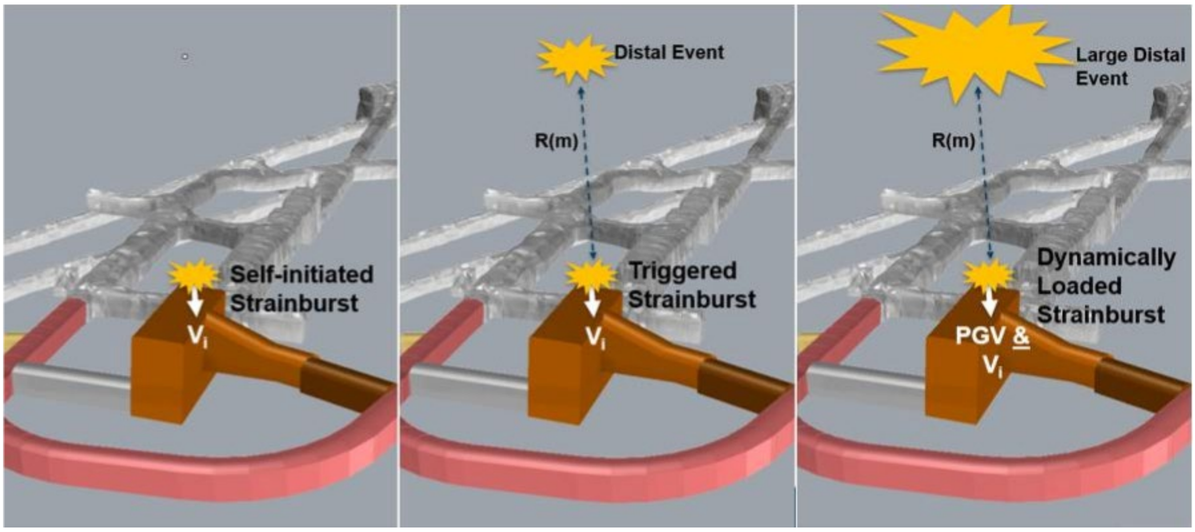

Figure 1 Mechanics of strainburst initiation and loading (after Lowther et al. 2022)

2.2 Self-initiated, triggered and dynamically loaded strainbursts

A fundamental component of the displacement-based approach is categorising strainbursts into three distinct scenarios:

- Self-initiated strainbursts occur when an excavation becomes overstressed due to a mining-induced stress change, generating a strainburst close to the excavation (Gao et al. 2019).
- Triggered strainbursts occur when an excavation is on the verge of failure due to a stress abutment and a remote seismic event acts as a catalyst. The remote event triggers the burst but does not contribute additional damage demand to the failure process.

- Dynamically loaded strainbursts occur when a remote seismic event has sufficient energy to generate additional dynamic stress and rock mass bulking at the excavation, effectively dynamically loading the local strainburst it triggered.

2.3 Re-evaluating dynamic velocity and energy demand

Conventional ground support design often oversimplifies dynamic demand by applying a blanket ejection velocity to all strainburst masses. As established by Potvin & Wesseloo (2013), dynamic demand on ground support is governed by complex site-specific attenuation and local site amplification, making assumed ejection velocities inherently flawed. Furthermore, Kaiser (2014) demonstrated that strainburst (bulking) velocity varies significantly across the depth of the strainburst.

The velocity of the fractured rock is at its maximum at the excavation boundary, while the velocity at the back of the strainburst volume (where it meets intact rock) is negligibly small or zero. Therefore, the kinetic energy of the strainburst volume is calculated using the average bulking velocity. In a dynamically loaded strainburst, the low-frequency peak ground velocity (PGV) generated by the remote seismic event permeates the rock mass, acting on the strainburst volume and adding further kinetic energy (Kaiser & Malovichko 2022). It is acknowledged that this boundary (ejection) velocity is itself the net result of energy released deeper within the strainburst source, which must propagate through – and is partially confined and dampened by – the intervening fracture zone; the boundary value therefore represents the net ejection velocity after this attenuation rather than the peak particle velocity within the source.

This distinction is fundamental to translating seismic hazard into quantifiable dynamic demand. Once the contributions of strainburst bulking velocity and remote event PGV are appropriately characterised, the resultant kinetic energy demand can be systematically evaluated against the energy absorption capacity of the installed ground support system – providing a rational basis for assessing whether current support prescriptions are adequate under the anticipated seismic loading conditions.

As shown in Figure 2, the depth of strainbursting, dSB, is taken as a proportion of the extreme depth of failure, dfe, according to dSB = qSB dfe. The parameter qSB defines the fraction of dfe assumed to occur dynamically, while the blue segmented line represents the original excavation surface for which the corresponding dSB for the case was considered. The parameter dBF defines the bulking between the original excavation surface and the surface following the event.

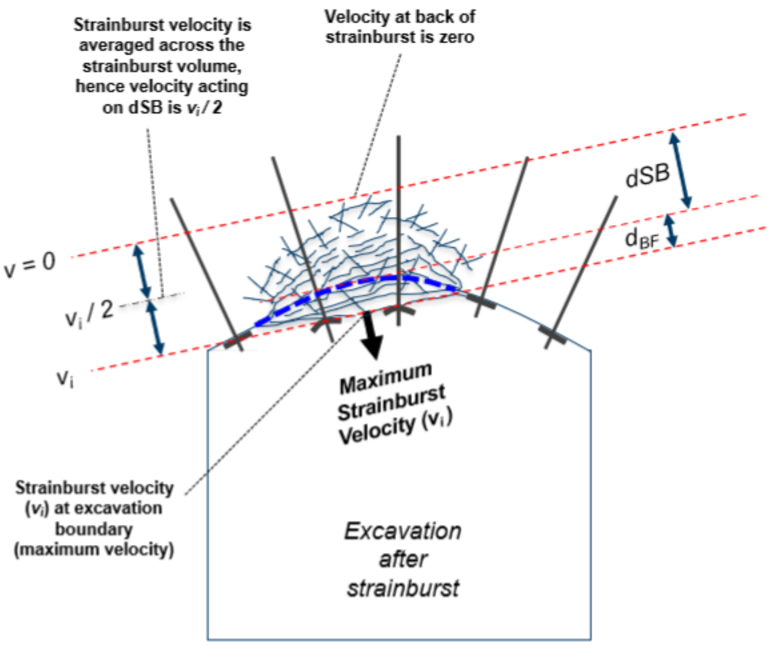

Figure 2 Strainburst volume velocity profile. The dashed line denotes the strainburst initiation surface at which the bulking (ejection) velocity is initiated

3 Deformation-based support design principles

3.1 The shift from energy to displacement capacity

DBSD shifts the focus of ground support engineering from matching installed energy capacity to accommodating the total expected displacement (Kaiser 2020a, 2020b; Kaiser & Moss 2022). A fundamentally important feature of this approach is considering the pre-existing displacement that support elements have experienced prior to sustaining a dynamic event.

If a support element has sustained pre-existing damage or static closure, its capacity has been reduced or consumed. Therefore, the ground support system's ability to survive a strainburst must be evaluated against its remnant capacity, after the prior deformation that the support has experienced and not its fresh, installed capacity. It is recognised that this remnant-capacity assessment is further complicated where bolts are subjected to shear in addition to axial loading, which can reduce their effective displacement capacity; a degree of conservatism is therefore warranted where shear displacement is anticipated.

3.2 Load distribution and surface support dynamics

To accurately calculate remnant capacity, the interaction between rockbolts and surface support must be quantified. Large-scale dynamic drop testing has demonstrated that the load distribution between anchor bolts and surface support is highly dependent on rock mass stiffness.

Bucher et al. (2013) found that in a strong, massive rock mass, approximately 25% of the dynamic energy is absorbed by the surface mesh, with the remaining 75% absorbed by the yielding rockbolts. Conversely, in a weak, blocky rock mass (which is typical of an advanced block cave extraction level), up to 70% of the energy is absorbed by the mesh and 30% by the bolts. For conservative DBSD calculations in yielding ground, a 50/50 or 70/30 (mesh-to-bolt) energy distribution is recommended. These energy-distribution ratios are derived predominantly from axial drop testing and do not explicitly capture shearing of the bolts prior to or during the burst; the recommended ratios should therefore be applied with appropriate conservatism in ground prone to shear displacement.

The proportion of dynamic energy absorbed by the surface support versus the reinforcement elements is not a fixed ratio but is governed by the stiffness of the surface support composite and the boundary conditions connecting stable and heavily damaged zones. Cuello et al. (2024) demonstrated through large-scale drop testing that varying the surface support type – while keeping reinforcement pattern constant – produces markedly different load transfer responses and energy dissipation rates, with high-tensile mesh systems engaging peripheral bolts at deflections below 60 mm while welded mesh systems require significantly greater deformation before load transfer occurs. This contrast in load transfer response is illustrated in Figure 3. It should be noted, however, that current large-scale test apparatuses, including those of Cuello et al. (2024), do not reproduce the resistance provided by the grout column along the bolt, which constrains bolt deformation in situ; this is a recognised limitation common to all published dynamic test configurations to date, and implies the laboratory load-distribution ratios may not fully capture field-scale bolt-grout interaction.

(a) (b)

Figure 3 Dynamic energy load distribution by rock mass stiffness. Bolt and cable support, and loading conditions, are identical for both tests shown in (a) and (b). Only the surface support is different, leading to vastly different deformation (after Cuello et al. 2024)

Furthermore, momentum transfer testing has proven that the material properties of the mesh strictly govern the ultimate displacement capacity of the system (Player et al. 2008). High-tensile chain-link mesh has demonstrated the ability to absorb up to 12 kJ of kinetic energy independently without unravelling, whereas conventional welded wire mesh typically fails at approximately 2 kJ under identical testing configurations. The dynamic testing of such reinforcement and surface support systems is further documented by Villaescusa et al. (2012).

3.3 Pillar design and extraction level application

The application of DBSD is particularly critical for the design of extraction level pillars. Hormazabal et al. (2020) introduced a simplified geotechnical risk-based approach for extraction level pillar design in block/panel caving mines, emphasising that pillar stability is highly sensitive to the progressive accumulation of static strain as the undercut advances. Failing to account for this initial strain consumption results in a vast overestimation of the pillar's ability to withstand subsequent dynamic loading events during mass extraction. More broadly, the mine sequence exerts a first-order control on the stress path: the choice of undercutting strategy – advance versus post-undercutting – materially changes how abutment stresses are managed ahead of the extraction level, and therefore the resulting rockburst hazard, and should be considered alongside pillar-scale strain accumulation.

4 Proposed probabilistic framework and rockburst hazard assessment implementation

Given the inherent uncertainties in predicting depth of failure and seismic ground motions, deterministic calculations yield overly conservative or inaccurate predictions. The proposed framework uses Monte Carlo simulations to assess the demand path against the support system's remnant capacity. In practice, this framework is operationalised through the rockburst hazard assessment (RBHA) tool, a dedicated software platform developed to execute these complex probabilistic calculations across mine-scale numerical models.

4.1 Numerical stress modelling integration

The foundation of the framework relies on 3D numerical stress modelling to define the evolving stress tensor along the excavation trajectory. Jarufe et al. (2020) demonstrated that outputs from continuum and discontinuum models can be utilised to calculate probabilistic seismic hazard directly in cave mining. By extracting deterministic stability indicators such as stress-to-strength ratios and expected plastic strain from these models, engineers can establish the mean state of the stress environment at various stages of cave propagation. As further explored by Jarufe (2024), integrating these seismic hazard outputs directly into underground mine planning allows for schedule optimisations that minimise hazardous stress superimposition.

4.2 Demand path assessment

The dynamically loaded strainburst event generates an energy and displacement demand path. The system's survivability is dictated by whether this demand path intersects the support's remnant capacity limit in the displacement-energy space. The demand path is defined as a parabolic function. As shown in Figure 4, the dynamic demand path is compared against the ground support remnant capacity for a case with observed damage and a case in which dynamic loading occurred without observed damage.

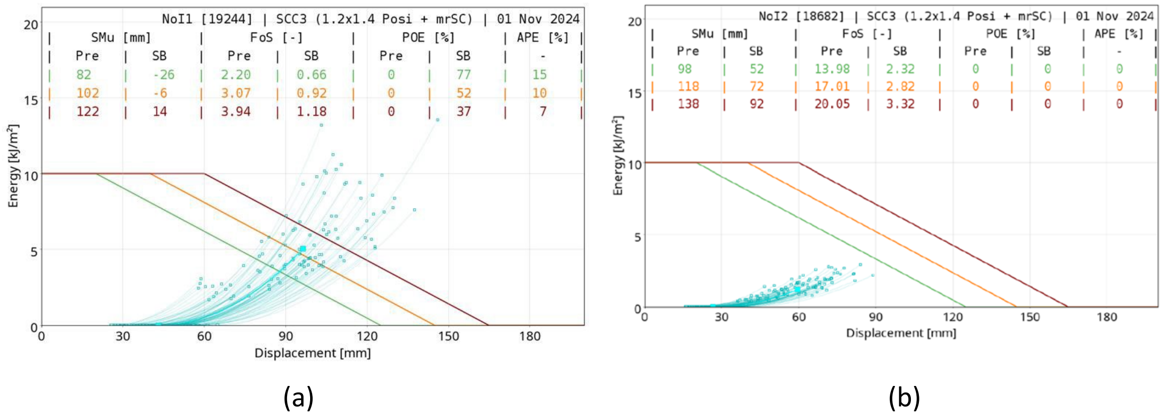

Figure 4 Expected patterns of dynamic demand and ground support capacity in cases with: (a) Observed damage; (b) In cases where dynamic loading occurred (e.g. a significant seismic event was recorded), but no damage was observed

4.3 Stochastic variable selection and multi-criteria analysis

To calculate the ultimate probability of exceedance of a defined damage threshold (probability of failure, Pf), the RBHA Monte Carlo simulation generates iterations sampling from specific probability distributions for the key input variables. As validated by Li et al. (2025) through the application of the multi-attributive ideal-real comparative analysis approach alongside Monte Carlo simulation, robust probabilistic prediction relies heavily on accurately defining these input distributions as:

- depth of strainburst, modelled using a triangular distribution to reflect field estimations of failure depth
- deformation/bulking time, modelled using a triangular distribution to allow the simulation to derive realistic strainburst velocities without relying on blanket assumptions
- pre-existing displacement, modelled using a triangular distribution to represent the variable static preconditioning of the tunnel prior to the dynamic event
- PGV, modelled using a normal distribution of ground motion from the remote triggering event.

4.4 Quantifying the probability of failure

Lowther et al. (2022) established that a probabilistic evaluation of the displacement-based ground support design approach provides superior decision-making clarity compared to deterministic factors of safety (FoS). The output of the Monte Carlo simulation is a series of normal distributions representing the local and overall FoS prior to, during and after the strainburst event.

The rockburst hazard is quantified strictly as the probability of exceeding the support capacity . This is defined simply as the percentage of simulation iterations where the calculated FoS is less than 1.0 (i.e. the demand path exceeded the remnant capacity). An example displacement-energy plot showing the probability of exceeding the installed surface support capacity is presented in Figure 5.

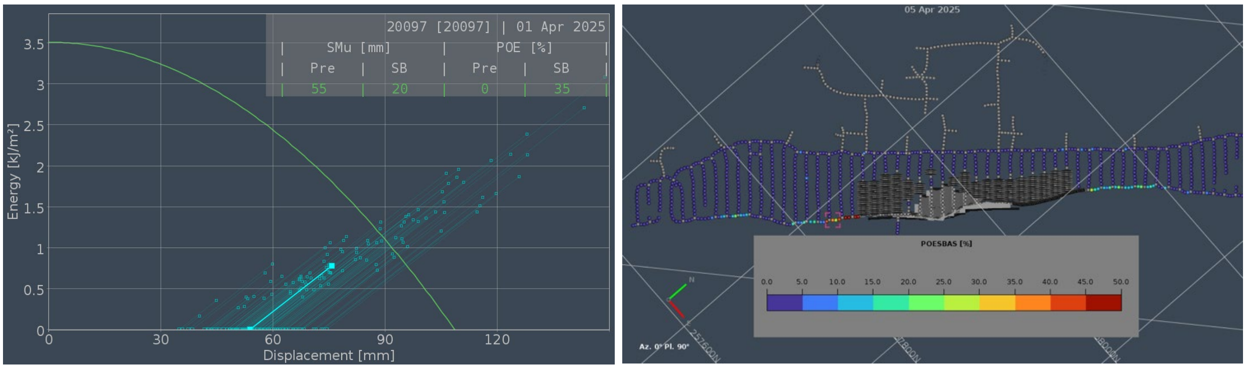

Figure 5 Example of displacement-energy plot showing the probability of exceedance of installed surface support capacity

4.5 Complex geometries and anisotropic strength

Applying the RBHA framework to active cave mines requires accounting for complex 3D geometries. Rigby & Malovichko (2024) expanded the tool's capabilities to explicitly approximate the complex stress tensors near tunnel intersections. Because standard 2D plane-strain assumptions fail at intersections, the RBHA methodology integrates a specific intersection module that evaluates failure depth using parabolic failure geometries and extensional strain criteria.

Additionally, Kaiser et al. (2025) demonstrated that the RBHA framework must account for rock mass anisotropy. In highly foliated or structured ground, the dynamic demand and resulting depth of strainburst dSB are heavily influenced by the orientation of the structures relative to the excavation boundary, requiring the limit state functions to incorporate anisotropic strength penalties.

5 Application to cave mining and operational governance

The probabilistic outputs derived from the RBHA framework seamlessly integrate into modern risk management protocols such as a layers of protection analysis (LOPA). The probability of exceeding the support capacity serves as a quantifiable independent protection layer (IPL) in the LOPA analysis.

5.1 Layers of protection analysis

Specific excavations and associated support profiles were then assessed using the LOPA methodology. LOPA is a risk assessment methodology that uses simplified, conservative rules to define risk as a function of both frequency and potential consequence severity. LOPA is part of the risk-based process safety framework adopted by Newcrest and was originally adopted from the Centre for Chemical Process Safety.

Conceptually, LOPA is used to understand how a process deviation can lead to a hazardous consequence if not interrupted by the successful operation of a safeguard called an IPL. In mining, these IPLs are known as 'critical controls'. An IPL, or critical control, is a safeguard that can prevent a scenario from propagating to a consequence of concern without being adversely affected by either the initiating event or by the action (or inaction) of any other protection layer in the same scenario:

$$Fic = FiI \times PFILi1 \times PFILi2 \times \ldots\ldots \times PFILii \quad (1)$$

where:

Fic = frequency of the consequence for scenario 1

FiI = frequency of the occurrence of the initial event

PF1Lii = Probability of failure of an IPL for scenario 1. The LOPA concept is illustrated in Figure 6, which shows the independent protection layers interposed between the initiating event and the final consequence.

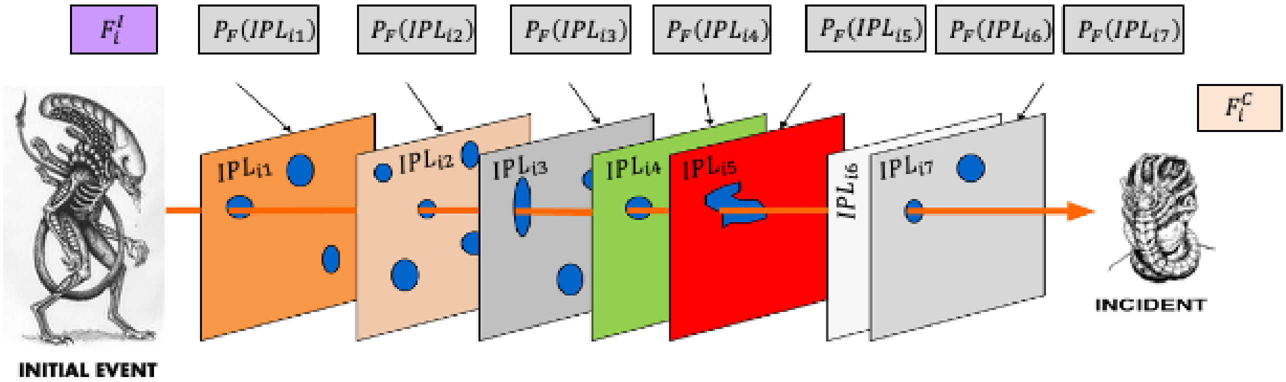

Figure 6 Diagram illustrating the layers of the protection analysis technique, showing the independent protection layers between the initiating hazard event and the detrimental outcome of the incident

5.2 Field monitoring and deformation-based support design calibration

The entire probabilistic framework is highly sensitive to the assumed pre-existing displacement (prior to the strainburst). To ensure the Monte Carlo inputs remain realistic, operations must continuously measure field closure. Primadiansyah et al. (2024) showcased the successful integration of stress fracturing and bulking monitoring for DBSD calibration in a deep caving operation. By utilising multi-point borehole extensometers and continuous visual inspections, site engineers were able to actively monitor the bulking process, verify the depth of strainburst and calibrate the remnant-capacity parameters within the hazard model in near real time.

5.3 Preventative support maintenance and mine planning

By accurately tracking pre-existing displacement and dynamically updating the remnant-capacity calculations, operations can implement preventative support maintenance (Moss & Kaiser 2022). Full-scale testing confirmed that systems integrating high-tensile mesh and yielding bolts can accommodate high rockburst demands. However, this capacity is strictly finite; once the pre-existing displacement reaches a pre-defined threshold, the consumed capacity must be identified and restored via supplemental bolting before the excavation is exposed to critical dynamic loading. Integrating these insights into short- and long-term mine planning allows operators to strategically sequence cave advancement, thereby mitigating extreme dynamic demand spikes entirely (Jarufe 2024). Critically, the outcomes of the hazard assessment must be explicitly acknowledged in the mine plan: anticipated rehabilitation should be scheduled as a planned event within the production sequence as part of the risk-range exercise, with contingency provisions to ensure ground support rehabilitation can be accommodated without compromising the broader extraction schedule.

6 Conclusion

Traditional energy-based rockburst forecasting methods, which rely on deterministic inputs and arbitrary ejection velocities, are increasingly inadequate for ensuring excavation stability in deep caving environments.

The probabilistic, deformation-based framework bridges the gap between macro-scale seismic hazard and excavation-scale failure mechanics. By explicitly calculating remnant capacity based on monitored pre-existing displacement, integrating verifiable limits from large-scale dynamic testing and modelling the demand path of dynamically loaded strainbursts using the rockburst hazard assessment tool, the framework provides a realistic assessment of strainburst risk. Integrated with Molchan diagram verification (Malovichko et al. 2025) and continuous field calibration, this robust methodology offers a defensible, risk-quantified tool for managing severe geohazards throughout the complex life cycle of a block cave. To secure operational buy-in, the framework is designed to distil these probabilistic outputs into a single, readily interpretable probability-of-failure metric and associated hazard ratings that frontline engineers can act on directly, ensuring the tool complements rather than complicates established site decision-making.

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