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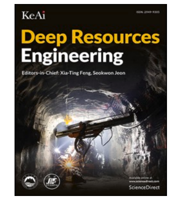

Full Length Article

Rockburst risk control and mitigation in deep mining

Ming Cai [a,b,c,*]

[a] School of Engineering and Computer Science, Laurentian University, Sudbury, ON, Canada
[b] MIRARCO – Mining Innovation, Laurentian University, Sudbury, ON, Canada
[c] Key Laboratory of Ministry of Education for Safe Mining of Deep Metal Mines, Northeastern University, Shenyang, China

A R T I C L E I N F O

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A B S T R A C T

It is important to understand and manage rockburst challenges in deep mining operations. This paper presents a systematic study of rockburst risk in underground mining, offering a detailed examination of influencing factors, risk assessment, and various control and mitigation methods. The complexities of rockburst phenomena are explained by examining factors that lead to the occurrence of rockbursts. A rockburst risk assessment using a bow-tie analysis is conducted, which provides insights into both risk evaluation and proactive control and mitigation systems.

The core of the paper presents a comprehensive array of rockburst risk control and mitigation methods, which range from controls to reduce rockburst hazard, and excavation vulnerability, to controls and mitigations to reduce exposure. Strategic engineering control methods, including mine design and mining sequencing, are discussed. Tactical engineering control measures, such as ground pre-conditioning and rock support, are scrutinized, along with administrative controls like evacuation and re-entry protocols and the use of mechanized equipment. A multiple-line defense system is advocated for rockburst risk management to address the uncertainties involved in the process.

Finally, emerging technologies and innovations as well as challenges are discussed, providing a roadmap for continued advancements in rockburst risk management in the future. This work serves as a valuable resource for mining professionals, researchers, and policymakers seeking a comprehensive understanding of rockburst risk management in deep mining.

1. Introduction

Mining at depth presents unique challenges, and among the foremost concerns is the occurrence of rockbursts. Rockbursts, characterized by sudden and violent releases of accumulated strain energy within the rock mass, pose significant threats to the safety of personnel and the integrity of underground infrastructure [1]. As mining activities migrate to deeper ground to extract valuable minerals, the complexities of geology and high mining-induced stresses amplify the risk of rockbursts, requiring a comprehensive understanding of the phenomenon and effective control measures.

Rockbursts, in the context of deep mining, refer to the sudden and explosive failure of the rock mass near excavation boundaries, often accompanied by the ejection of rock fragments and the release of strain energy [2,3]. It should be noted that a rockburst is associated with damage to an excavation or its support. A seismic event is a transient stress wave caused by inelastic deformation that occurs within a rock volume and there is a need to differentiate between a seismic event and a rockburst event. A seismic event alone, without causing damage, is not a rockburst [1]. Rockbursts can cause injuries, fatalities, and extensive damage to infrastructure, resulting in operational downtime and financial losses. Addressing the challenges posed by rockbursts is not only a matter of safety, but also a critical aspect of sustainable and efficient mining at depth.

Despite many decades of research and development, rockbursts continue to pose a significant risk in deep underground mines. Hence, comprehensive rockburst risk control and mitigation strategies must be in place for mining at depth.

This paper aims to provide a comprehensive examination of rockburst risk control and mitigation in deep mining operations. It aims to contribute to the collective knowledge that underpins safe and efficient deep mining operations by investigating the causes of rockburst, factors

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* Corresponding author at: School of Engineering and Computer Science, Laurentian University, Sudbury, ON, Canada.
E-mail address: mcai@laurentian.ca.

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that influence rockburst damage, rockburst risk, risk assessment, and control and mitigation methods. Through a study of the current state of research, case studies, and emerging technologies, it aims to provide insights that can guide both industry practices and future research endeavors.

2. Rockburst hazard and risk

2.1. Rockburst phenomena

The study of rockbursts in deep mining has a rich historical context, reflecting the evolving understanding of this complex phenomenon. Advancements in rock mechanics, rock engineering, and seismology have facilitated a better understanding of the geological and mining-related factors contributing to rockburst occurrences. A critical examination of the current knowledge on rockbursts in deep mining highlights recent advancements. From rockburst mechanisms, the development of sophisticated monitoring techniques, the seismic signatures associated with impending rock failures, to rock support, researchers have made substantial contributions to the field [1–9].

Rockbursts are frequently encountered in deep hard rock mines. Rock masses in deep mining areas are subjected to high in-situ stresses. The process of excavating underground mine openings redistributes stress in the surrounding rock mass, creating zones of high-stress concentration, especially in the vicinity of mine workings. In general, the tangential stresses near the excavation boundary are high when the in-situ stresses are high. When the tangential stresses on the excavation walls reach the rock strength, rock failure will occur. Rockbursts are mostly associated with hard rock that is 'intrinsically' strong and brittle, i.e., rock that can store substantial amounts of strain energy before failure and release this energy during a rapid post-peak strength loss. If these rocks fail suddenly in an unstable and violent manner, most of the stored strain energy in the rock surrounding the failing rock will be released. For a rock to fail in an unstable manner, the loading system must be soft. In a stiff loading environment, rock failure is stable and non-violent, which has been demonstrated in laboratory tests using a very stiff test machine [10,11]. Hence, the four conditions listed in Fig. 1 are the necessary and sufficient conditions for a rockburst to occur.

There are three main rockburst types: fault-slip burst, pillar burst, and strainburst [1,2,12,13], although some researchers [3,5] classify five types of rockbursts. Among the three, strainbursts are the most commonly encountered rockbursts in underground mines [13]. A strainburst is a sudden and violent failure of rock near an excavation boundary caused by excessive straining of an un-fractured or partially fractured volume of brittle rock [1]. Strainbursting occurs at the location where the tangential stress is the highest and the rock mass is the most vulnerable to unstable failure. Strainbursts can be initiated either by a stress change induced by the drift advance or near-by mining, potentially triggered by a dynamic stress pulse from blasting, or by dynamic stress loading by seismic waves from a large remote fault-slip burst or pillar burst event. The energy released from a fault-slip burst event is large. Therefore, a fault-slip burst event can potentially trigger pillar bursts and strainbursts at multiple locations (Fig. 2). In other words, damage to underground excavations by a fault-slip burst event is often seen in the forms of pillar burst and strainburst. A pillar burst can also potentially trigger strainbursts at one or multiple locations in a mine. When only the pillar wall bursts, it is classified as a strainburst. Only when the pillar core fails violently will it be called a pillar burst [1]. In extremely rare cases, a mining-induced strainburst can potentially trigger a pillar burst or a fault-slip burst when the pillar or the fault is in critical equilibrium. Similarly, a mining-induced pillar burst can potentially trigger a fault-slip burst when the fault is in critical equilibrium (Fig. 2).

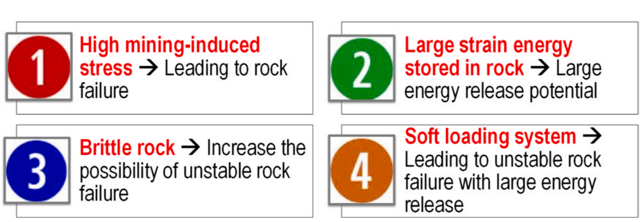


Fig. 1. Four conditions for rockburst occurrence.

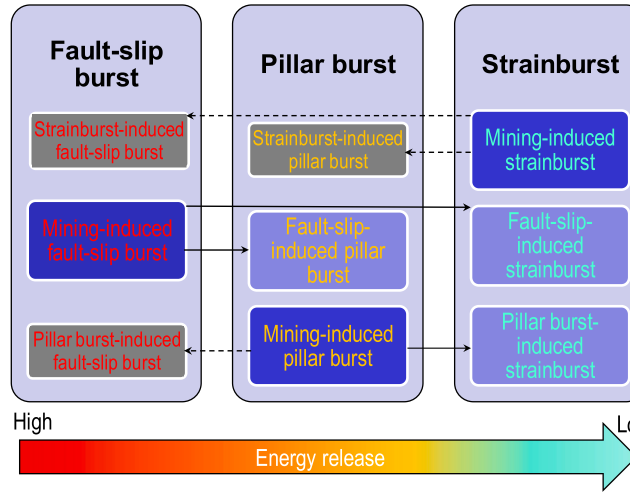


Fig. 2. Types of rockbursts and triggering of rockbursts in underground mines.

2.2. Factors that influence rockburst damage

As we navigate through the evidence documented in the literature, it becomes evident that a good understanding of rockburst damage necessitates a comprehensive approach, considering factors in geotechnical engineering, geology, mining, and seismology.

Rockburst damage near excavations can be in the form of stress fracturing or strainbursting, shakedown, and rock ejection [14]. Sudden stress fracturing of rock leads to a disintegration of the rock mass, and this is associated with rock mass bulking in the radial direction of drifts. Seismically induced rock falls, which occur frequently at drift intersections where the span is large and the confinement of the roof rock is low, are caused by seismic waves from relatively large and remote seismic events that shake the entire volume of a potentially unstable mass of rock. Rock ejection can be caused by a strainburst, by a remote seismic event through dynamic energy or momentum transfer, or by a combination of both. In most cases, rocks are ejected during a strainburst by the energy coming from stored energy in the failing rock and the surrounding rock mass.

Rockburst damage severity can be roughly classified into minor, moderate, and major (or severe) levels based on the volume of failed or displaced rock, the degree of rock support damage, and the violence of the energy release in terms of impact or ejection velocity [2,4]. As shown in Fig. 3, the damage severity levels depend not only on seismic event intensity, but also on many factors such as in-situ stress, rock mass quality, rock brittleness, support effectiveness, local mine stiffness, geological structures, opening size and orientation, and excavation sequence. The vulnerability of an excavation must be considered to assess rockburst damage severity.

2.2.1. Influence of mine loading system stiffness on rockburst

When the stress reaches the strength of the rock, rock failure occurs. Rock failure can be stable or unstable, depending on the loading system stiffness [10,15]. Assume that a complete load–displacement curve for a volume of rock is defined by OABC and the mine loading system stiffness is defined by the slope of line AD (Fig. 4). In a stiff loading environment

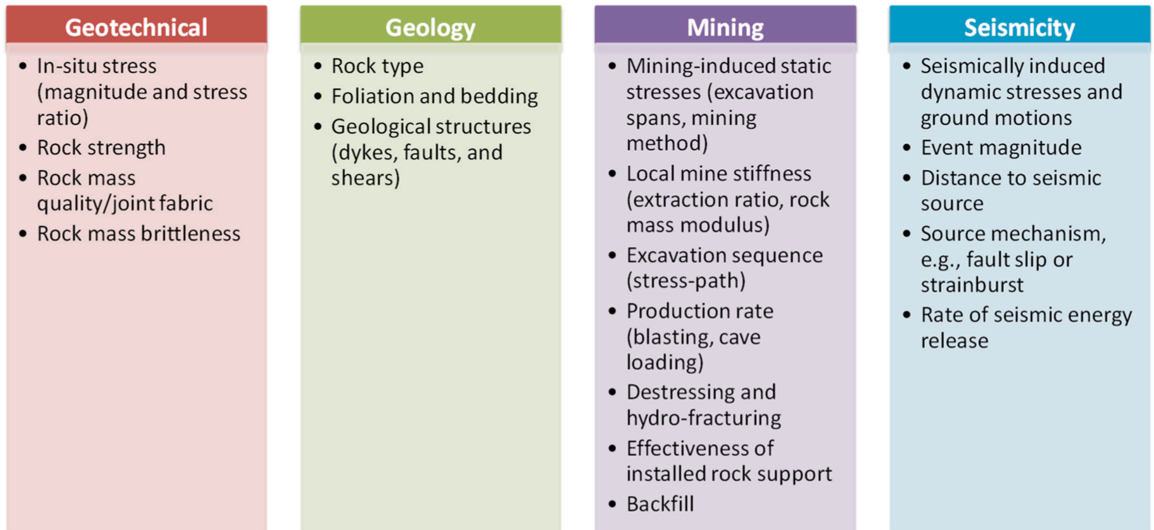


Fig. 3. Main factors influencing rockburst damage potential and severity [1].

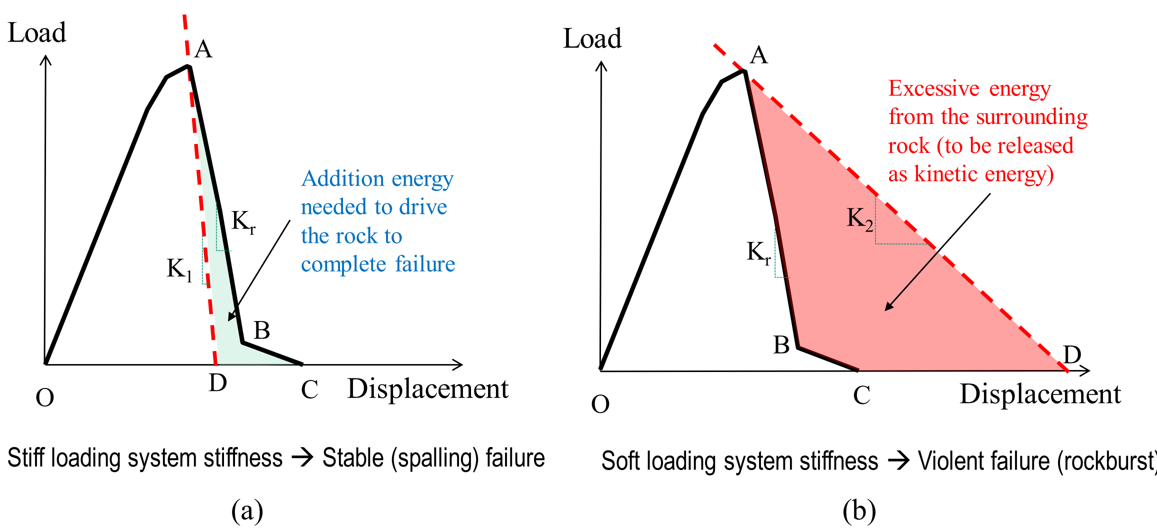


Fig. 4. Influence of mine loading system stiffness on rock failure: (a) stiff mine loading system stiffness leads to stable rock failure; (b) soft mine loading system stiffness leads to unstable rock failure or rockburst.

where the unloading stiffness K_1 is higher than the post-peak stiffness of the rock K_r, rock failure is stable without large excessive strain energy release, often in the form of spalling. In fact, from the peak load to the complete failure of the rock, additional energy, which is equal to the area under line ABC and above line AD, is needed to drive the rock failure process. However, in a soft loading environment where the unloading stiffness K_2 is much smaller than the post-peak stiffness of the rock K_r, rock failure is unstable with a large excessive strain energy release (which is equal to the area under line AD and above lines ABC) when the rock fails, and this phenomenon is what we know as a rockburst.

In underground mines, large geological structures such as faults, shears, and large joints can significantly reduce the mine loading system stiffness. A large extraction ratio can also reduce the mine loading system stiffness. This is why large rockbursts often occur at the late stage of mining when the extraction ratio is high and at locations close to large geological structures.

2.2.2. *Influence of rock type*

In general, brittle hard rocks are more burst-prone. This is because brittle hard rocks are stiff and strong, with elastic Young's moduli and UCS (uniaxial compressive strength) in the ranges of 50–100 GPa and 150–250 MPa, respectively. Stiff and strong brittle rocks can store a large amount of strain energy before failure. The ability to be able to store a high density of strain energy in a rock volume is a pre-condition for rockburst occurrence (Fig. 1). Most dykes are fine-grained hard rocks with high Young's modulus and UCS strength (200–400 MPa). Due to the modulus difference of different rock zones, high stress is trapped in the dykes. Hence, strainburst is frequently encountered when mining through dykes.

2.2.3. *Mining-related factors*

2.2.3.1. Mining methods and their impact on rockburst risk. The choice of mining methods, such as room-and-pillar, cut-and-fill, sublevel open stoping, or block caving, influences the stress distribution within the rock mass. High extraction ratios or rapid excavation rates can intensify stress concentrations, potentially leading to rockbursts. Evaluating the impact of mining methods on stress evolution is critical for designing safer mining operations.

Underground mining methods can be divided into entry and non-entry types. The entry-type mining methods, such as room-and-pillar, and cut-and-fill require workers to be present inside stopes. Any rockburst occurring inside the stope poses a great danger to workers. On the other hand, non-entry type mining methods, such as sublevel open stoping, vertical retreat mining, and block caving do not allow mining personnel to enter stopes. Hence, rockburst occurring inside the stopes pose no direct harm to workers.

2.2.3.2. Mining sequences and their impact on rockburst risk. The mining sequence determines the stress path and the rock failure process [4,16,17]. The mining sequence, which includes the order and methods by which mining activities are conducted, can impact the stress distribution and thus trockburst potential. Improper sequencing, coupled with inadequate ground support, can lead to heightened stress levels, creating conditions favorable for rockbursts. In particular, mining in seismically active areas can induce or exacerbate seismicity, increasing the risk of rockburst. If ground support measures such as backfill are not implemented promptly and effectively according to the mining sequence, there is an increased risk of rock mass instability and potential rockbursts.

2.2.3.3. Rock support. Excavation vulnerability is high when the stress-to-strength ratio is high. When the extraction ratio is high, the deformation potential is high, and if there is insufficient rock support rockburst could result. Insufficient rock support is the dominant factor that makes an excavation vulnerable to rockburst damage.

2.2.4. Dynamic loading and unloading

As shown in Fig. 2, many strainbursts occurring on drift roofs and walls can be triggered by dynamic loading from a fault-slip seismic event or a pillar burst event. Cai and Kaiser [1] classified strainbursts into self-initiated, seismically triggered, and dynamically loaded strainbursts. A strainburst is classified as a dynamically loaded strainburst when a remote seismic event causes a substantial dynamic stress increment near the damage location. This is often the case when a large fault-slip event triggers strainbursts at multiple locations. Furthermore, the dynamic stress can also temporarily reduce the clamping forces of wedges in the back of a drift, causing seismically-induced falls of ground.

2.3. Rockburst risk assessment and rockburst prediction

2.3.1. Rockburst risk

Rockburst risk is the likelihood or probability of experiencing a rockburst event and the potential consequences associated with such an event. Rockburst risk considers the interaction between the rockburst hazard, the excavation vulnerability, and the exposure or consequences in terms of safety, operational disruptions, and potential damage (Fig. 5).

Rockburst risk should not be confused with rockburst hazard. A hazard is defined as an event that has the potential to cause harm. Rockburst hazard refers to the inherent potential of a geological setting or mining area to experience sudden and violent releases of accumulated strain energy within the rock mass, leading to rockburst damages. These events, known as rockbursts, can result from the excavation process, inducing stress concentrations and dynamic loading in the rock mass. The rockburst hazard considers the geological and geotechnical characteristics of the rock mass, the stress field, and other factors that contribute to the likelihood of rockburst occurrences. In deep mining, rockburst hazards cannot be eliminated completely but can be reduced. To reduce rockburst hazards, actions or engineering measures are needed (Fig. 5). Because rockburst hazard lays the foundation for identifying potential burst-prone areas and understanding the geological complexities, the actions taken to reduce the rockburst hazard are mainly strategic ones, which are discussed in Section 3.3. Some tactical measures can also reduce the rockburst hazard.

Excavation vulnerability to rockbursts refers to the susceptibility of underground mine excavations, such as shafts, drifts, and stopes, to the occurrence of rockburst. The vulnerability of an excavation to rockbursts depends on various factors related to the geological, geotechnical, and operational conditions. Understanding and assessing excavation vulnerability is crucial for implementing effective rockburst risk management strategies.

Heal et al. [18] proposed to assess the rockburst damage severity by introducing an Excavation Vulnerability Potential index EVP, defined as EVP $=$ (E1$\times$E3)/(E2$\times$E4). This index takes the following four factors into account: stress condition (E1), total ground system support capacity (E2), excavation span (E3), and geological structures (E4). They related EVP to PPV (peak particle velocity) to assess the rockburst damage. Their ratings of E1 to E4 are such that a large EVP value means a large

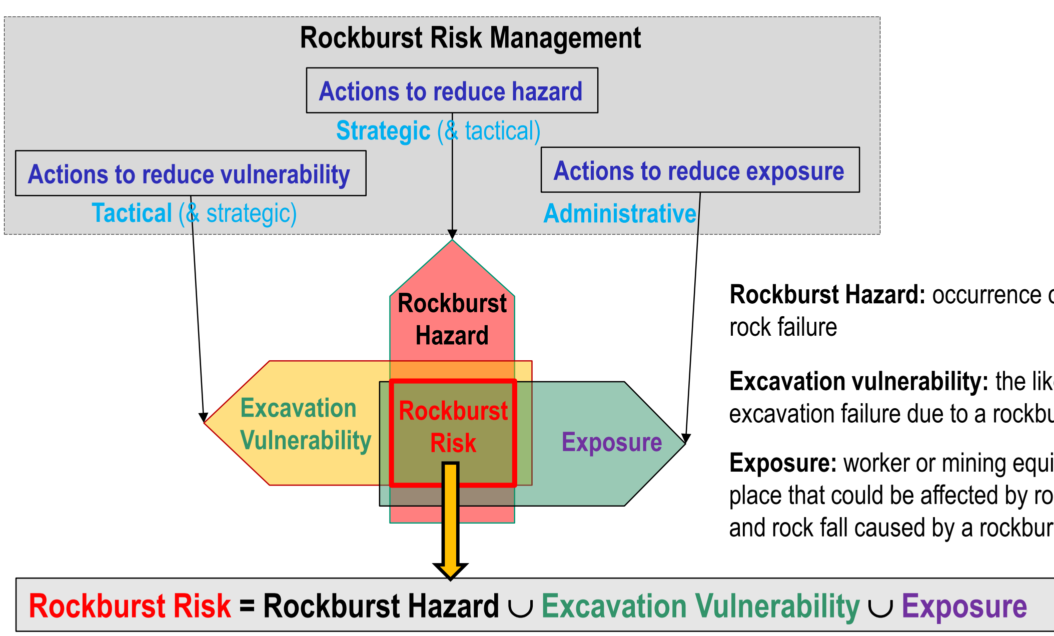


Fig. 5. Rockburst risk and its three routes. Rockburst risk is the union (indicated by ∪ in the equation) of rockburst hazard, excavation vulnerability, and exposure.

vulnerability.

From an engineering control point of view, it is practical and efficient to address the stress, rock support, and excavation size to reduce excavation vulnerability. The engineering measures, to be discussed in Section 3.4, are mainly tactical measures. The effectiveness of ground support systems plays a crucial role in reducing excavation vulnerability. In fact, ground support is the most important and effective tool to reduce excavation vulnerability. Some strategic measures can also reduce the excavation vulnerability. For example, mining sequence can impact excavation vulnerability. Sequencing of mining activities, such as stoping or pillar extraction in an improper sequence, can elevate stress levels and contribute to high excavation vulnerability.

Exposure related to rockburst hazard refers to the elements or entities within a mining environment that are subject to potential harm or adverse impacts in the event of a rockburst. The exposure can encompass various aspects of mining operations, including personnel, infrastructure, equipment, and the overall safety and continuity of mining activities. The primary exposure is to the safety of miners and other personnel working in the mine. Rockbursts can pose direct physical risks, including fatal injuries from falling rocks or ejected rocks, making the safety of workers a critical concern. Underground infrastructure, such as drifts and stopes, is exposed to potential damage during a rockburst; the structural integrity of these excavations can be compromised, leading to collapses, operation disruption and downtime, equipment damage, and potential revenue loss. Effectively addressing these exposures involves implementing rockburst risk mitigation measures, including real-time MS (microseismic) event monitoring, emergency response planning, exclusion and re-entry protocols, automation, and ongoing assessment and adaptation of mining practices to minimize the impact of rockburst. Those measures are mainly administrative ones, which will be discussed in Section 3.5.

Understanding the factors and conducting a comprehensive rockburst risk assessment allows mining engineers to implement targeted control measures, such as optimized mine design, support systems, destress blasting, and effective monitoring, to reduce the risk of rockbursts in excavations. A bow-tie analysis of rockburst risk is presented in Section 3 to generate a global picture of the issue of rockburst risk and its control and mitigation.

2.3.2. *Rockburst warning and attempts at prediction*

Rockburst hazard assessment are important aspects of rockburst risk management in deep mining operations. The ability to anticipate and respond to potential rockbursts is crucial. The integration of multiple monitoring techniques, advanced data analysis, and predictive numerical modeling can contribute to a robust rockburst warning system. By providing early indications of potential rockbursts, the system can empower mining operations to implement timely and effective rockburst risk control and mitigation measures, thereby enhancing overall safety and minimizing the impact of rockburst events.

Many researchers have proposed empirical criteria in an attempt to predict rockburst or rockburst potential [19]. For example, Hoek and Brown [20] used the stress ratio σ_{max}/σ_c to predict rockbursts, where σ_{max} is the maximum tangential stress around the tunnel and σ_c is the UCS of rock. When the stress ratio is in the range of < 0.34, 0.34–0.42, 0.42–0.56, 0.56–0.72, and > 0.72, it predicts no rockburst, light, medium, heavy, and severe rockbursts, respectively. Neyman et al. [21] used the energy ratio $W_{et} = E_e/E_p$ to predict rockburst, where E_e is the elastic energy stored in the rock through loading up to the peak stress and E_p is the dissipated energy in the creation of micro-fractures and plastic deformation of the rock in one cycle of loading. It predicts no rockburst, light, medium, and heavy rockbursts when the energy ratio is in the range of < 2.0, 2.0–3.5, 3.5–5.0, and > 5.0, respectively. Peng et al. [22] proposed to use the compressive to tensile strength ratio σ_c/σ_t to predict rockbursts. When the strength ratio is in the range of > 40, 40–26.7, 26.7–14.5, and < 14.5, this criterion predicts no rockburst, light, medium, heavy, and severe rockbursts, respectively. The stress ratio, energy ratio, and strength ratio indicate the stress level, energy storage potential, and rock brittleness, respectively. Satisfying only one condition shown in Fig. 1 does not necessarily lead to rockbursts. This is why applying those empirical criteria rarely gives accurate predictions of rockbursts.

Realizing the shortcomings of the single index criteria, Gu [23] proposed a multi-index rockburst prediction criterion. Four conditions, i.e., (1) $\sigma_c \geq 15\,\sigma_t$, (2) $W_{et} \geq 2.0$, (3) $\sigma_{max} \geq 0.3\sigma_c$, (4) $K_v \geq 0.55$ (where $K_v = (v_p/v_s)^2$, v_p and v_s are the p-wave and s-wave velocities of the rock mass), must be satisfied simultaneously for a rockburst to occur. A five-index criterion for rockburst prediction was proposed by Zhang et al. [24]. These multi-index criteria are better than the single index ones; however, all of them lack the soft loading system stiffness criterion shown in Fig. 1, which is a required criterion for rockbursts to occur. The mine loading system stiffness is extremely difficult to assess, which is why it is not possible to predict rockbursts using either single or multiple index empirical criteria.

MS monitoring could be a potentially useful tool for rockburst warning. Implementing a real-time monitoring system enables rapid data analysis and decision-making. Advanced algorithms and machine learning techniques can process large datasets, identifying patterns and anomalies that may precede rockburst events.

However, identifying precursors to rockbursts from MS monitoring data is not straightforward in mining. An increase in seismic activity, which indicates increasing stress in the rock mass that may potentially lead to a rock failure, can serve as a warning sign of potential rockbursts. This could be useful for providing rockburst warnings in civil tunnels because the stress concentration is near the tunnel face [25]. The timing and magnitude of the rockburst event are still impossible to predict. A change in increased methane gas emissions in coal mines can also serve as an indicator of heightened stress levels in the rock mass. Analysis of MS monitoring data using various techniques, such as clustering analysis, focal mechanism analysis, temporal distribution analysis, cumulative energy release analysis, migration of MS activity, can reveal some characteristics of the MS events; however, it is not possible to establish a consistent correlation between those characteristics and large rockbursts that occurred. In summary, the occurrence of large seismic events in a mine or a mining area is somewhat random concerning the time of occurrence, location, and event magnitude.

Numerical modeling is now widely used in mine design. The predictive capabilities of numerical modeling depend on the accuracy of input parameters, the understanding of the complexity of the geological and geotechnical conditions, and the sophistication of the modeling techniques employed. Based on current technology, it is not possible to know the accurate geological conditions in a mine; it is also a challenge to assess the rock mass mechanical properties accurately; there are also limitations inherent in the modeling approach, e.g., the constitutive model and failure criterion of rock masses. Hence, it is not possible to use numerical modeling to predict rockburst. While numerical models cannot predict rockbursts with certainty, they provide insights into the behavior of the rock mass, stress distribution [26], the influence of fault on rockburst [27], and potential failure mechanisms [28,29]. Numerical modeling is most effective when integrated with other monitoring and assessment methods, creating a comprehensive approach to rockburst hazard management in deep mining.

Various mathematical models and advanced computational techniques, including uncertainty theory, artificial neural networks (ANN), fuzzy set theory, deep learning, machine learning algorithms, and data fusion have been explored in the context of predicting rockbursts and assessing rockburst risk [30]. Each of these approaches brings unique strengths and considerations to the field of rock mechanics and rock engineering. For example, ANNs have been employed for rockburst prediction by training on historical data, including seismic events, stress conditions, and mining parameters. Deep learning models can be trained on large datasets to extract complex features and relations. Convolutional Neural Networks (CNNs) and Recurrent Neural Networks (RNNs) are examples of architectures used for analyzing seismic and geotechnical data related to rockburst hazard. Machine learning algorithms can analyze diverse datasets related to geology, seismicity, stress conditions, and mining operations to identify patterns and contribute to rockburst risk assessment. While these mathematical models and computational techniques show promise, it is crucial to recognize the challenges and limitations associated with their application to rockburst prediction. The “randomness” of the occurrence of rockburst is one of the biggest obstacles. The availability of high-quality data is another obstacle because most mining companies keep the data proprietary and are unwilling to share data with other parties. Furthermore, the representativeness of the training dataset and the incorporation of domain knowledge are also critical. While the future of applying these mathematical models to predict rockburst might be promising, currently we cannot rely on them to assist us in rockburst prediction.

There is a great need for the ability to predict rockbursts. Some researchers believe that installing an MS monitoring system in a mine will allow for the prediction of rockbursts. Some believe that AI will someday be able to predict rockburst in deep underground mines. Many intelligent individuals worldwide have devoted many years to earthquake prediction. There are various opinions on the feasibility of earthquake prediction, and the author of this paper do not want to engage in this controversy. The question should be asked: even if we can predict earthquakes, then what? Before an earthquake occurs, we can avoid staying in buildings or driving on overpasses; however, after the earthquake, if the houses are destroyed, where do we live? If the roads are damaged, how do we travel by car? From a societal perspective, strengthening earthquake-resistant design for buildings and infrastructure is the important aspect. The author of this paper prefers living in earthquake-resistant buildings to have peace of mind than having the ability to predict earthquakes, but having to live in poorly designed and constructed buildings.

Similarly, even if we can predict rockbursts, so what? Assume that we correctly predict a rockburst’s occurrence time, location, and magnitude, then, we can evacuate workers from the mining area in a timely fashion. However, if we do not support the drifts and stopes well against rockburst damage, severe damage to mine openings might lead to disruption of mining operations. In extreme cases, it might lead to mine closure to the occurrence at the Falconbridge Mine in Sudbury, Ontario, Canada in 1984. The mine had to be permanently closed after several rockburst events [31]. We want the workers to be safe no matter what; we also want the investment to be safe.

Like earthquakes, large rockbursts are considered Black Swan events, characterized by three key features: (1) they are unpredictable, (2) the events have significant consequences once they occur, and (3) they become explainable in hindsight [32]. Therefore, instead of focusing on earthquake prediction or rockburst prediction, it is essential to focus on earthquake-resistant design for buildings and rockburst-resistant support in deep mines. Instead of telling others “I told you so” after a devastating rockburst event, let us focus on being well-prepared for controlling and reducing the consequences of rockburst.

In the next section, we will first conduct a bow-tie analysis of rockburst risk and then explore the diverse range of control and mitigation methods that can be employed to address the challenges posed by rockbursts in deep mining operations.

3. Rockburst risk control and mitigation methods

Rockburst risk control and mitigation are essential in deep mining for several compelling reasons, primarily focused on ensuring the safety of personnel, protecting infrastructure, and maintaining operational efficiency [33–37]. Effective rockburst risk control and mitigation requires a combination of proactive design considerations, strategic planning, and the implementation of targeted engineering control and mitigation measures. In this section, we first conduct a bow-tie analysis of rockburst risk, followed by a discussion of the hierarchy of controls. Then, strategic, tactical, and administrative control methods are presented. Whenever possible, case examples are used to highlight the control and mitigation methods. The examination of specific case examples provides valuable insights into the real-world application of rockburst risk control and mitigation strategies, offering lessons learned and best practices.

3.1. Bow-tie analysis of rockburst risk

Bow-tie analysis is a risk assessment methodology that visually represents the relation between potential causes, consequences, and preventive or mitigation barriers of a specific hazard. In the context of rockbursts, a bow-tie analysis offers a concise and structured overview of the factors contributing to rockburst risk and the corresponding control and mitigation measures.

Fig. 6 presents a detailed bow-tie analysis of rockburst. On the left side of the rockburst bow-tie, potential threats or causes of rockbursts are depicted. Those include high mining-induced stresses, large geological structures such as faults and shears, poor mine design, large extraction ratio, and insufficient rock support. On the right side of the rockburst bow-tie, the potential consequences or effects of a rockburst are depicted. This may involve injury to personnel, fatalities, damage to mine infrastructure and mining equipment, loss of orebody, and operational disruptions. The central knot of the bow-tie represents the "Top Event," which is the occurrence of a rockburst. This is the focal point where threats converge with consequences.

Between the causes and the rockburst event lie the preventive barriers or control measures that can reduce the likelihood of a rockburst, which may include improved mine design and mining sequence, preconditioning of ground, rock support, etc. Between the rockburst event and the consequences lie the mitigation barriers or mitigation measures that can minimize the impact of a rockburst, which may involve evacuation procedures and re-entry protocols, use of remote mining equipment and PPE (personal protective equipment). Among all the controls to manage the rockburst risk, the critical controls are improving mine design and mining sequence as well as rock support. Based on the 80/20 Rule (Pareto principle), it is believed that 20% of effort spent on those critical controls can manage 80% of the rockburst risk.

The rockburst bow-tie presented in Fig. 6 offers a clear and visual representation of the complex relation between causes, consequences, and control measures associated with rockbursts. It facilitates effective communication of rockburst risks and control methods to stakeholders, including miners, engineers, management, and safety personnel. It also enables proactive rockburst risk management by identifying potential threats and implementing preventive measures to reduce the likelihood of rockbursts in deep mining. In the next subsection, we discuss the hierarchy of controls in the context of rockburst risk control. The rockburst risk control and mitigation methods are presented in Sections 3.3 to 3.5.

3.2. Hierarchy of controls

Reducing rockburst hazard and excavation vulnerability as well as controlling the exposures to rockburst hazards in underground mines are vital to protecting workers and investment. The hierarchy of controls is a way of determining which actions will best control hazards and exposures. As shown in Fig. 7, the hierarchy of controls has five levels of actions to reduce or remove hazards. The preferred order of action based on general effectiveness is from “Elimination” to “PPE”. Elimination removes the rockburst hazard at the source. Substitution is using a safer alternative to the source of the rockburst hazard. Elimination and substitution are best used at the mine design or development stages. They are considered the strategic control measures, which are the most effective and often the cheapest options. Engineering controls reduce or prevent rockburst hazards from coming into contact with workers and equipment and they are tactical control measures. Administrative

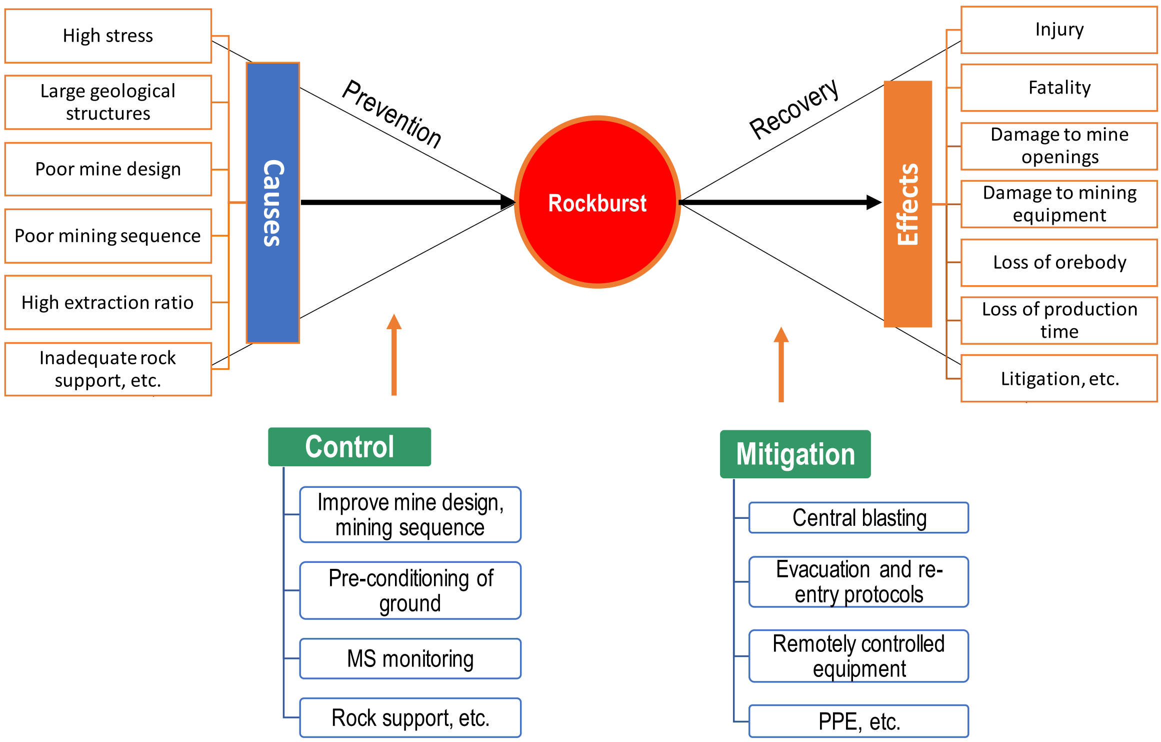


Fig. 6. Bow-tie analysis of rockburst risk.

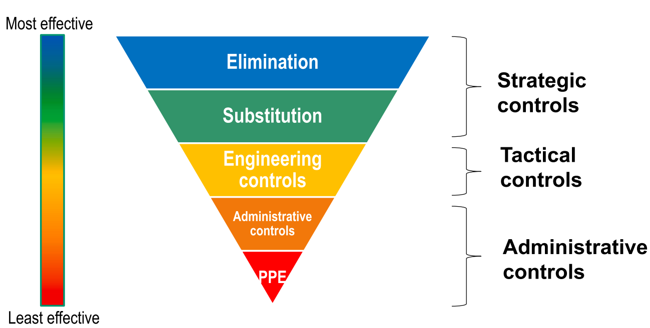


Fig. 7. Hierarchy of controls (reproduced and modified based on the image at https://www.cdc.gov/niosh/topics/hierarchy/default.html).

controls establish work practices that reduce the duration, frequency, or intensity of exposure of workers to hazards. PPE, as a part of administrative control, is equipment worn by workers to minimize exposure to hazards and it is the least effective measure in the hierarchy of controls.

In the context of rockburst risk control, the practical controls, following the guidelines of the hierarchy of hazard control shown in Fig. 7, are presented in Fig. 8. Again, these controls can be grouped into three: strategic, tactical, and administrative controls. They are ordered similarly to the hierarchy of controls, i.e., from the most to the least effective. In the following subsections, we discuss each control and mitigation method to address the rockburst risk.

3.3. *Strategic engineering control methods*

Strategic engineering control measures are high-level, overarching actions and policies designed to manage and mitigate risks at a broader organizational or project level. These measures are often long-term and involve comprehensive planning and decision-making. In contrast, tactical engineering control measures are specific, detailed actions and procedures implemented at a more operational level. These measures focus on day-to-day activities and address immediate or short-term risks. Both levels of control are essential for a robust and effective rockburst risk management framework. In this section (Section 3.3), the author

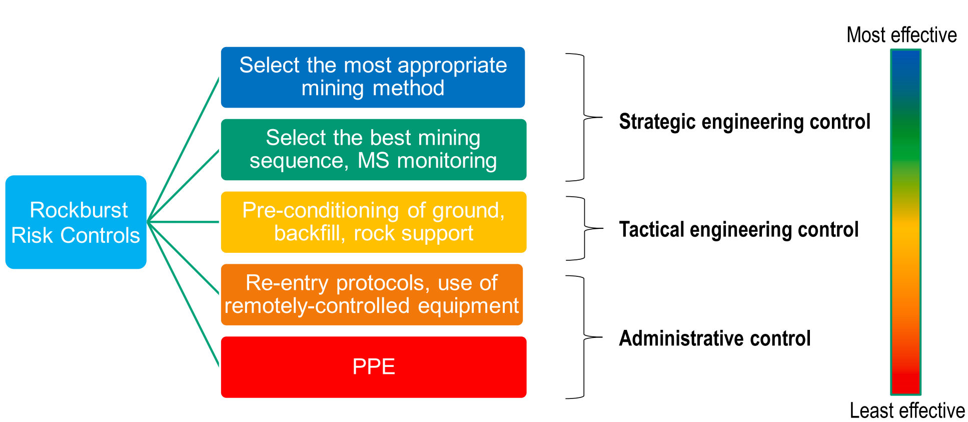


Fig. 8. Rockburst risk controls.

presents the strategic engineering control measures for rockburst risk control and mitigation. The tactical engineering control measures are presented in Section 3.4 and the administrative control measures are presented in Section 3.5.

3.3.1. Mine design considerations

Thoughtful mine layout, stope design, and pillar design are fundamental to minimizing the risk of rockburst. Good engineering designs, which consider the geological characteristics of the deposit, the mining method, and the mine layout to reduce the stress concentration and increase the mine system stiffness, will contribute to a more stable underground environment. Traditional mine design has a design goal of minimizing cost and maximizing profit. In deep mines, this mine design goal must consider the cost associated with rockburst risk management. The financial impact due to severe and repeated rockbursts must be considered in the design process.

3.3.1.1. Mining method. Underground mining method selection needs to consider many factors such as orebody geometry, size, grade distribution, in-situ stress, rock mass properties, capital and operation expenses, safety regulations, environment, economic, and labor market considerations. Several underground mining methods are considered more suitable for mitigating rockburst risk. In this aspect, non-entry mining methods, such as blasthole stoping, sublevel stoping, vertical retreat mining, sublevel caving, and block caving are better than the entry-type mining methods such as shrinkage stoping, cut-and-fill, and room-and-pillar mining. Non-entry mining methods do not allow workers to enter stopes, which can reduce the exposure of workers to rockburst occurring inside the stopes. The adopted mining method can influence the rockburst damage potential and severity. For example, most mines that convert from cut-and-fill to longhole stoping experience larger rockbursts [38]. Non-entry methods such as block caving may pose a risk of uncontrolled caving, leading to sudden stress releases and rockbursts as well as air blasts [39].

Macassa Mine in Canada started with the shrinkage mining method. As the mining progressed, the rockburst problem intensified at the mine site. At depth, the mining method was changed to overhand cut-and-fill mining using development waste as rockfill. To further address the rockburst issue, the mining method was changed to longhole mining with paste fill [38].

The cut-and-fill mining method is widely used for irregular orebodies and varying rock conditions. It provides active support through backfilling, reducing stress concentrations. It also allows for control over ground stability to reduce dilution. Cut-and-fill mining can be conducted using the overhand cut-and-fill mining method (Fig. 9(a)) or the underhand cut-and-fill mining method (Fig. 9(b)). At the Lucky Friday Mine in the USA, the traditional overhand cut-and-fill mining method was used until 1986. Due to several fatalities caused by rockbursts, a switch over to the Lucky Friday Underhand Longwall (LFUL) method was introduced in mid-1987 to manage the rockburst risk [40]. No rockburst fatalities have occurred at the Lucky Friday Mine since the LFUL method was put into practice. Although the change in mining method limited mining to only three mechanized stopes on a single level, the increased safety of the LFUL was considered a reasonable trade-off.

Fig. 9(a) and (b) show the high stress concentrations in the stope mined using the overhand and underhand cut-and-fill mining methods. The underhand cut-and-fill mining is generally a safer method in high stress grounds due to the following two factors: (1) it reduces the risk of personnel exposure to highly stressed ground in the back (in the case of overhand cut-and-fill mining) which can be subject to adverse seismicity; (2) it allows mining to take place underneath the backfill (an engineered material) that requires a ground support system for stabilizing gravity-driven risks exclusively.

Using the underhand cut-and-fill mining, the rockburst hazard on the back is eliminated. However, in highly stressed ground, the risk of floor rockburst during mining can be high, posing a risk to workers. To address this floor-bursting challenge, Lucky Friday Mine developed the Underhand Closed Bench (UCB) mining method [41], as illustrated in Fig. 9(c). Between 2020 and 2022, the mine started to experiment to destress the floor through destress blasting, using 3 in, 24 ft deep blasthole along 250 ft of the stope floor and 25,000 lb of explosives to blast 10,000 t of rock beneath the floor at once. This released over 90% of the total seismic energy around the stope within 12 hr of the blast. It also produced more fragmented ores than the conventional underhand cut-and-fill mining method, rendering a safer and more productive mining method. The drill stope was mucked and then backfilled first, followed by mucking one stope height of the blasted ore. The stope was backfilled and the second stope height was mucked and backfilled. Because the large blast could potentially fracture the rock and the unmined ore below the blasted stope, the stress concentration in the

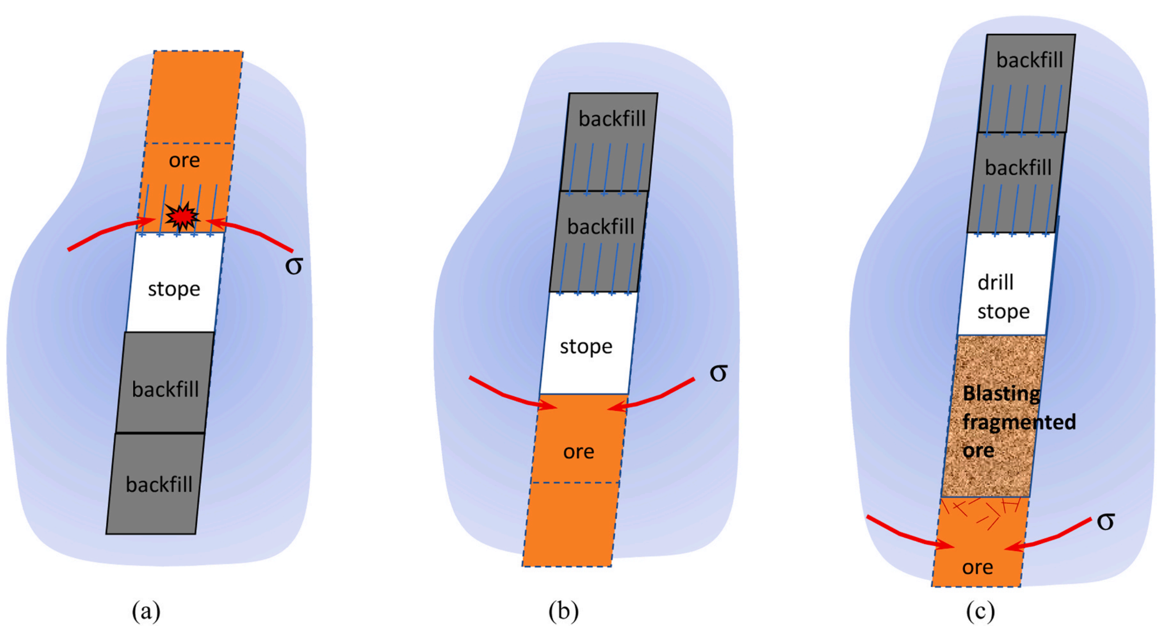


Fig. 9. Concentrations of the maximum principal stress: (a) overhand cut-and-fill mining; (b) underhand cut-and-fill mining; (c) UCB mining.

unmined ore was pushed further away from the floor, reducing the risk of floor burst when the last stope height was mucked. In addition, the risk of face burst when driving the next round of drill stope was also reduced due to the de-stressing caused by fractured ores.

Longwall mining was used widely in South Africa to mine the tubular orebodies. Sequential grid mining has been employed as the primary mining strategy at the AngloGold West Wits Elandsrand Mine since 1988. Handley et al. [42] showed that the seismic hazard due to potentially damaging events was far lower in a sequential grid mine than in an equivalent longwall mine. The examples of Lucky Friday Mine and Elandsrand Mine demonstrate that one should not stick to the mining method selected during the feasibility study. Mining method selection and changes of the method should be considered as a rockburst risk control measure.

It is important to note that there is no one-size-fits-all answer to which mining method is better in terms of rockburst risk control. There is a need for a careful evaluation of mining methods concerning the geological setting to mitigate the rockburst hazard effectively. The adaptability of the mining method to specific orebody characteristics and geotechnical conditions is crucial for successful rockburst risk control. A comprehensive cost-benefit analysis, considering ore recovery, operational costs, and rockburst risk mitigation measures, should guide the selection of the most suitable mining method.

3.3.1.2. Mine layout and pillar design. The layout of underground workings is one of the critical factors in mitigating rockburst hazards. Mining engineers must consider the geological characteristics of the deposit in the mine infrastructure layout, including the presence of fault zones, joint systems, in-situ stress, and varying rock types. In deep mining, they should develop a layout that prioritizes rockburst risk reduction while optimizing ore recovery and operational efficiency. A comprehensive geological model informs the positioning of main access drifts, crosscuts, and stopes, aiming to minimize stress concentrations and promote stable excavation. Numerical modeling can be utilized to simulate stress distribution within the rock mass and assess the impact of mining-induced stresses on the stability of excavations.

An underground mine typically has many drifts for transportation and drilling blast holes. Whenever possible, the drifts should be aligned with the direction of the maximum horizontal stress to minimize stress concentration. Permanent openings such as shafts, ramps, and crusher stations should be located further away from the orebody to be mined.

Pillar design is a key element of rockburst control, involving the determination of appropriate dimensions and spacing to provide necessary support to the surrounding rock mass [43]. The size and shape of pillars depend on factors such as depth, the characteristics of the rock mass, and the chosen mining method. Pillar bursts often occur when the extraction ratio is high. For example, mines using the room-and-pillar mining method that experienced cascading pillar failure generally had an extraction ratio greater than 60% [44]. Hence, in room-and-pillar mining, limiting the extraction ratio is key to reducing the risk of pillar burst and pillar run (chain reaction failure of multiple pillars).

3.3.1.3. Pillar-less mining. Block caving and sublevel caving are pillar-less mining methods where the entire orebody is extracted, leaving no pillars behind for stope support. In conventional open stoping of large orebodies, sill or rib pillars are left in place for ground support. At depth, the sill or rib pillars can store a large amount of strain energy, increasing the risk of rockburst.

Fig. 10 shows some stopes at Creighton Mine in Canada at the deep levels from 6400 to 7810 ft (1950–2380 m). Below 2000 m, mining was conducted using the pillar-less open stoping method with a V front. The avoidance of pillars within a center-out sequence pushes the high stresses into the abutments, providing a zone of relaxation below mined-out areas for subsequent mining. A similar pillar-less mining method was used at Brunswick Mine to address the rockburst problem. The mine

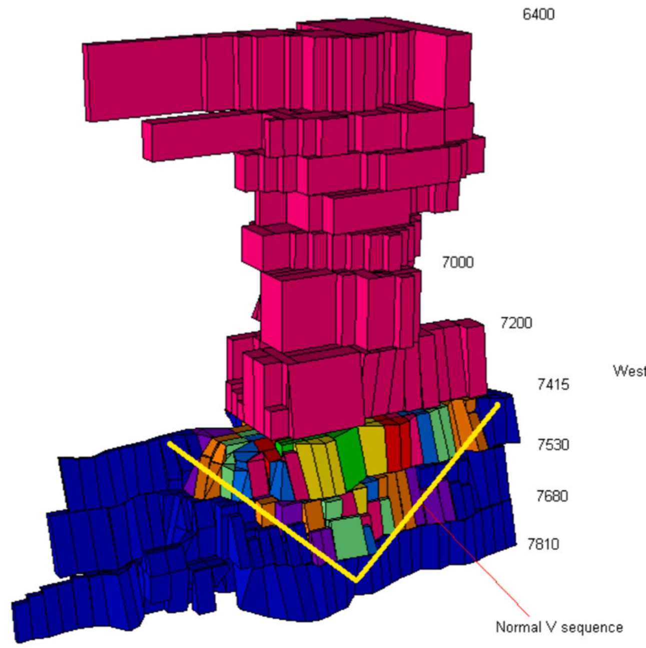


Fig. 10. Pillar-less open stoping and a top-down center-out sequence at Creighton Mine [45]. The depths of the stope levels are in ft.

changed the primary-secondary stoping to the pyramidal pillar-less mining method with each mined block paste backfilled before the mining of the adjacent block [38].

It is evident from the above examples that for effective rockburst hazard control, we need to apply the dynamic mine design principles that allow for adaptive planning and design based on ongoing monitoring and risk assessments.

3.3.2. Mining sequence

The stress change in a rock mass is stress path or excavation sequence dependent [16]. Different mining sequences will generate different stress distributions in the rock mass, impacting rock failure and deformation of mine excavations. Numerical modeling can be used to determine the optimal sequence of stope excavation to avoid converging mining fronts and reduce excessive stress buildup to reduce rockburst hazards.

Using a simple numerical model, Hedley [4] demonstrated that a stoping sequence retreating from faults or shears results in a more even seismic energy release, reducing the risk of large rockbursts. As shown in Fig. 11, if the mining sequence is approaching the fault (advancing), there will be no seismic energy release in the first six mining steps but there will be a very large energy release at mining Step 11. In addition, the total release of seismic energy in the advancing sequence was about 25% greater than that by the retreating sequence. In the advancing sequence case, the rockburst risk is high and rockburst support might be needed to reduce the risk. Therefore, in the presence of an active geological structure, it is advisable to mine away from the structure rather than toward it. Numerical modeling can be employed to design the optimal sequence, aiming to minimize mining-induced shear stress on geological structures.

Center-out mining sequences in open stoping and transverse cut-and-fill stoping are widely practiced to reduce rockburst hazards. The center-out, bottom-up mining sequence was practiced in INCO's mines in Sudbury, Ontario, Canada, starting in the early 1960 s [46]. The goal was to manage stress concentrations and control the release of accumulated strain energy, especially in situations where there was a risk of rockburst caused by high-stress concentrations. The mining sequence began with the extraction of ore from the lower portions of the orebody, starting from the central region first. As mining progresses, ore

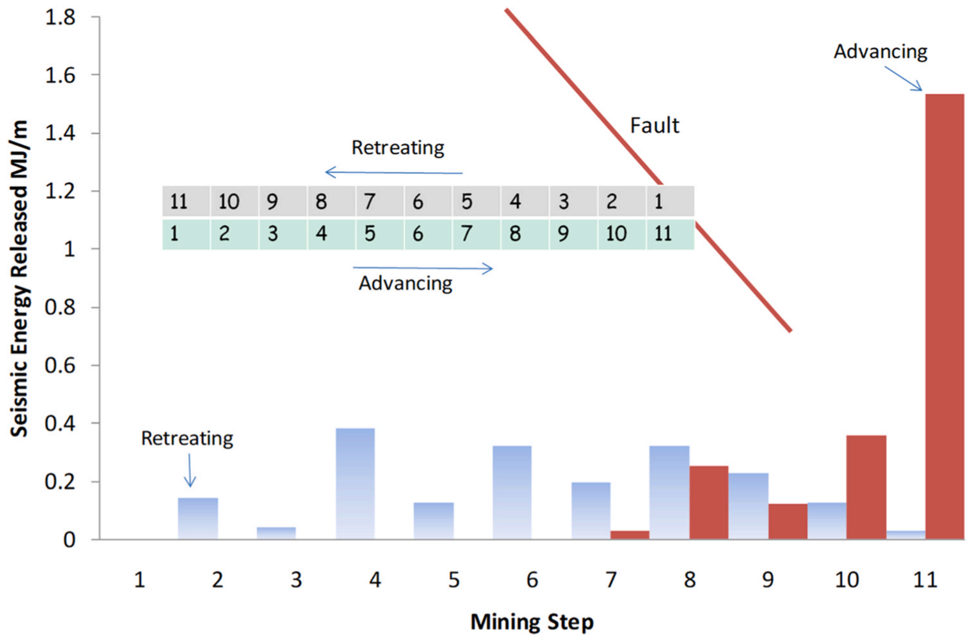


Fig. 11. Impact of mining sequence on rockburst hazard (modified from Hedley [4]).

extraction continued systematically, moving from the bottom to the top and from the center to the periphery. This is often referred to as the bottom-up "chevron" mining sequence (Fig. 12(a)).

A variation of the bottom-up "chevron" mining sequence is the top-down "chevron" mining sequence. The top-down "chevron" mining sequence has been successfully used at LaRonde Mine [47]. With the modified top-down sequence, high-stress concentration on the seismically active east side of the mine was avoided due to the early extraction of the sill pillar on that side.

Using either a bottom-up or a top-down, center-out sequencing aims to push stress towards the sides and avoid diminishing pillars (Fig. 12 (b)). The effect of the bottom-up, center-out sequencing on stress distribution can be seen in Fig. 13, which shows the clustering of MS events around the stoping areas in Nickel Rim South Mine in Sudbury, Ontario, Canada.

In block caving, stress shadowing can be used for mine development to reduce the risk of rockbursts and other geotechnical issues. In conventional block caving development, the production level is developed first, or ahead of the development of the undercut level. In this fashion, drawpoint development locations experience high stresses, presenting a significant risk of rockburst. Employing the pre-undercut sequencing method creates a stress shadowing zone in the drawpoint development area, enhancing the safety of the excavation process in these regions (Fig. 14).

3.3.3. MS monitoring

Microseismic (MS) monitoring plays a key role in detecting and understanding the precursors and manifestations of rockbursts. MS monitoring involves the deployment of seismometers, strategically placed within the mining environment. These sensors continuously capture and record seismic events caused by rock fracturing and failure, providing valuable data on their location, magnitude, frequency, and other source parameters such as apparent stress, apparent volume, corner frequency, source radius, source mechanism, etc. [49]. When combining MS monitoring data with other data such as geology, geotechnical, numerical modeling, and deformation and stress monitoring data, a comprehensive rockburst hazard assessment (RHA) can be conducted [50–52].

MS monitoring allows for the identification of stress changes and potential rockburst-prone zones by analyzing the subtle seismic events and patterns. Early warning systems focus on identifying indicators of impending rockbursts. Increases in seismic activity, coupled with other indicators such as increased ground deformation, gas emissions, or anomalous geotechnical measurements can serve as signals of heightened stress levels in the rock mass. Recognizing these signs allows for proactive measures such as evacuation, temporary work stoppage, or reinforcement of critical areas to mitigate the rockburst risk.

In general, it is not possible to predict rockburst using MS precursors such as energy accumulation and a quiet period of MS activities before rockburst. However, MS monitoring provides data for RHA, numerical model calibration, and exclusion and re-entry protocols. It is thus considered a strategic tool for rockburst risk management.

3.3.4. Rockburst hazard assessment (RHA)

Although it is not possible to predict rockburst (i.e., to tell the time of occurrence, location, and magnitude), we can identify areas in a mine with a high rockburst potential using RHA. RHA is a critical aspect of risk management in deep mining operations. Seismically active mines need a RHA plan for short, medium, and long terms.

RHA is conducted by integrating geological (e.g., rock types, fault zones, joints), geotechnical (e.g., in-situ stress, rock mass classifications), MS monitoring, numerical modeling (distribution of stress within the rock mass), ground support (installed capacities, support damage), and deformation monitoring data to understand and mitigate the rockburst risk and to develop effective strategies for ensuring safety and stability of underground excavations. Conducting an RHA is an iterative process that requires collaboration among geologists, geotechnical engineers, and mining experts. The assessment should be regularly reviewed and updated to account for changes in mining activities, ground conditions, and new data obtained from monitoring systems.

In addition to commonly used tools for geological, geotechnical, and numerical modeling, engineering tools that can be used to conduct RHA include Geoscience INTEGRATOR from Mira Geoscience, mXrap from ACG, and RBHA software from IMS. The RBHA tool can be used for rockburst hazard forecasting for different design stages, scenario assessment, determination of the probability of exceedance, and annual rate of exceedance.

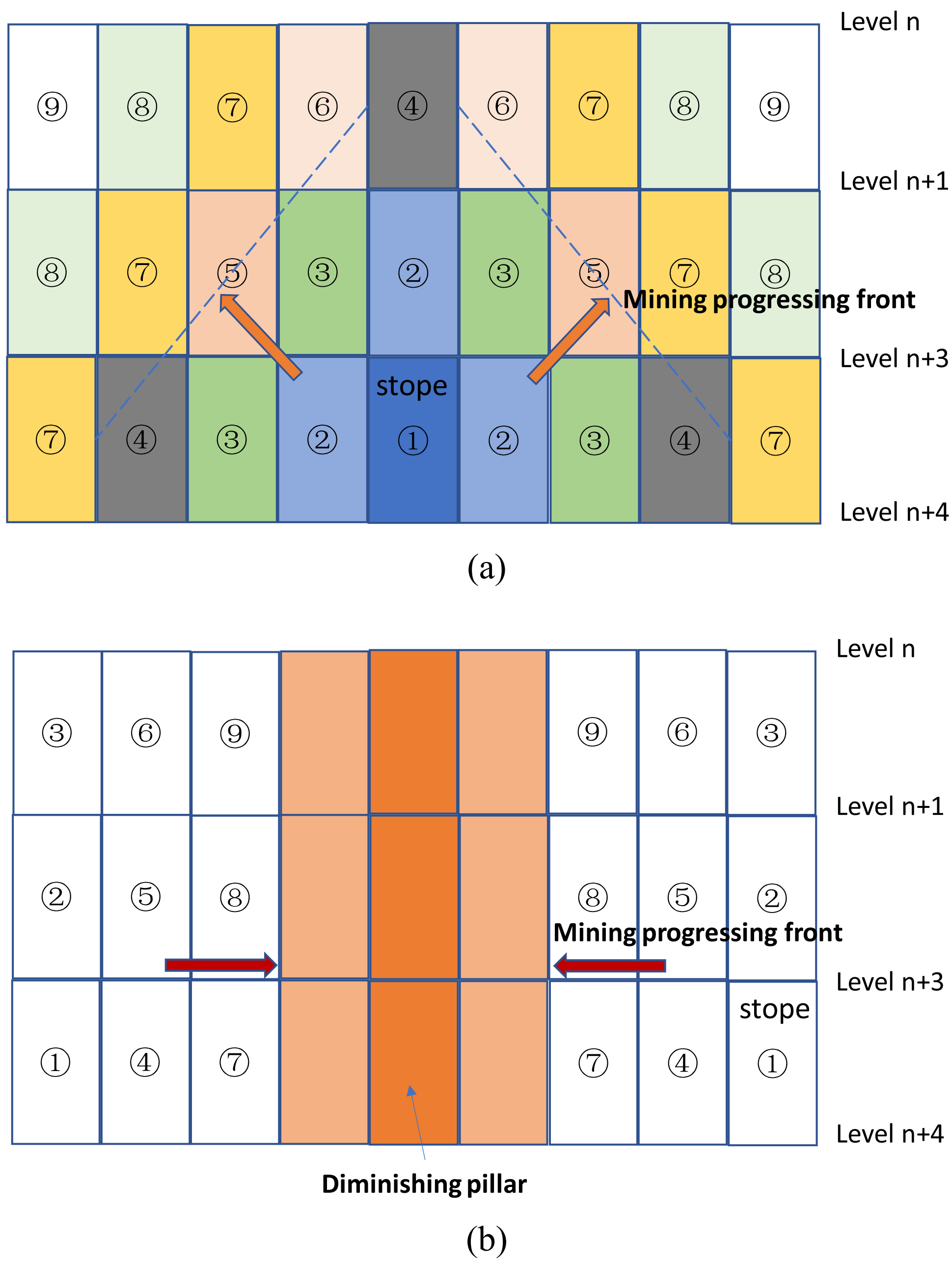


Fig. 12. (a) Bottom-up "chevron" mining sequence; (b) mining sequence leading to diminishing pillar.

3.4. Tactical engineering control methods

3.4.1. Pre-conditioning of ground

Pre-conditioning of ground in underground mining involves deliberately inducing controlled fractures to alter the stress in the rock mass or to change the rock properties by injecting water or chemicals into the ground to reduce the risk of rockbursts. Several methods for pre-conditioning ground, such as de-stress blasting, hydro-fracturing, and water injection, can be utilized. Regular monitoring and assessment are needed to evaluate the effectiveness of pre-conditioning of the ground and make necessary adjustments based on the evolving conditions of the rock mass.

In high-stress environments, smooth blasting or perimeter blasting minimizes damage to rocks near the excavation boundary, increasing the chance of strainburst because the rock near the wall of an excavation can sustain a higher tangential stress before failure. By inducing controlled fractures in the rock mass, de-stress blasting aims to manage stress release during excavation, minimizing the risk of rockbursts.

De-stress blasting has been used for a long time in highly stressed grounds to prevent and mitigate strainbursts [35, 53–55]. De-stress blasting involves the use of explosives to create fractures in predetermined locations within the rock mass. Some mines conduct de-stress blasting to fracture rock ahead of the tunnel, shaft, or stope face to reduce the strainburst risk during mine development. Field experiments conducted in Canadian and South African mines demonstrated that de-stress blasting effectively reduced the risk of face-bursting and gained widespread implementation. Stope de-stress blasting [56] and sill pillar de-stress blasting [57] were also conducted in some mines.

The design of these de-stress blasts should be carefully planned to induce controlled fracturing without causing significant rock damage. Various design parameters need to be considered, including the number of boreholes, borehole length and location, explosive charge, timing, sequencing, etc. It is important to note that there is no standard for de-stress blasting design. Field monitoring techniques, such as MS

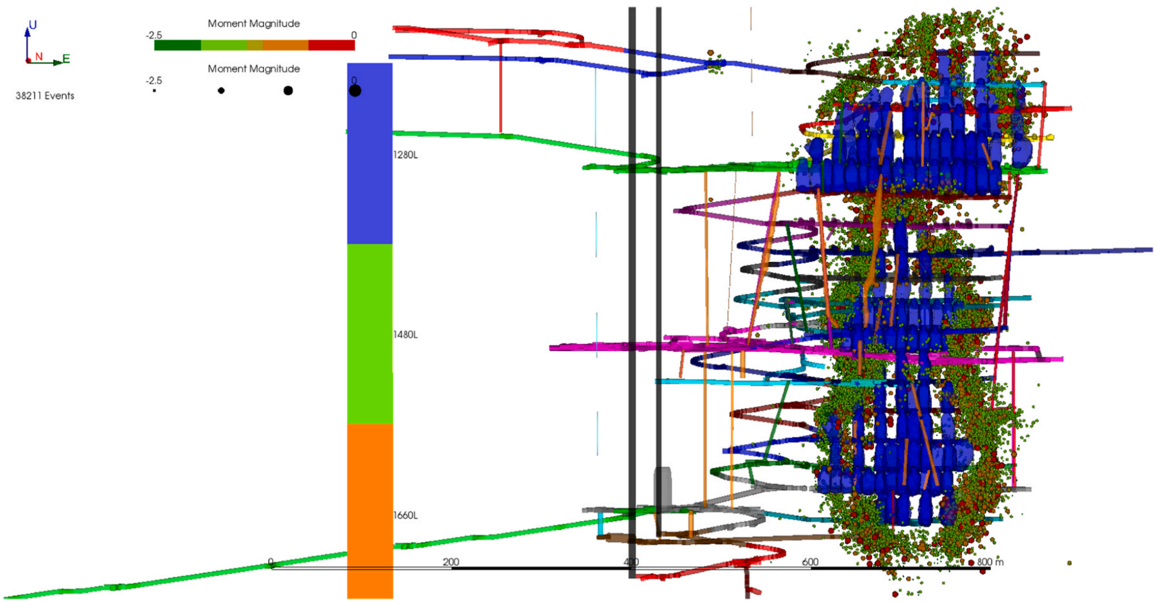


Fig. 13. Clustering of MS events around the stoping areas in Nickel Rim South Mine (image courtesy: B. Simser).

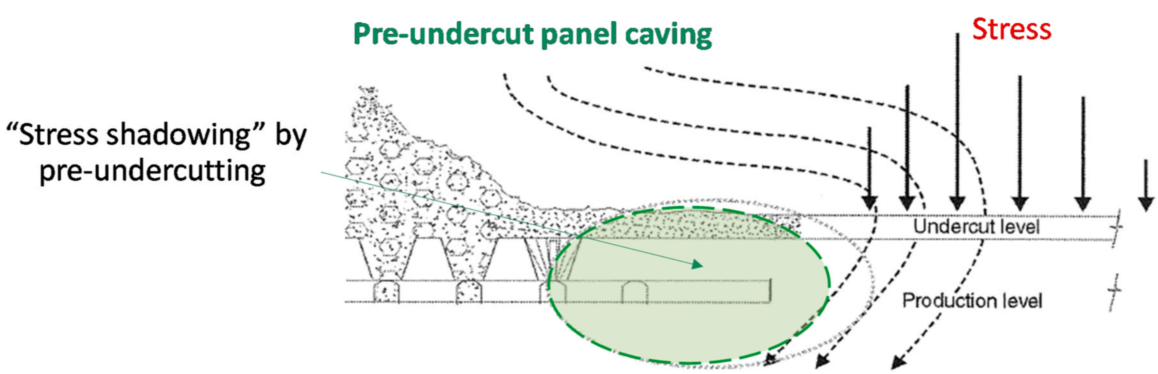


Fig. 14. Using pre-undercut to create stress shadowing for drawbell development [48].

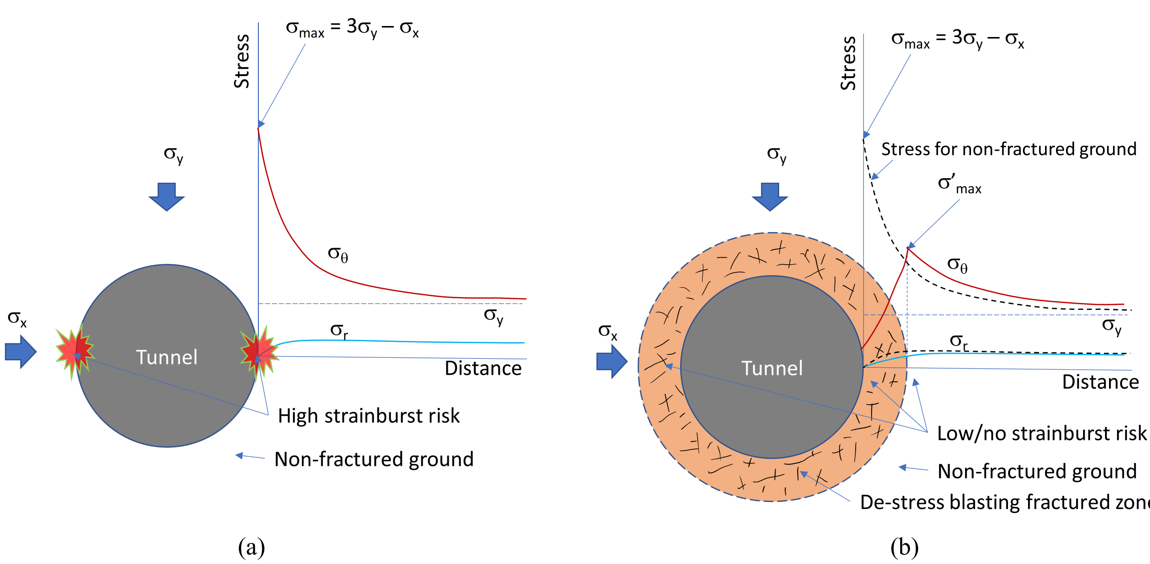


Fig. 15. Tangential stress distributions in (a) non-fractured elastic ground and (b) de-stress blasting-fractured elasto-plastic ground.

monitoring and deformation monitoring, can be employed to assess the effectiveness of de-stress blasting. Adjustments to blasting strategies may be necessary based on the data obtained from monitoring. Precautions should be taken to ensure that the induced fractures do not compromise the integrity of surrounding infrastructure or pose risks to personnel. In addition, undetonated explosives left in some de-stress blasting holes pose a danger and must be safely removed before excavation can proceed.

The mechanism why de-stress blasting can reduce strainburst risk can be explained using Fig. 15. The tangential stress is the driver of rock failure near the excavation boundary. For a circular tunnel with the horizontal (σ_x) and vertical (σ_y with $\sigma_y > \sigma_x$) in-situ stresses given, the maximum tangential stress on the tunnel boundary of the undamaged ground is $\sigma_{max} = 3\sigma_y - \sigma_x$. When σ_{max} reaches the UCS of the rock, failure will occur on the tunnel walls. If the local mine system stiffness is low, unstable or violent failure (strainburst) will occur (Fig. 15(a)). If de-stress blasting fractured a layer of rock near the tunnel boundary (Fig. 15 (b)), the tangential stress on the tunnel wall is significantly reduced. In this case, the maximum tangential stress σ'_{max} is at the boundary between the fractured and non-fractured grounds. σ'_{max} is much lower than σ_{max}. In addition, the rock is confined (i.e., the radial stress σ_r is not zero) at the location of σ'_{max}. Hence, it is difficult for σ'_{max} to drive the rock to failure at the boundary between the fractured and non-fractured grounds. As a result, the risk of strainburst of a ground treated by de-stress blasting is reduced.

In block caving, hydro-fracturing is widely used to induce fractures in the rock mass to facilitate controlled caving [58,59]. More recently hydro-fracturing has been introduced as an effective means of seismic energy release control [60,61]. This method involves injecting high-pressure water into predefined boreholes to induce controlled fractures in the rock mass to release accumulated strain energy in a controlled manner, mitigating the risk of rockburst. Research is being conducted in Canada to test the effectiveness of hydro-fracturing in drift development to reduce strainburst risk. It is hoped that this technique can be adopted as an alternative tool to de-stress blasting in mine development, contributing to rockburst risk management.

In coal mines, water injection into coal seams is used to mitigate the risk of rockburst [62]. This method works when a rock soaked with water reduces its stiffness and strength, eliminating some factors needed for a rockburst to occur (see Fig. 1). Although water injection is a common practice in coal mining, its effectiveness in hard rock mining is yet to be demonstrated and, therefore, is not practiced.

3.4.2. Backfill

Backfilling is one of the techniques used in underground mining for ground control. It involves filling mined-out spaces with various backfill materials to provide support, control subsidence, and mitigate the risk of rockbursts. The use of backfill serves multiple purposes, such as reducing stress concentrations, improving ground stability, better recovery of ore, and mine waste disposal [63]. Backfilling not only enhances safety but also contributes to efficient ore recovery and sustainable mining practices.

Backfill is placed in the stope voids after ore extraction, particularly in areas prone to high-stress concentrations to reduce the risk of rockbursts. One significant contribution of backfill in mitigating the risk of rockburst is its capability to restrict rock mass deformation, thereby enhancing the stiffness of the mine loading system. As shown in Fig. 1, if the mine loading system stiffness is increased, the potential for rockburst is reduced. Hence, timely placement of backfill in mined-out stopes is critical for rockburst risk control. When paste fill is used, the capacity of the paste fill plant must be designed to meet the demand of the mining rate to avoid delays in backfill. The stiffness of the backfill is also an important factor to consider. In general, cemented rockfill is the best when high stiffness is needed to restrict rock mass deformation.

3.4.3. Rock support

Commenting on the Bible's true story of Noah's ark, Warren Buffet said, "Predicting rain does not count. Building arks does." What he refers to is that having a keen sense of awareness regarding possible scenarios or coming danger does little to make you a better leader. Rather, it is how you plan, prepare, and take control of your situation that truly matters. In the case of rockburst risk management, it can be asserted that the key lies not in predicting rockbursts but in effectively supporting the rock mass.

Rock support is the most effective tool to reduce excavation vulnerability, a key factor contributing to rockburst risk. Well-supported mine excavations, just like well-reinforced buildings that can withstand strong ground shaking caused by a large earthquake, can reduce the rockburst risk significantly. To address earthquake risks, the crucial factor is not our capacity to predict earthquakes but rather the survivability of buildings and infrastructure. The same principle should be applied in managing rockburst risk. Hence, rock support is a critical and useful tool to control and mitigate the consequences of rockburst.

Designing and implementing a robust rock support system, which includes rockbolts, mesh, mesh straps, and shotcrete, enhances the integrity of underground excavations. The rock support system reinforces rock mass strength, distributes stresses, controls deformation, and reduces the likelihood of rock mass failure. Rock support is the last line of defense against rockburst damage [64]. It is also the most important line of defense. Almost all deep mines experiencing rockburst problems rely profoundly on using effective rock support as a means of rockburst hazard control.

Kaiser et al. [2] defined three primary support functions: (1) reinforce, (2) retain, and (3) hold. A fourth function, connect, is added to the support functions (Fig. 16) [1]. A rock support system is composed of tendon components such as friction bolts, rebars, dynamic rockbolts, cablebolts, and areal (surface) support components such as mesh, shotcrete, cable lacing, and straps. Some tendons are better at reinforcing the rock mass, while others excel in energy absorption and holding. The combination of various tendons and areal support components secures the rock mass in place to prevent gravity-, static stress-, and dynamic stress-driven rock mass failures.

In a rockburst event, rock failure is unstable, leading to the release of a large amount of strain energy. Hence, a rock support system must be able to yield to accommodate large rock mass bulking and dissipate dynamic energy. In other words, dynamic rockbolts must be installed to fulfill the holding/yielding role. Reinforcement bolts such as rebars and areal support such as strong mesh are needed to form an integrated support system. The desired energy dissipation capacity of a support system is only achieved if all rock support elements are well integrated, connected, and interact with the rock mass.

Cook and Ortlepp [65] first suggested the use of dynamic or yielding support in deep gold mines in South Africa and a smooth-bar yielding rockbolt was developed and tested for this purpose. The bolt can slide

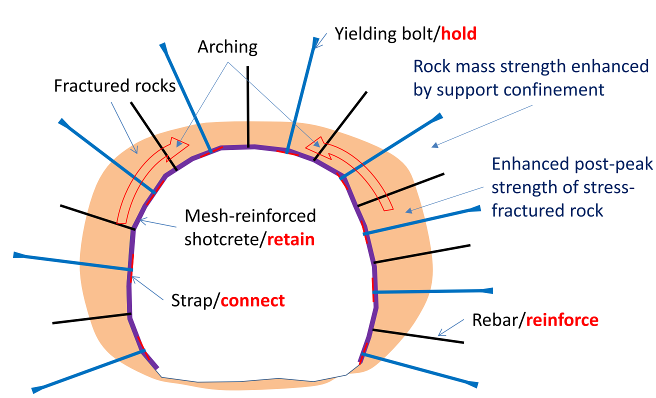


Fig. 16. Rock support functions [1].

with the resistance created by steel-grout friction. The first generation of conebolts was developed by the Chamber of Mines Research Organization in 1987 in South Africa [66]. The library of dynamic rockbolts has been enriched with the addition of many new bolts such as Durabar [67], modified conebolt (MCB) [68,69], Garford solid bar [70], MCB33 [71–73], Yield-lok [74], D-bolt [75], VersaBolt [76], Dynatork bolt [77], HE-bolt [78], MP1 bolt [79], MDX bolt [80], Superbolts [81], PSS-bolt [82], etc. The dynamic rockbolts absorb energy through three mechanisms [83]: frictional resistance (e.g., MCB), steel stretching (e.g., D-bolt), and device yielding (e.g., Garford solid bar). As shown in Fig. 17, the energy absorption rate (the slope of the energy–displacement plot) of a rockbolt depends on the energy absorption mechanism of the bolt. Rockbolts with pure steel stretching and steel-rock frictional sliding energy absorption mechanisms have the highest and the lowest energy absorption rates, respectively.

It is estimated that more than twenty different types of dynamic rockbolts have been developed and new dynamic rockbolts continue to be developed. Dynamic rockbolts play a key role in rock support in burst-prone ground, but they need to work together with a robust areal support system. The energy absorption capacity of a rock support system is not the simple arithmetic summation of the energy capacities of each support element in the system but rather depends on a complex interaction among the support elements and the rock mass [1]. Areal support is often the weakest link in a rock support system [64,71,84], and a weak areal support system can reduce the overall support capacity of the support system significantly. Methods to address the weakest link issue include using larger wire diameter weld mesh (e.g., #4), utilizing high-strength chain-link mesh (e.g., Tecco mesh [85]), implementing mesh-reinforced shotcrete, or adopting a multi-layer system [86]. The multi-layer support system used at El Teniente Mine in Chile is constructed by applying 50 mm shotcrete and then installing 25 mm threadbars with G80/4 high-strength chain-link mesh. Next, 25 mm shotcrete is applied, and another plate is installed on the threadbars. Finally, the second G80/5 high-strength chain-link mesh is installed using 15.2 mm twin plain strand cablebolts. For critical infrastructures like the production level of a deep block caving mine, the implementation of a multi-layer support system is considered essential.

Most mines use a two-pass system for rock support installation. In the first pass, rebars with mesh are installed to reinforce the rock mass. At a later time, the second pass of rock support consisting of dynamic rockbolts and mesh straps or high-strength mesh is installed. Using the conventional two-pass system to install rockburst support can put workers at great risk because a rockburst can occur before the rockburst-resistant support is installed. Hence, it is recommended to employ a one-pass rock support system in drifts prone to rockbursts. For example, at Creighton Mine, rebar (for reinforcement) and MCB33 (for yielding support) were installed in one pass [45]. Hybrid bolts like Garock hybrid bolts and Superbolts, which combine reinforcement and yielding support functions, provide a simple solution for installing a one-pass rock support system, accelerating drift development without compromising safety.

Shear failure of rockbolts is often associated with strainbursts. Rockbolts relying on steel stretching to absorb energy have little to no shear capacity once the yield process has been initiated and the steel deforms plastically [83]. To increase the shear capacity of a rock support system, hybrid bolts such as LaRonde hybrid bolt, Garock hybrid bolt, MD bolt, and Superbolts can be used.

When mining shallow-dipping orebodies at depth using the entry-type of mining methods, the entire hanging wall needs to be supported because miners enter the stopes. For this type of orebody, the convergences are large and the installed rock support must be yieldable. Through trial and error, the support technologies in the South African mining industry for stope support include yielding elongate support units such as rapid yielding hydraulic props, filled backfill paddock, and yieldable timber packs [87].

There is a perception that the cost of dynamic rock support is high, leading to hesitancy among some mine managers to implement it for rockburst damage control and mitigation. It is crucial to strike a balance

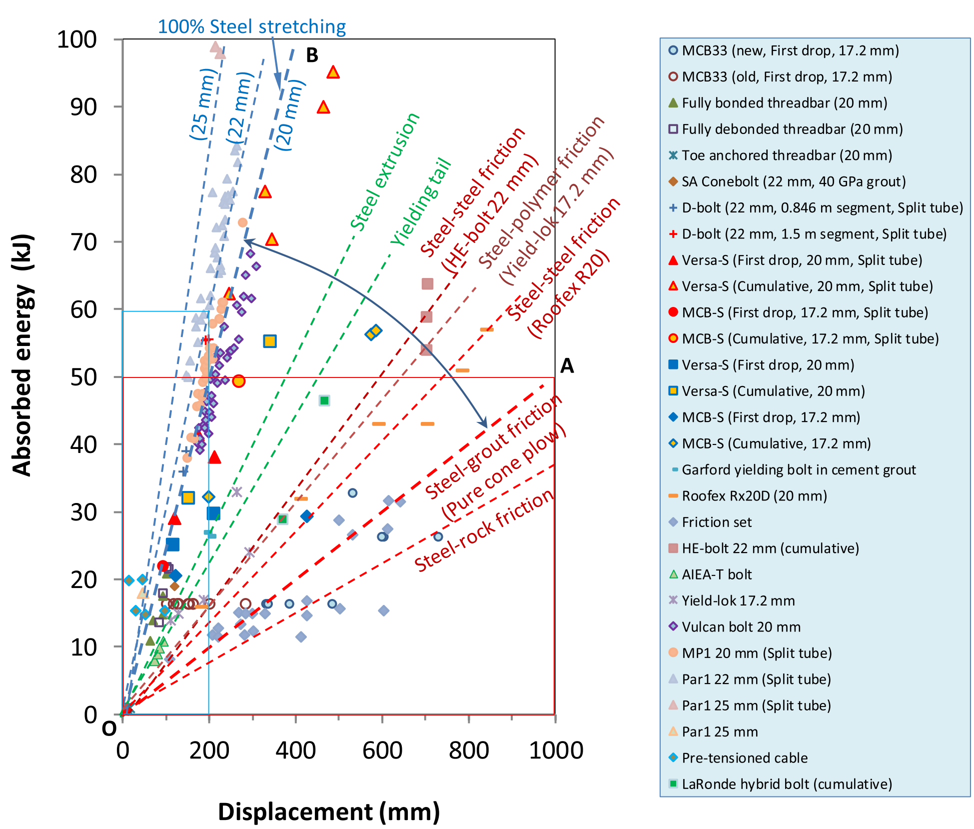


Fig. 17. Comparison of energy dissipation capacities and rates of different rockbolts [83].

between the costs of excavation strengthening using rockburst support and the risks of not taking such measures. The expense of dynamic rock support becomes more reasonable when it effectively reduces excavation vulnerability, subsequently lowering rockburst risk. The savings from risk reduction are substantial, encompassing the avoidance of damage to the excavation, prevention of production disruption, and elimination of mine shutdown [64].

In terms of rockburst support, it is important to be aware of the dilemma of prevention success. The prevention paradox arises when preventive measures are successful in avoiding rockbursts in a mine operation, but the success leads some individuals or mine managers to question the necessity or cost-effectiveness of the preventive efforts such as using rockburst support systems. It is seen that rockburst damage is prevented and is a success in itself. It indicates that the investment in enhanced dynamic rock support is effective in achieving the intended goal of safeguarding the mine – its mineral resources, infrastructure, and the well-being of workers. The absence of observable damage may be precisely because the preventive measures are implemented. Prevention efforts often involve upfront costs, and their benefits may not always be immediately apparent. Prevention is much cheaper than rehabilitation [64]. Recently, Moganedi and Stacey [88] conducted two case studies of financial analysis and demonstrated that if yielding support systems (more expensive at face value when compared with the cost of the stiff damaged support) were used, then the rockburst damage would have been avoided and the mines could have created values.

Because gradual and sudden stress-fracturing loads and deforms the rock support, part of its load and energy dissipation capacities is gradually consumed, leaving less and less remnant capacity at the time when the support is needed, i.e., during a rockburst. If the support capacity can be consumed by rock deformation, it can also be restored by preventive support maintenance (PSM) [89]. It is important to conduct regular inspections of rock support elements and perform immediate maintenance or reinforcement as needed. Accounting for rock support system capacity consumption and integrating PSM into the mine development and operation schedule provide means for prudent asset management and opportunities for cost optimization [89].

In summary, rock support emerges as a crucial and attractive tool for mitigating rockburst risk, given the well-established technology for enhancing the rockburst resistance of excavations. The application of rock support offers a reliable reduction in rockburst risk with significantly less uncertainty compared with other rockburst risk control measures. When mining in highly stressed grounds, key underground excavations not supported using rockburst-resistant support for the sake of project progress and cost-saving should be considered as a failure to perform due diligence by the mine management and engineers.

3.4.4. *Reduced excavation size*

Small blasts and excavations generally cause small stress changes, and hence small energy releases. Fig. 18 shows the number of rockbursts per mine level from January 2000 to September 2013 at Creighton Mine in Canada [90]. The stope heights were between 53 and 60 m above the 7400 (2255 m) level in the 400 orebody. Above the 7400 level, there was a noticeable upward trend in rockburst occurrences with the increase in mining depth. To counteract this trend, the mine opted to reduce the stope height to 26 m below the 7400 level for the 400 orebody. Subsequently, in a further effort to minimize the risk of rockburst, the stope height was reduced to 26 m for the 461 orebody. Consequently, the incidence of rockbursts peaked at the 7400 level and exhibited a subsequent decrease in deeper levels.

Similarly, at Pyhäsalmi Mine in Finland, where stopes with a height of 50 m and a length of 40–60 m were initially common, challenges such as prolonged mucking periods and issues like rockbursting, onion skinning, and caving of stope walls in the primaries prompted a decision to scale down stope dimensions to 25 m in height [91]. These examples clearly show that reducing excavation size can minimize stress concentrations, control the release of stored strain energy, and promote the overall stability of stopes. It is a simple tool to use when mining at depth.

Similarly, in deep mining operations, it is advisable to keep drift dimensions as small as possible and steer clear of four-way intersections due to their larger spans. Smaller drifts have a lower risk of rockfall and rockburst. While opting for smaller drifts might necessitate the use of smaller mining equipment, potentially affecting productivity, it is crucial to prioritize safety over productivity in case of conflicting interests. These design considerations, coupled with a comprehensive array of ground control measures, collectively contribute to fostering a safer and more controlled mining environment.

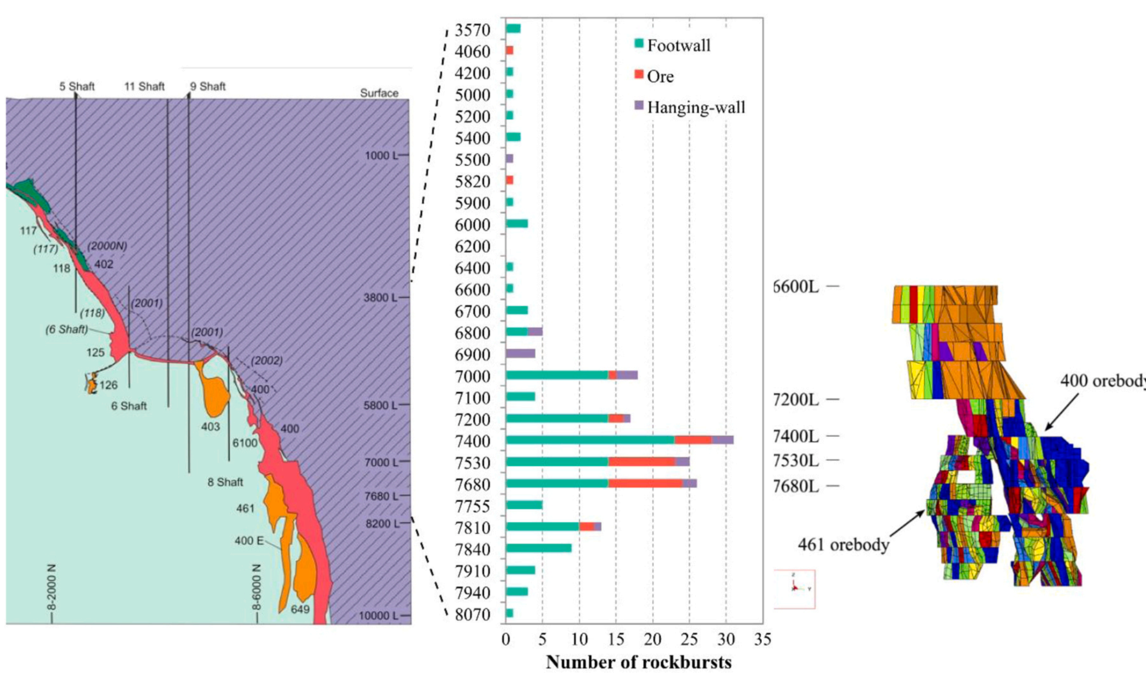


Fig. 18. The number of rockbursts per mine level from January 2000 to September 2013 at Creighton Mine, with a view of the 400 and 461 orebodies and stope sizes [90].

3.4.5. Reduced advance rate

The amount of released strain energy is related to not only the size of the excavation but also the rate of excavation. Higher rates of tunnel advance or stope extraction increase the risk of rockburst, as the released energy increases and there is not enough time available to allow the ground to settle down and reach a new equilibrium. Short face advance steps can improve the mining face stability in the extraction of highly stressed regions, and this has been practised in the South African gold mines for many years based on empirical evidence [92]. Salamon [93] demonstrated that the amount of released energy can be drastically reduced if the number of mining steps is increased. He shows that for a circular tunnel created instantaneously (in one mining step), 62.5% of released energy becomes seismic energy and 37.5% as stored strain energy. On the other hand, if mining is conducted in 64 steps (like using a tunnel boring machine), only 3.4% of the released energy is seismic energy and 96.6% is stored strain energy. Hence, reducing the mining steps can reduce the seismic efficiency, and hence the rockburst potential. Dykes typically exhibit greater stiffness than the surrounding rock, leading to the concentration of high stress within these stiffer formations. This is why when passing through dykes in drift development, a smaller round length is needed along with the use of enhanced rock support.

The relation between stoping rate and seismicity is poorly understood. However, reducing the stoping rate in a high-risk area can be an option for rockburst risk management. This will allow the ground to have more time to settle down and timely backfill of mined-out stopes.

3.5. Administrative control (mitigation) methods

Administrative controls focus on limiting or reducing the exposure of workers and mining equipment to rockburst environments. Several proven methods can be employed to achieve this objective (Fig. 19), which are discussed in the following subsections.

3.5.1. Centralized production blasting and exclusion

The majority of large seismic events occur within a few hours after a large production blast [94]. It is a standard procedure in Canadian hard rock mines employing bulk non-entry mining methods to schedule production blasts at the end of a shift when no personnel are present underground. After a blast, ground conditions are closely monitored using the MS monitoring system. Decisions regarding the resumption of regular shifts and entry into the mine are contingent upon the observed ground conditions.

The rules for exclusion time and zone are determined based on statistical analyses of the historical seismic response to blasting. The die-down exclusion time depends on conditions at each mine site. For example, the exclusion time is 2 hr at Mount Charlotte Mine [95], and 6–9 hr at LaRonde Mine [96]. The exclusion area is often site-specific and constrained by operational considerations.

3.5.2. Evacuation and re-entry protocols

Rockburst risk control and mitigation not only rely on engineering solutions but also involve the development of robust safety protocols. Clear communication and well-defined evacuation procedures and re-entry protocols contribute to safeguarding the well-being of workers. Regular training, drills, and simulations can be conducted to ensure that the workforce is well-prepared to respond to rockburst emergencies, encouraging workers to report observations and concerns related to potential rockburst risks and fostering a culture of continuous improvement.

MS monitoring data can show real-time seismic activities in a mine. Many mines have developed re-entry protocols through MS monitoring [97,98]. The MS monitoring data can be utilized to temporarily evacuate parts of the mine or adjust mine plans if a region becomes suddenly seismically active. Skilled workers can also develop a sense of the rock mass response and know when to evacuate a location based on indications of unstable ground such as nearby rock noise. A mine site can develop a Trigger Action Response Plan (TARP) exclusion protocol for workers to follow depending on the perceived hazard level whether to just report noise but continue work, withdraw from the work area, evacuate to refuge stations, or evacuate from the mine. To work in an area with elevated rockburst hazards, it will be necessary to have two access drifts to provide a safe evacuation route.

The rockburst re-entry protocols determine the time to wait before safely re-entry into seismically active areas following large rockburst events. The seismic decay can be assessed using MS parameters such as event rate, seismic energy, or seismic moment. One method shown in Fig. 20 uses seismic work to establish the re-entry time. The seismic work is a parameter derived from the seismic moment [97]. Right after a large seismic event, the ground is unstable and the accumulative seismic work increases rapidly in the unstable period. There is a transition period where the rate of seismic work increase slows down gradually. Eventually, the rate of seismic work increase will be constant and return to the background level, which is determined by using MS monitoring data in periods without blasts or large seismic events. The boundary between the transition and stable periods defines the time that workers can re-enter the mine or mining area to resume work. The time for safe re-entry depends on the size of the seismic event. For events with a Nuttli magnitude less than 2, the re-entry time can vary from less than an hour to several hours. Longer wait time (> 12 hr) is needed after a larger seismic event. In general, the decision to allow workers to resume work underground is made collectively by the ground control engineer, the mine manager, and the health and safety representative of the mine. The re-entry protocols can also be applied to centralized stope blasting.

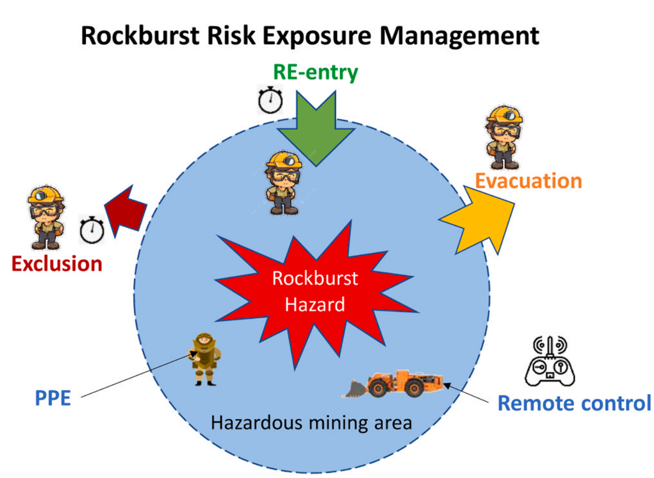


Fig. 19. Rockburst risk exposure management methods.

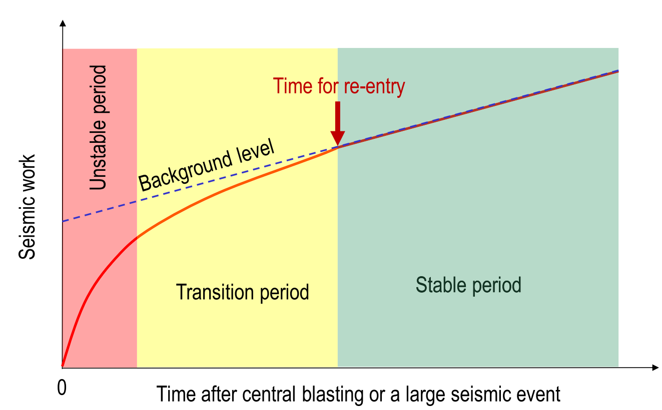
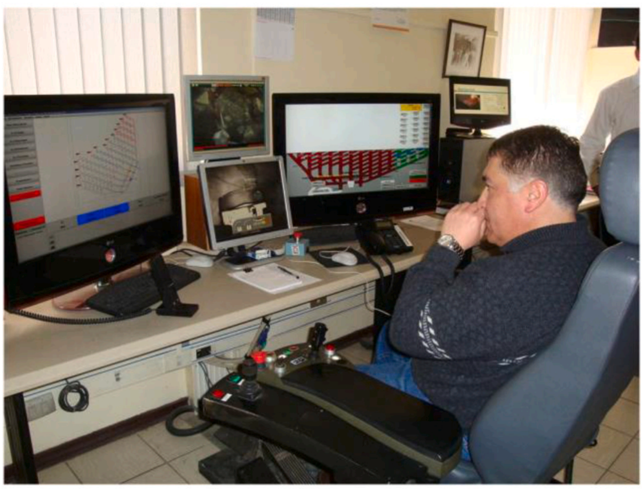


Fig. 20. Relation between the seismic work and time after a large seismic event.

(a)



(b)

Fig. 21. (a) Miners drilling in a stope using stopers (photo source: wikipedia.org). (b) A miner is sitting in an office on the surface to operate LHDs working underground at EL Teniente Mine in Chile.

3.5.3. Use of mechanized and remotely controlled mining equipment

Moving away from hand-held mining equipment such as jacklegs and stoppers (Fig. 21(a)) and employing mechanized equipment such as jumbos and bolters can significantly reduce the exposure of workers to rockburst hazards. Mechanized mining equipment provides protective cabins to shield workers from rock ejection and rock fall hazards. Tele-remote equipment further reduces workers' exposure to rockburst hazards. The mining equipment can be remotely operated from well-supported drifts, underground offices, or even surface offices (Fig. 21(b)). The use of tele-remote mining equipment not only improves safety but also increases productivity.

3.5.4. PPE

Standard personal protective equipment (PPE) in Canadian hard rock mines typically includes a hard hat, safety glasses or goggles, steel-toed boots, high-visibility clothing, gloves, ear protection, and fall protection equipment. In burst-prone ground, the standard PPE is crucial, with additional consideration warranted. For example, during the construction of the Micangshan Tunnel of the Bashan-Shaanxi Expressway in China, rock ejection due to small strainbursts at the face posed a threat to workers. To enhance worker safety, bulletproof vests and helmets were provided (Fig. 22). While the effectiveness of such measures can be debated, it is understandable that providing workers with bullet-proof vests and helmets offers psychological assurance when working on burst-prone ground.

Fig. 22. Workers are equipped with bullet-proof vests and helmets to work in the strainburst-prone Micangshan Tunnel of the Bashan-Shaanxi Expressway (photo source: www.guancha.cn).

3.6. A multiple-line defense system

Many methods, whether strategic, tactical, or administrative, are available for rockburst risk management. Whatever is implemented, the rockburst risk cannot be eliminated. The reality is that in deep mining, we have to accept the occurrence of rockbursts.

As can be seen from Fig. 5, rockburst risks stem from a combination of the rockburst hazard, excavation vulnerability, and exposure. Hence, the control and mitigation methods discussed in Sections 3.3 to 3.5 can be employed to address those three aspects of the rockburst risk. The administrative control methods are mainly for risk exposure control (see Fig. 19). Both the strategic and tactical methods can be used for rockburst hazard and excavation vulnerability management. For rockburst hazard management, the most effective methods are those that can reduce stress concentrations because high stress is the main driver of rockburst (Fig. 23(a)). For this reason, we need to pay attention to mining method selection, mining sequence determination, and mine layout. For excavation vulnerability management, the most effective method is rock support because a well-designed and implemented dynamic rock support system can eliminate rockburst damage, safeguarding workers and investment (Fig. 23(b)). Improved mine design can reduce stress concentrations and make excavations less vulnerable. However, in deep mines, the mining-induced stresses will always be high. This is why excavation vulnerability is best managed using dynamic rock support with the assistance of other measures such as limiting excavation sizes.

The best approach for rockburst risk management is to build a multiple-line defense system, establishing and maintaining multiple lines or layers of defense, each serving a specific purpose. Understanding the rockburst mechanism is important for developing and choosing engineering tools to manage rockburst risk. The author of this paper refers it to as the outpost because it provides valuable information for us to address the rockburst risk (Fig. 24). Rockburst mechanism research provides us with the information needed to win the battle against the enemy, which is rockburst in this case. Improved mine design and mining sequencing aim at reducing the rockburst hazard, and it is the first line of defense. MS monitoring contributes to exposure control that is aimed at mitigating the consequences of rockburst, and it is the second line of defense. Rockburst-resistant support aims at reducing the vulnerability of mine excavations, and it is the last line of defense. In this

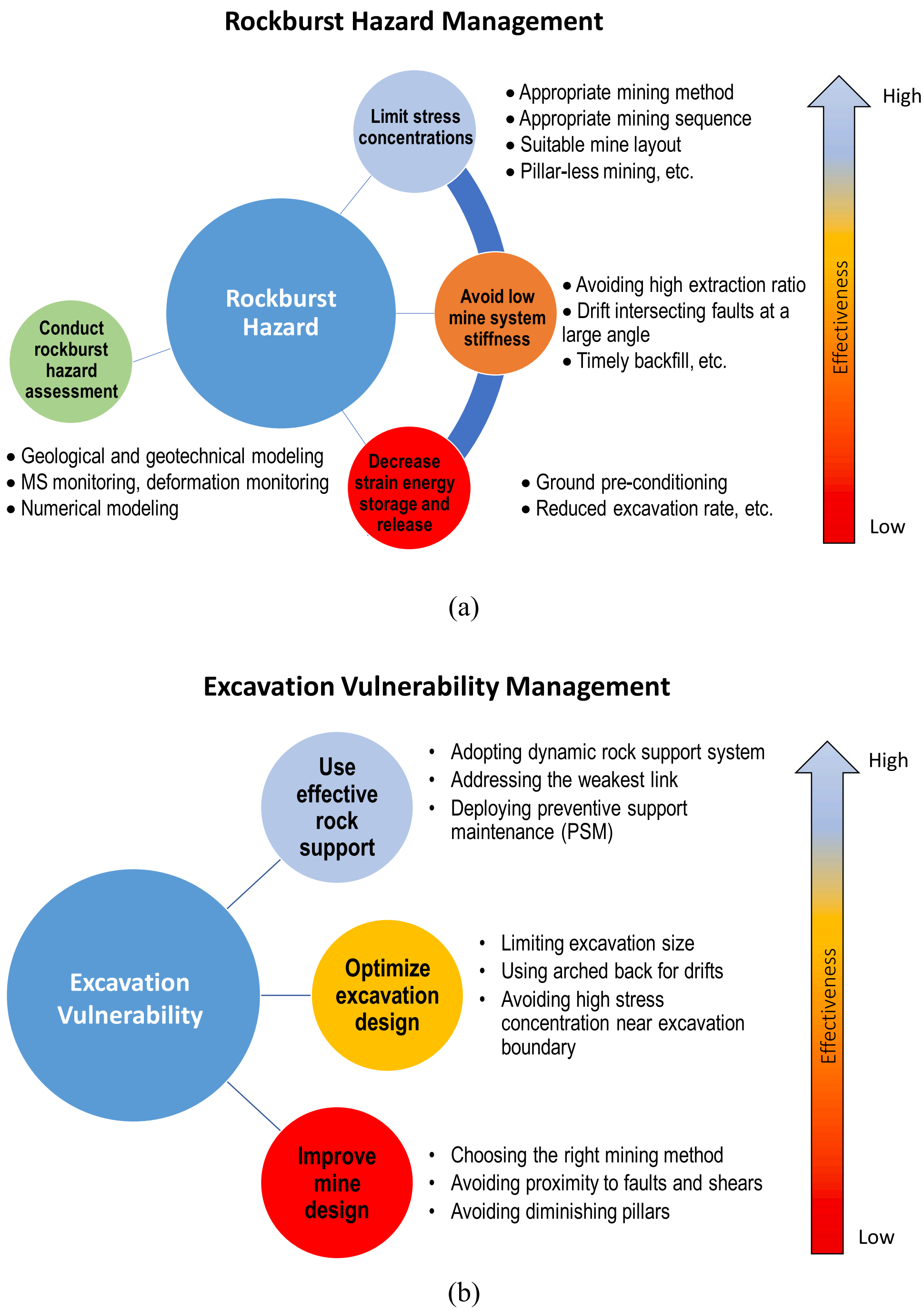


Fig. 23. (a) Actions to reduce rockburst hazard; (b) actions to reduce excavation vulnerability.

manner, we build a multiple-line defense system that can provide depth to the overall rockburst risk management strategy (Fig. 24). If one line is breached or compromised, there are additional layers that can stop or reduce the risk, protecting the critical assets namely workers and the investment.

Effective rockburst control and mitigation must be contingent on a proactive and adaptive strategy. To be successful, we need to prioritize a thorough understanding of geological conditions, implement tailored control measures, and continually refine strategies based on ongoing monitoring and lessons learned from past experiences. The risk control and mitigation methods presented in this section provide a foundation for shaping industry best practices and guiding future research efforts in the field of rockburst risk management.

4. Discussions

4.1. Emerging technologies and innovations

The dynamic nature of the mining industry has spurred the development of innovative technologies aimed at enhancing the prediction, prevention, and control of rockbursts in deep mining operations. This section explores the forefront of technological advancements that show promise in reshaping rockburst risk management in the future.

4.1.1. Technological advances in rockburst prediction

Emerging fiber-optic distributed acoustic sensor arrays for MS monitoring, in combination with existing advanced MS monitoring systems, advanced velocity models, and machine learning algorithms,

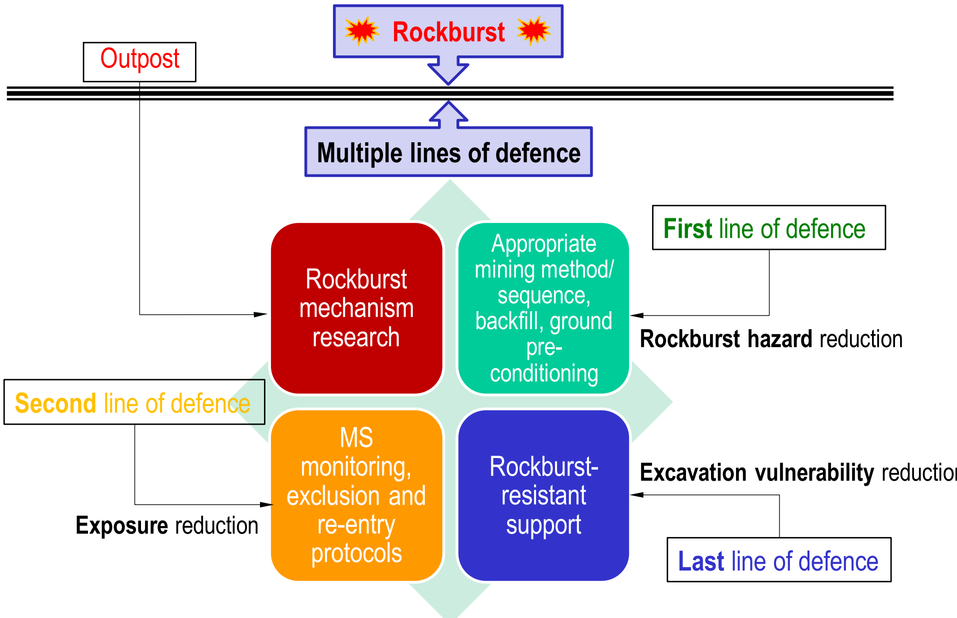


Fig. 24. Multiple lines of defense to deal with rockburst problems in deep mines.

can potentially further improve the accuracy of seismic event source locations. Real-time analysis of MS monitoring data and correlating the data to geological, geotechnical, and mining data may enable the identification of subtle precursors and patterns associated with impending rock failures, offering a more nuanced understanding of the evolving underground conditions.

Rockburst prediction is very difficult due to the uncertainty associated with the mine geology and rock mass properties. However, artificial intelligence (AI) and intelligent analysis of large engineering data may potentially provide hope. The integration of AI into predictive modeling holds the potential for advancing rockburst hazard management. AI algorithms can analyze vast datasets, identifying complex patterns and relations that may elude traditional modeling approaches. As AI technologies continue to mature, their application in rockburst hazard assessment is poised to become increasingly sophisticated. Of course, even if we can predict the occurrence of rockburst with increased confidence levels, engineering control measures detailed in this paper are still needed to ensure safety and protect the investment.

4.1.2. Innovative control measures and technologies

LiDAR (Light Detection and Ranging) sensing technology is increasingly integrated into mine operations. This technology, when deployed frequently and extensively, provides a comprehensive and timely view of stope and drift wall deformations, allowing for early identification of ground changes that may contribute to rockburst risks. The collected datasets are huge, which requires dedicated powerful computers for processing and storage.

The development of smart ground support systems (e.g., smart cable, smart bolt) involves the integration of sensors into traditional support elements such as rockbolts and cablebolts. These systems continuously monitor the rock mass, offering real-time warning of ground movement and stress build-up in the rock mass. When strategically deployed to locations of high rockburst hazard, they can enhance the understanding of ground behavior, provide insight for proactive rock support maintenance, and reduce the risk of rockburst. They are also useful for providing data for decision-making to restrict access to certain mining areas with high risks of impending rockbursts.

Steel is the main material for manufacturing ground support components such as rockbolts, cablebolts, and mesh. Conventional low-carbon steel for weld mesh and rockbolts (e.g., HSLA, CMn in Fig. 25) has a good elongation property (15–25%), but the strength is low (400–500 MPa). High-strength steel (e.g., PHS) for making cablebolts

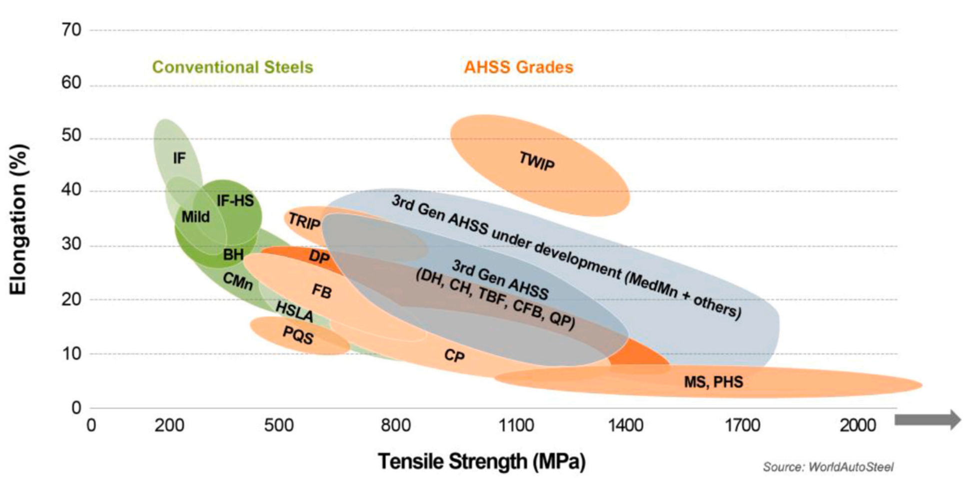


Fig. 25. Relation between strength and elongation of current and emerging steel grades (image source: www.worldautosteel.org).

and Tecco mesh has a higher strength in the order of 1800 MPa, but with limited elongation (3–4%). Recent advances in material science have produced many new steels with improved strength and elongation properties (Fig. 25). For example, Yang et al. [99] reported a medium Mn steel with a tensile strength of 1073 MPa and a total elongation of 76%. The TWIP (twinning-induced plasticity) steel poses the desired properties (Fig. 25) for making ground support components. For example, if a TWIP steel with a tensile strength of 1200 MPa and an elongation of 45% is used to make a 20 mm diameter, 2.4 m long yielding bolt (with a stretching length of 1.5 m), the load, displacement, energy capacities of the bolt will be 377 kN, 675 mm, 254 kJ, respectively. This is superior to all existing bolts of the same diameter and stretching capacity (e.g., D-bolt, Par1 bolt) based on steel stretching to absorb energy. For reference, the load, displacement, and energy capacities of a 20 mm diameter, 2.4 m long D-bolt (with a stretching length of 1.5 m) are approximately 200 kN, 250 mm, and 45 kJ, respectively. TWIP steel's superb strength and elongation properties make it easy to manufacture rockbolts and mesh with very high load and energy absorption capacities, which are desired properties for dynamic rock support. If the material cost can be brought down, its extensive application to making ground support components will further enhance mine safety.

4.1.3. *Prospects for future technological developments*

Intelligent robots can be utilized in deep mining to enhance safety, efficiency, and productivity. Large autonomous haul trucks and autonomous drilling systems are now used in some open-pit mines in Canada, Australia, and the USA. Their use in deep underground mines holds great potential to significantly reduce the exposure of workers to rockburst hazards.

The use of 5 G technology in underground mining can bring about several benefits, such as enhancing safety, productivity, and efficiency. For example, real-time monitoring of MS events, equipment, ventilation, and environmental conditions can be achieved using sensors connected to a 5 G network. Remote operation of mining equipment from a control center on the surface can be conducted utilizing 5 G connectivity. Drones connected to a 5 G network can provide real-time video feeds and collect data for mapping inaccessible stopes and drifts. Thus, implementing a robust 5 G network in deep mines can revolutionize the mining industry by providing the connectivity necessary for advanced technologies to thrive.

The Internet of Things (IoT) for real-time monitoring and sharing of data of personal and mining equipment can further enhance the implementation of administrative control measures. The deployment of IoT devices in deep mining operations facilitates comprehensive and real-time monitoring. IoT sensors can provide continuous data on various parameters, including displacement, stress, AE/MS, temperature, and gas emissions, enabling a holistic understanding of the subsurface conditions.

As we explore emerging technologies and innovations, it is evident that the future of rockburst risk management in deep mining lies in the integration of cutting-edge technologies with proven engineering control measures. These advancements not only refine existing strategies but also open new possibilities for proactive risk mitigation and enhanced safety in deep mining operations. Continued collaboration between industry stakeholders and researchers will be crucial in harnessing the full potential of these emerging technologies.

4.2. *Challenges and future directions*

The pursuit of effective rockburst risk management in deep mining is not without its challenges. Understanding and addressing these challenges are crucial for advancing the field and ensuring the safety and sustainability of mining operations at depth.

The heterogeneous nature of geological and geotechnical conditions poses a persistent challenge in rockburst risk management. Geological complexities, such as fault zones and changing stress regimes, require adaptive engineering control and mitigation strategies. In reality, how to dynamically account for these variations and uncertainties remains a considerable challenge.

While emerging technologies show promise, their adaptation and seamless integration into existing deep mining operations can be challenging. Many mining companies have a wait-and-see attitude and want to be the first to be second. Implementing advanced monitoring systems, smart ground support, and AI-based predictive models requires overcoming technical, logistical, economic, and cultural barriers. Achieving a harmonious integration of these technologies is a key challenge in modernizing rockburst risk management practices.

Despite some advancements made, identifying reliable precursors to rockbursts remains an ongoing research challenge. There is a need for in-depth studies to decipher subtle signals and early indicators, enhancing the predictability of impending unstable rock failures. An improved understanding of precursor mechanisms is essential for providing early warning of a rockburst in a mining area.

Each mining operation is unique, requiring a site-specific approach to rockburst risk control and mitigation. Experiences gained from other mines, successful or not, can be used to tailor an approach that is best for addressing the specific challenges presented by the geological and stress conditions of your mine site.

Future directions in rockburst risk management call for the development of holistic risk management strategies. Integrating geological, geotechnical, mining, and technological aspects into a unified framework will enhance the ability to anticipate and mitigate rockburst risks. Collaborative research initiatives that bridge disciplinary boundaries will play a key role in shaping these comprehensive strategies. Hence, it is important to establish collaborative platforms for industry stakeholders and researchers to share data, insights, and best practices for advancing rockburst risk management.

5. Concluding remarks

This paper provides a comprehensive overview of the challenges, strategies, and future directions in rockburst risk management. Four conditions for rockburst occurrence are stated. The fourth condition – soft loading system stiffness – is very difficult to assess. This is why rockburst prediction is extremely difficult, close to impossible. Hence, the focus should shift from prediction to proactive preparedness to mitigate the impact of mining-induced seismic events. It is important to protect mine infrastructure against rockburst damage, decreasing the excavation vulnerability through rockburst-resistant support.

The detailed bow-tie analysis of rockburst risk offers a clear and visual representation of the complex relation between causes, consequences, and control measures associated with rockbursts. Because rockburst risk is the result of the interaction among rockburst hazard, excavation vulnerability, and exposure, different strategic, tactical, and administrative control methods can be employed to address the rockburst risk. Various methods under each group are illustrated with examples. Based on the hierarchy of controls of the methods presented, it is seen that the strategic control methods are the most effective, while the administrative control methods are the least effective.

As we explore control and mitigation methods for rockburst risk management, it becomes evident that a multiple-line defense system is required due to the uncertainty involved in the rockburst risk. If one line of defense is breached or compromised, additional layers are in place to stop or reduce the risk, safeguarding workers and investment. The integration of mine design considerations, ground pre-conditioning, dynamic rock support systems, and MS monitoring contributes to the key development of a comprehensive strategy to manage rockburst risk in deep mining operations. The use of a multiple-line defense system is a holistic approach to rockburst risk management.

As emerging technologies, such as advanced seismic monitoring, smart ground support systems, automatous mining equipment, and artificial intelligence, continue to mature, the potential to transform rockburst risk management becomes increasingly apparent. However, the integration of these innovations into existing mining practices requires thoughtful consideration of technical, logistical, and economic factors.

In conclusion, the future of rockburst risk control and mitigation in deep mining lies in a holistic and collaborative approach. A combination of refined mine design considerations, strategic mine planning, ongoing monitoring, rockburst-resistant ground support, and the integration of emerging technologies will contribute to safer and more sustainable underground operations. By collectively addressing challenges and pursuing future research endeavors, mining engineers can shape the future of rockburst management, ensuring the continued advancement of safety and efficiency in deep mining operations.

Declaration of Competing Interest

The author wishes to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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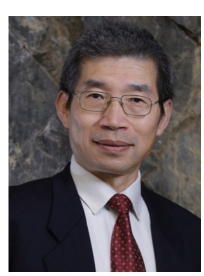

Dr. Cai is a Full Professor in Laurentian University's School of Engineering and Computer Science and holds a position as Geomechanics Research Chair. Dr. Cai holds Bachelor and Master degrees from Tsinghua University in China and a PhD degree from the University of Tokyo in Japan. Prior to joining Laurentian, he worked for Mansour Group Inc., MIRARCO, Tokyo Electric Power Services Ltd., and Tsinghua University and had over 30 years' research, education, and industry experience. He has a wide variety of interests in rock mechanics and rock engineering, and has made exceptional technical and scientific contributions to many topics including constitutive modeling of rock masses, rock mass characterization, rock support in burst-prone ground, interpretation of AE and microseismic monitoring data, and rock failure process simulation. Dr. Cai is the author/co-author of more than 250 scientific publications. He was awarded the Canadian Geotechnical Society's John A. Franklin Award in 2017.