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Towards the development of an empirical method to assist in the selection of ground support systems in rockburst-prone conditions

Audrey Mathieu [a,*], Yves Potvin [b], Martin Grenon [c]

[a] *Australian Centre for Geomechanics, The University of Western Australia, Canada*

[b] *Australian Centre for Geomechanics, The University of Western Australia, Australia*

[c] *Université Laval, Canada*

Abstract

Rockburst is one of the major risks in deep underground mines. It affects mining personnel safety and the operations and profitability of the mine. Although it is impossible to eliminate the probability of occurrence of a major seismic event, some measures need to be implemented to reduce the probability of seismically induced rockfalls (rockbursts). This is generally achieved with the installation of enhanced ground support systems, often referred to as dynamic ground support systems.

The design of (dynamic) ground support systems in mines with rockburst-prone conditions is often based on the experience and knowledge acquired at each mine. This is used to create site-specific dynamic support designs. Stacey (2012) concluded that since the dynamic capacity of ground support systems and the demand from seismically induced dynamic loading cannot be reliably quantified, then '…a clear case of design indeterminacy' results, making it '…impossible to determine the required support using the classical engineering design approach.' This paper looks at the influence of combinations of ground motion factors (GMFs) and various geotechnical conditions on the reliability of numerous ground support strategies subjected to dynamic loading conditions.

The performance of seven ground support systems strategies have been investigated for a range of GMFs expressed as a function of the seismic event magnitude and distance between the seismic source and damage. The performance criterion is the survivability of the ground support system (i.e. no fall of ground, although rehabilitation may be required). A reliability index was developed to classify the reliability of the performance. Results are shown as a preliminary version of a 'survivability matrix' which can provide insight into the selection of ground support systems in underground mines with rockburst-prone conditions.

Keywords: *ground support, rockburst, seismicity empirical design*

1 Introduction

Rockbursting constitutes one of the major risks in deep mines as the potential consequence can be extreme, including multiple fatalities as well as temporary or permanent mine closure. Due to the intense complexity of the mechanisms involved in the seismically induced damage of underground excavations, it is expected that reliable analytical methods for designing ground support systems in rockburst-prone conditions are decades away. In particular, the nature of rockburst damage is such that within a metre or so, the ground support can vary from total destruction to no signs of loading (Figure 1). The granularity of analytical calculations regarding ground support subjected to dynamic loading does not allow for such drastic variations over short distances.

* Corresponding author. Email address: audreymathieu2@outlook.com

The dynamic loading and support capacity calculations for both the 'no damage' and the 'total destruction' areas in Figure 1 would be the same with outcomes at both ends of the damage spectrum.

Figure 1 Photographs of rockburst damage showing the variation from no damage to intolerable damage (total destruction) of ground support within a very short distance. Note that the calculations for ground support capacity and demand would be the same for the no damage and total destruction areas

Until further advances in analytical solutions progress, guidelines based on empirical approaches can provide substitute solutions to this difficult problem. In particular, the concept of reliability of ground support performance can be useful to overcome the binary solutions resulting in either stable or failed solutions. The main existing empirical methods will be briefly described in the next section followed by the description of a new approach currently under development called the 'survivability matrix' inspired by the work of Counter (2017) at the Kidd Mine in Timmins, Ontario.

2 Review of existing empirical methods

A recent literature review by Mathieu (2023) showed that at least five empirical methods to assist in the selection of adequate dynamic ground support systems have been proposed during the last couple of decades. They all have some limitations and none of them has found widespread acceptance in the mining industry.

Mikula & Gebremedhin (2017), Morissette & Hadjigeorgiou (2019), and Counter (2017) developed site-specific methods. Although the methodologies can be replicated at any site, the design charts are not readily applicable at sites other than where they have been developed. All methods have good concepts and ideas that can be incorporated into a new empirical design approach; however, the format of the Kidd survivability matrix (Figure 2) stands out for its simplicity and user-friendliness to assist in the selection of reliable ground support elements at Kidd mine.

M_N	Distance m	Twin Cables	Cone Yield Lok	0 Ga Strap	SS * < 1m²	Rebar * < 1m²	WWM * < 1m²	SS * >2m²	Rebar * > 2m²	WWM * > 2m²	SFRS
<1	>50	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	10-50	✓	✓	✓	✓	✓	✓	✓	✓	✓	±
	<10	✓	✓	✓	✓	✓	✓	±	±	±	✗
1-2	>50	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	10-50	✓	✓	✓	✓	✓	✓	±	±	±	✗
	<10	✓	✓	✓	±	±	±#	±	✗#	✗#	✗
2-3	>50	✓	✓	✓	✓	✓	✓	✓	✓	✓	±
	10-50	✓	✓	✓	✓	✓	✓	±	±#	±#	✗
	<10	✓	✓	±	±	±	±	±	✗	✗	✗
3+	>50	✓	✓	✓	✓	✓	✓	✓	±	±	±
	10-50	✓	±	±	±	±	±	±	±	±	✗
	<10	±	±	±	✗	✗	✗	✗	✗	✗	✗

* Density expressed as square metres per tendon. > or < inferred as 'or equal to'

Mesh without secondary reinforcement can fail at low Nuttli magnitudes (M_N) resulting in tendon stripping

SS is split set and WWM is welded wire mesh

Figure 2 Survivability matrix for events from MN0.5 to 3.8 by support type (Counter 2017)

There are two non-site-specific methods that are meant to be universally applicable. Villaescusa et al. (2014) proposed a methodology to select dynamic reinforcement based on an extensive database of laboratory dynamic tests. Although useful when considering which rockbolts would be suitable for certain conditions, it focuses only on reinforcement without recommended bolting density and with no guidance for surface support.

Heal (2010) proposed a comprehensive approach to evaluate possible rockburst damage potential (RDP) of an excavation considering two main parameters: an estimated peak particle velocity (PPV) from a designed seismic event (generally the largest anticipated event) to account for dynamic demand and the excavation vulnerability potential (EVP). The EVP accounts for four factors that influence the stability of an excavation when it is subjected to dynamic loading (including ground support) (Equation 1):

$$EVP = \frac{Stress\ Conditions\ (E_1)}{Ground\ Support\ Capacity\ (E_2)} \times \frac{Excavation\ Span\ (E_3)}{Geological\ Structure\ (E_4)} \tag{1}$$

Given certain ground conditions (PPV, stress, excavation span, and geological structure), the factor accounting for ground support capacity can be adjusted in the calculation of EVP to obtain an RDP that would be considered tolerable (i.e. R1, R2, or R3) according to Figure 3.

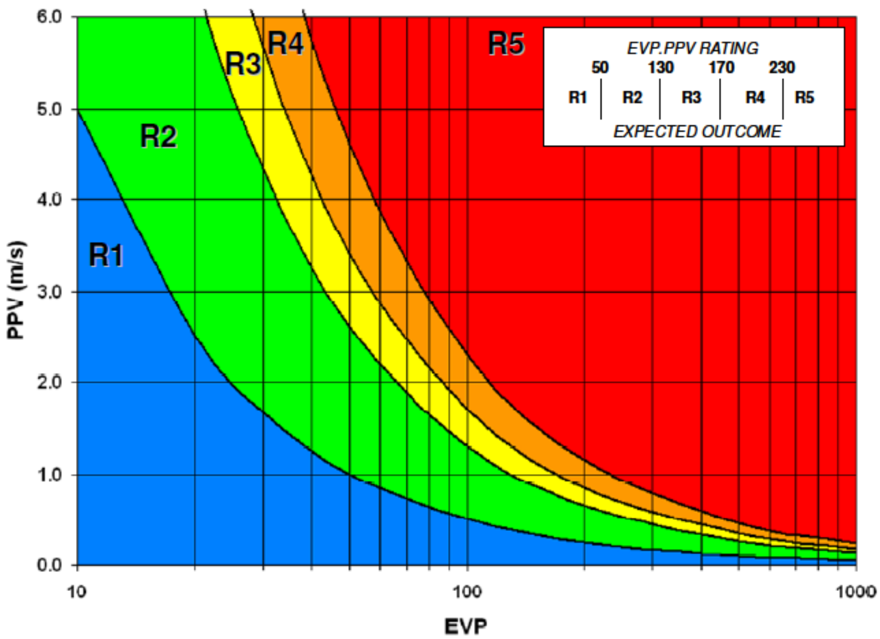


Figure 3 Rockburst damage potential chart (Heal 2010)

One of the drawbacks from the RDP approach is that the ground support capacity factor was developed two decades ago when there were very limited dynamic ground support options available at the time.

Given that the rockburst risk is increasing with the expansion of deep mines, the amount of money spent on dynamic ground support systems, and the limitations of current methods, there is a compelling case for further development of a simple empirical approach for selecting reliable dynamic ground support systems that can be applied universally.

3 Towards a new empirical approach: data collection

3.1 Description of the participating mines

Five open stoping mines contribute to the database to date. Three of them are located in Canada and two in Australia. For the Canadian mines and one of the Australian mines, weldmesh was commonly used as surface support in rockburst-prone areas. In-cycle fibrecrete with mesh was used by one Australian mine and one Canadian mine. For the bolting strategies, friction bolts and rebar were commonly used in static conditions and an enhanced support scheme comprised of dynamic bolts (hybrid or D-bolt) and straps was to be installed in rockburst-prone conditions. Foliation was observed in two mines. A total of 119 rockburst case studies were compiled from the five mines.

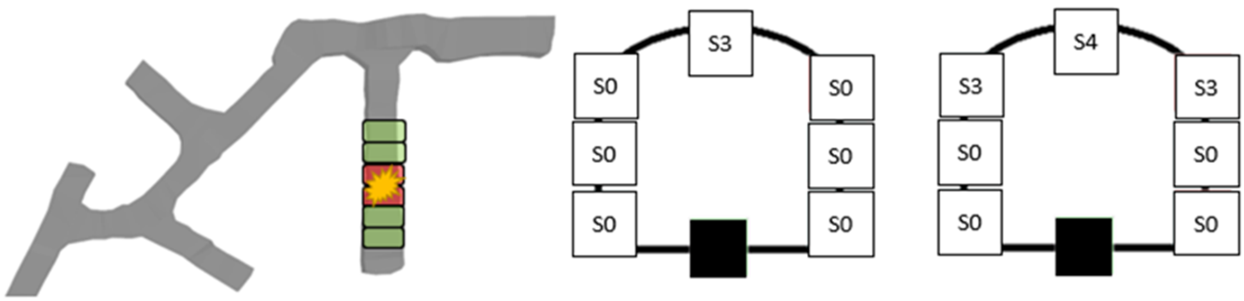
3.2 Collecting rockburst data

An empirical approach is only as good as its underlying database. To achieve a comprehensive and high-quality database, the damage mapping app from the mXrap platform was developed to collect all the data in a systematic and standardised manner (Cumming-Potvin et al. 2019). This was to overcome the chronic inconsistency in existing rockburst reports which has been one of the main barriers to developing reliable empirical ground support design guidelines to date.

Using this app enabled the creation of a database with high levels of detail. One of many advantages of using the app is that it assigns data (including damage) to specific areas of the tunnel profile such as the wall, shoulder, and back. The tunnel profile is subdivided into three points on each sidewall, one on the back and one on the floor. An example of how the Damage Mapping App discretises excavations to record data according to the location around the tunnel profile is shown in Figure 4. The damage is then recorded at each point as S0 (no damage) to S5 (total destruction) and interpreted as 'acceptable', 'tolerable', or 'intolerable' damage, according to Mikula (2012), which is a simplified version of the Kaiser et al. (1992) support damage classification (Table 1).

Table 1 Relationship between the support damage scale (Kaiser et al. 1992) and ground support damage classification (Mikula 2012)

Support damage scale		Support performance
S0	No damage	Acceptable: rehab not required
S1	First signs of distress	
S2	Support system is loaded, loose in mesh, plates deformed	
S3	Some broken bolts	Tolerable: rehab required
S4	Major damage to support system	Intolerable: fall of ground with potential for injury
S5	Complete failure of support system	



(a) (b)

Figure 4 Example of how the mXrap Damage Mapping App assigns data to specific parts of the tunnel profile. (a) Plan view: Red boxes are tracks with damage and green tracks have no damage; (b) Cross-sections showing the intensity and location of damage on the tunnel profile

Case studies used in developing previous empirical methods generally assigned the worst damage scale class to the rockburst area, and only focused on the tunnel area that suffered damage. The database has been extended to account for sections of tunnel adjacent to the damaged area that have not shown any damage. These tunnel sections, whether they have suffered damage or not, would have in theory experienced similar ground motion considering their distance from the seismic source. They also have comparable ground conditions and ground support systems.

For each damage case, 18 m linear lengths of tunnel have been considered in which the damage area is included (Figure 4a). The data adjacent to the damage (Figure 1) will be considered towards the development of a ground support reliability concept rather than stable/failed criteria.

3.3 Ground support reliability index

Referring to Figure 4 and considering that a cross-section is 3 m thick, the 18 linear metres considered for each damage case would include six cross-sections (four green and two red sections in Figure 4a). If the floor is ignored (which has no ground support), each cross-section has seven points along its profile (three in each wall and one in the back; Figure 4b) for a total of 42 points over the 18 linear metres. In this example, there is only one point out of 42 in the intolerable category (S4–S5) and 41 points in acceptable and tolerable categories (no damage, S1–S2, or S3) (Table 2).

Table 2 Number of points per category

Damage category	No damage (S0)	S1-S2	S3	S4-S5
Number of points	38	0	3	1

The reliability of the ground support system performance can then be evaluated with Equation 2.

$$Reliability\ (\%) = \left(1 - \frac{(Number\ of\ points\ with\ damage\ S4\ and\ S5)}{Total\ number\ of\ points}\right) \times 100\% \tag{2}$$

The reliability index of the ground support system for this example is calculated as (1–1/42) × 100 = 98%. This reflects that 98% of the support system has survived within that 18 m linear section. The 18 m was selected arbitrarily because 90% of all cases in the database had less than 18 m linear damage. This can be refined in future research.

3.4 Categorising ground support systems

Developing an empirical method for selecting ground support systems universally applicable to multiple mines requires some form of grouping of support systems to create a manageable number of categories that are representative of the wide variety of support systems used in the industry. Support systems can be challenging to regroup into categories because there is a wide variety of reinforcement elements on the market[1], the reinforcement patterns/bolt density can vary considerably, and these can be combined with a number of surface support techniques.

To develop the new empirical method, ground support systems were categorised and subdivided according to the type of surface support, the bolt density, and whether straps were included in the system, as shown in the following list:

- Surface support
  - Mesh
  - Shotcrete over mesh
  - Mesh over shotcrete
- Bolting strategies
  - Low (0.5–0.75 bolt/m^2)
  - Moderate (0.75–1.5 bolt/m^2)
  - High (1.5 + bolt/m^2)
- Straps
  - Straps[2]
  - No straps

For the surface support, there is no differentiation between the types of mesh found in the database. The shotcrete and fibrecrete are considered as the same, and there is no minimum thickness.

[1] At this stage, this method does not differentiate between the numerous types of rockbolts used at mine sites.

[2] Osro or zero gauge mesh straps are generally used at mines that have provided data.

Even with the above simplification, there are 18 possible combinations of surface support, bolting strategies and straps (used or not) (Figure 5a). However, because the current database has an inadequate number of cases involving shotcrete, it was decided to combine the shotcrete over mesh and mesh over shotcrete categories until more data can be collected. Some other categories were also not sufficiently represented in the database so, at this stage, development of the empirical method has progressed with seven ground support system categories (Figure 5b).

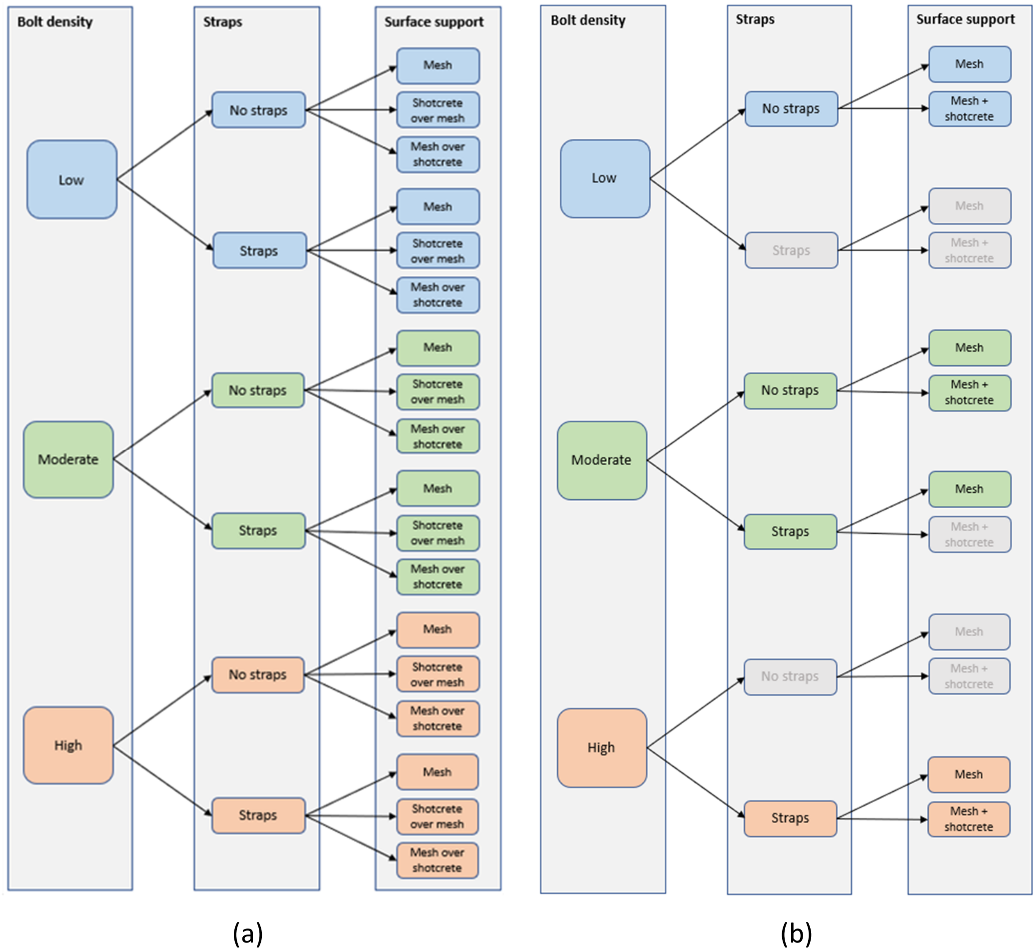


Figure 5 (a) All possible combinations of bolt strategy (density), use of straps, and surface support technique; (b) Seven surface support categories are retained at this stage based on sufficient amounts of data

3.5 Classifying ground conditions

The data from the five mines involved in this study indicated that the ground conditions could strongly influence the performance of ground support subjected to dynamic loading. For simplicity, two criteria, geological strength index (GSI) and foliation, were used to classify the ground conditions as 'standard' or 'unfavourable'. Figure 6 provides a flow diagram on how to classify the ground conditions. If the GSI ≤ 40, the condition is classified as unfavourable. For GSI > 40, there are two decision branches leading to unfavourable conditions, one for the presence of a geological structure, and the other for foliation intersecting the tunnel at a shallow angle (< 25°), based on Mercier-Langevin & Hadjigeorgiou (2011). All other cases with GSI > 40 are classified as standard conditions.

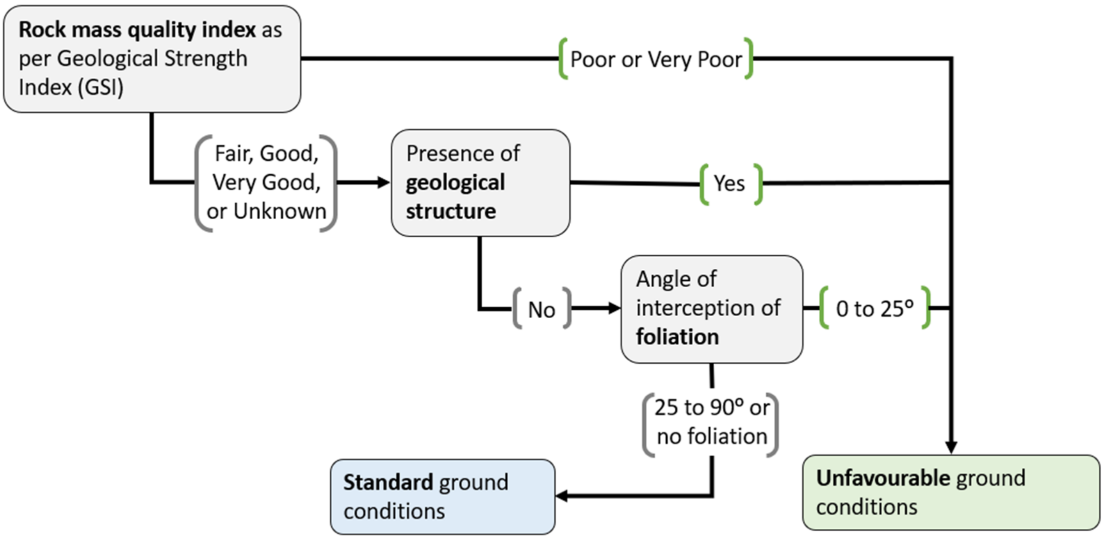


Figure 6 Flowchart describing the process to classify the ground conditions as standard or unfavourable

3.6 Dynamic demand on ground support: the ground motion factor

Experience has shown that large events close to an excavation are more likely to produce rockburst damage than small events far away from an excavation. Hence, most dynamic ground support design methods rely on a magnitude–distance relationship to account for the attenuation with distance of dynamic demand on ground support. For the proposed empirical method, the scaled–distance relationship of Potvin et al. (2010; Equation 3) as ground motion factor (GMF) is proposed to characterise the effect of magnitude and distance on the ground support system performance.

$$GMF = \frac{C \cdot 10^{\frac{1}{2}(M_L+1.5)}}{R + R_0} \quad (3)$$

Where:

- C = a constant, and a value between 0.2 and 0.3 is recommended for design purposes by Potvin et al. (2010). A midway value of 0.25 was retained.
- M_L = local magnitude.
- R = distance between the seismic event and the damage in metres.
- R0 = source radius in metres estimated as:

$$R_0 = \alpha \cdot 10^{\frac{1}{3}(M_L+1.5)} \quad (4)$$

where α is a constant (value 0.53–1.14). A value of 0.53 was used for this research, which is the most conservative value from the range. This approach was also used by Duan et al. (2015). This relationship considers the impact of near field and far field on the particle velocity, which reduces the impact of the seismic event occurring in the near field. Other formulas tend to overestimate the impact of those seismic events.

4 Development of the survivability matrix concept

As mentioned earlier, the format Counter (2017) used to create a universally applicable matrix for ground support systems rather than for individual reinforcement elements was adopted. Because the database indicated that ground support systems tend to perform worst in poor ground conditions (Section 3.5), two matrices were created; one for standard ground conditions and one for unfavourable ground conditions (Figure 7).

	Standard ground conditions						
	Mesh				Mesh + shotcrete		
GMF (m/s)	High density with straps	Moderate density with straps	Moderate density without straps	Low density no straps	High density with straps	Moderate density without straps	Low density without straps
[- , 0.2[	✓	✓	✓	✓		✓	✓
[0.2, 0.4[	✓	✓	✓	✓	✓	±	✓
[0.4, 0.6[	✓	±	±	✗	✓	±	✓
[0.6, 0.8[	✓	±	±	✗	✓		
[0.8, +[	±				✗		

	Unfavourable ground conditions						
	Mesh				Mesh + shotcrete		
GMF (m/s)	High density with straps	Moderate density with straps	Moderate density without straps	Low density no straps	High density with straps	Moderate density without straps	Low density without straps
[- , 0.2[	✓	±	±	✗			
[0.2, 0.4[	±	±	±	✗	✓		✗
[0.4, 0.6[	±	±	±		±		
[0.6, 0.8[	±		±		±		
[0.8, +[	±		±		✗		

Figure 7 Preliminary version of the support systems survivability matrices for standard (top matrix) and unfavourable ground conditions (bottom matrix)

The matrices are designed to have the dynamic demand parameter GMF (Section 3.6) on the vertical y-axis against the seven ground support system categories (Section 3.4) on the horizontal x-axis. The definition of bolt densities (high, medium, and low) is given in Section 3.4.

According to the database, the three symbols within the cells of the matrices indicate the reliability of the support system categories calculated, as described in Section 3.3, when subjected to a range of GMFs (PPV). The criteria for high, medium, and low reliability used in the matrices (Figure 7) are shown in Table 3. Note that these reliability indexes can be adjusted by users according to mine risk appetite. The cells coloured in red indicate cases lacking data to produce a reliable outcome.

Table 3 Ground support reliability criteria

Reliability level	Range of application of the reliability index (RI)	Symbol
Higher	95% ≤ RI	✓
Medium	85% ≤ RI < 95%	±
Lower	RI < 85%	✗

5 Conclusion

The proposed survivability matrices are very promising, but it is important to realise that this is only a preliminary development and should not be used at this stage due to major gaps in the data. A second major data collection campaign is currently being undertaken in Canada and Australia, and finalising development of the matrices is aimed for 2026. One of the purposes of this paper is to raise awareness within the mining industry about this project and seek contributions from mines with regards to providing further rockburst damage data.

More details on the development of the method can be found in Mathieu (2023).

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