ABSTRACT: As mining and civil tunneling progresses to deep grounds, excavation-induced seismicity and rockburst problems increase and cannot be prevented. As an important line of defense, ground control measures and burst-resistant rock support are used to prevent or minimize damage to excavations and thus to enhance workplace safety. Rock support in burst-prone ground differs from conventional rock support where controlling gravity-induced rockfalls and managing shallow loosening zones is the main target. Rock support in burst-prone grounds needs to resist dynamic loads and large rock dilation due to violent rock failure. This paper reviews the rockburst phenomenon, types of rockbursts, damage mechanism, rockburst support design principles and design acceptability criteria, and presents a detailed discussion of rockburst support design procedures. It is pointed out that the support selection process is iterative, requiring design verification and modification based on field observations, and design tools to facilitate a systematic and consistent rock support design approach.

Subject: Analysis techniques and design methods

Keywords: rock support; bolts and anchors; rock bursts; dynamics; tunneling; mine design

1 INTRODUCTION

In Canada and South Africa, hard rock mines are being developed at great depths near or exceeding 3000 m and hard rock tunnels are being constructed at depth greater than 2000 m in many parts of the world (e.g., in Europe, China, Chile, and Peru). As the depth of mining and underground civil construction increases, stress induced rock fracturing is inevitable and in some cases rocks fail violently, leading to seismic events and rockbursts (defined below).

Rockbursts can cause fatalities and injuries to workers, damage to mine infrastructure and equipment, and substantially increase investment risk. Rockburst is a twentieth century phenomenon as the first recorded incident occurred in the early 1900s in the gold mines in the Witwatersrand, South Africa (Blake and Hedley, 2003). In the mining world, several recent mining-induced rockbursts have reached the media due to either tragic nature or damage severity. For example, on 25 April 2006, a rockburst at the Beaconsfield gold mine in Tasmania, Australia, trapped three miners. After almost two weeks, only two miners could be rescued. A magnitude $m_N = 3.8$ seismic event on January 6, 2009, caused extensive damage to four levels at the Kidd Creek Mine in Timmins, Ontario, Canada. One drift supported by standard rock support with mesh and rebar totally collapsed and mining equipment was damaged. Fortunately, the event occurred at a time when the nightshift was going off duty and heading to surface and no injuries were reported.

In the civil tunneling world, two large-scale hydropower projects, the Jingping-II hydropower intake tunneling project in China and the Olmos Trans-Andean tunneling project in Peru, attract significant attention due to severe rockburst problems at these sites. At the Olmos Trans-Andean tunnel site, a large rockburst occurred on May 28, 2010, severely damaging the rock support system and the TBM (Tunnel Boring Machine). Fortunately, there were no casualties and the machine was reparable. At the Jingping-II hydropower intake tunnel site, a major rockburst occurred on Nov. 28, 2009, resulting in seven deaths and one injury, and an TBM machine was damaged beyond repair. In both cases, rockbursts caused major delays in tunneling advance rates.

Considerable research effort, at an international scale (Australia, Canada, South Africa), has been devoted to the understanding of the rockburst phenomenon. Various microseismic monitoring systems are in operation at many mines and tunnel construction sites around the world. From the waveforms recorded, the time, location, radiated energy, seismic moment and other source parameters of a seismic event can be estimated. Monitoring of seismic events in mines is a very useful tool for outlining potentially hazardous ground conditions and assisting mine management in effective re-entry decision-making. Advanced 3D numerical modeling and visualization (Kaiser et al., 2005) can identify potentially hazardous areas and assist in mine planning and design.

Rockburst risk can often be reduced by selecting appropriate mining or excavation methods and sequences, and by strategically placing developments and infrastructure. However, due to uncertainties in rock mass properties and boundary conditions (e.g., in-situ stress, fault zone distribution), all engineering design, calculations, and seismicity monitoring will have to rely on ground control measures and burst-resistant rock support as an important line of defense to ensure underground safety. Therefore, it is imperative to design proper burst-resistant support when mining and tunneling at depth.
2 ROCKBURSTING AND ROCKBURST DAMAGE

2.1 Rockburst phenomenon

Rockburst is the result of sudden and violent failure of rock. A rockburst is defined as damage to an excavation that occurs in a sudden or violent manner and is associated with a seismic event (Kaiser et al., 1996). There is a clear linkage of rockburst activities and mining depth. As mining migrates to deeper ground, in-situ stress becomes high and the likelihood of rockburst increases drastically. Rockbursts are mostly associated with hard rocks and geological structures such as faults and dykes, and, in mining, are often related to high extraction ratios and associated with mining methods causing unfavorable stress conditions.

2.2 Types of rockbursts

Ortlepp and Stacey (1994) and Ortlepp (1997) classified rockbursts into five types (strainburst, buckling, face crush/pillar burst, shear rupture, fault-slip burst). In a broad sense, buckling type rockbursts can be grouped into strainbursts and shear rupture type rockbursts can be considered as fault slip rockbursts. For the brevity of discussion, we consider here three rockburst types, i.e., strainburst, pillar burst, and fault-slip burst. Based on the rockburst triggering mechanism, rockbursts are either self-initiated (i.e., strainbursts) or triggered by a remote seismic event (e.g., fault slip events) (Kaiser et al., 1996).

Strainbursts occur at or near the excavation boundary where the stress concentration is high and the excavation induced stress exceeds the strength of the rock mass. Pillar burst, as the name implies, is defined as violent failure and complete collapse of support pillars. A fault-slip burst is caused by slippage along a pre-existing fault or along a newly generated shear rupture.

Strainbursts are found to be associated with civil excavation methods such as TBM drives that produce less or undamaged rocks near the excavation boundary compared to drill and blast advances. In TBM tunnels more elastic strain energy can be stored and once the rock peak strength is reached, the rocks tend to fail violently. On the other hand, drill-and-blast tunneling causes rock damage near the excavation boundary and high tangential stresses are shifted to deeper ground. Hence, strainbursts tend to be less intense in deep tunnels excavated by drill-and-blast method.

2.3 Rockburst damage mechanism

Understanding the rockburst source mechanism is critical to derive strategies to eliminate and mitigate rockburst hazard, and a thorough understanding of the rockburst damage mechanism is needed to work out tactics to implement rockburst support.

Kaiser et al. (1996) classified rockburst damage into three types, i.e., rock bulking due to fracturing, rock ejection due to seismic energy transfer, and rockfalls induced by seismic shaking (see Figure 1). Rock bulking due to rock fracturing can be caused by both a remote seismic event and the bursting event itself. Rock ejection can be caused either by a strainburst event, or by a remote seismic event. Seismically induced rockfalls, as the name suggests, are caused by the shaking of ground due to large remote seismic events induced by pillar burst or fault-slip.

There are many factors (Hedley, 1992; Kaiser et al., 1996; Durrheim et al., 1998; Heal et al., 2006) that influence rockburst damage and damage severity. Figure 2 summarizes the main factors and groups them into four categories – seismic event, geology, geotechnical, and mining. Factors in the first two groups (seismic event and geology) determine the intensity of dynamic load at the damage locations, and the factors in the last two groups (geotechnical and mining) determine site response due to seismic impulses. Rockburst damage is therefore governed by a combination of these factors. For example, a combination of high stress, brittle rock, high extraction ratio, with faults is likely to generate large seismic events in a mine, and if the installed rock support system is insufficient, severe rockburst damage is inevitable. Rockburst damage severity is often classified by the depth of failure or the volume of rock failed and the degree of damage to the installed rock support system. A three-class (minor, moderate, major) classification can be found in Figure 1.

It is interesting to note from Figure 2 that many factors, such as mining sequence, excavation span, and installed rock support system are in the mining activity category. These factors are created by mining operations, and hence working on these factors provides us manageable means to reduce and control rockburst damage potential. There are many methods to achieve this goal, such as changing of mining method, altering mining sequence, changing drift location, etc. This is where having a good underground construction strategy will pay off quickly. It should be pointed out that having a good construction strategy is not enough and there must be a rockburst support plan implemented. The importance of having effective rock support systems in bursting ground has been demonstrated by numerous case histories. In the next section,
3 ROCKBURST SUPPORT PRINCIPLES AND DESIGN ACCEPTABILITY CRITERIA

3.1 Rock support functions

The mechanics of rock support is complex, and no models exist that can fully explain the interaction of many support components in a rock support system. Nevertheless, Kaiser et al. (1996) summarized three key support functions as: (1) reinforce the rockmass to strengthen it and to control bulking, (2) retain broken rock to prevent key block failure and unraveling, and (3) hold key blocks and securely tie back the retaining element(s) to stable ground.

The goal of reinforcing the rockmass using rockbolts and/or rebars is not only to strengthen it, thus enabling the rockmass to support itself (Hooke and Brown, 1980) but also to control the bulking process as rockbolts/rebars prevent fractures from propagating and opening up.

Under high stress conditions, fractured rocks between the reinforcing/holding elements may unravel if they are not properly retained. Widely used retaining elements are wire mesh, reinforced shotcrete, strap, steel arch, or cast-in concrete. Shotcrete needs to be reinforced by fiber or mesh to increase its tensile strength and toughness. Mesh-reinforced shotcrete or mesh over shotcrete has an important retaining function under rockburst conditions.

The holding function is needed to tie retaining elements of the support system and loose rock back to stable ground, to dissipate dynamic energy due to rock ejection and rock movement, and to prevent gravity-driven falls of ground. When rockburst damage is anticipated, yielding holding elements such as cone bolts and friction bolts must be used in the support system.

The reinforcement, retaining, and holding functions do not act independently. These support functions are achieved by various rock support elements that are well connected, forming an integrated rock support system. The connection between the retaining elements and the holding elements often constitutes the weakest link in a support system, and hence deserves special attention to ensure optimal overall capacity of the support system. Figure 1 illustrates that all three support functions are needed in an effective rockburst support system no matter what the rockburst damage mechanism or damage severity is.

3.2 Rockburst support design principles

In underground construction, strategy is the art of commanding the entire mining or tunneling operation. Tactic, on the other hand, is the skill of using various kinds of tools for the construction itself and dealing with the immediate needs in the field. Most engineers are forced to be tacticians as everyday tasks make them think of how to deal with the most immediate problems. To think strategically is more difficult and often demands long-term thinking to get out of the reactive mode to rockburst damage.

As Ralph Waldo Emerson, an American essayist, philosopher and poet (1803–1882), said, “As to methods there may be a million and then some, but principles are few. The man who grasps principles can successfully select his own methods. The man, who tries methods, ignoring principles, is sure to have trouble.” Realizing the importance of understanding rockburst support design guiding principles, Cai and Champagne (2009) summarized some of their and other practitioners’ experiences into a few simple and easy-to-understand principles (Figure 3).

The first principle is to avoid rockburst. The supreme excellence in rock support in burst-prone ground is to avoid rockburst conditions and the best rock support in burst-prone ground is no rockburst support at all. Hence, the best strategy is to stabilize the rock without fighting against the loads and stresses in the rocks using heavy rock support. Methods to avoid rockburst risks include changing of drift location, use of different excavation shapes, changing the stope size and/or shape, altering mining sequencing and potentially switching mining methods.

The second principle advocates the use of yielding support in bursting grounds. When a brittle rock fails, it is always associated with large rock dilation. When a seismic event occurs, rocks can be subjected to large impact energy. Therefore, the installed rock support system must be able to absorb dynamic energy while also accommodating large static and dynamic rock deformation due to rock failure. It is often uneconomical to prevent rockburst damage from happening by increasing the load capacity of rock support. The support behavior must be fundamentally changed to allow for yielding. A yielding support system is able to tolerate large tunnel convergence without “self-destruction” while at the same time absorbing large dynamic energy, thus providing necessary support to ensure safety and maintain serviceability of the tunnel. A yielding rock support system is a system in harmony with its surrounding rock mass.

A chain is only as strong as its weakest link. In conventional rock support systems, the retaining element is often the weakest link. The connection between bolts and screen often fails in large rockburst events. Consequently, the effectiveness of a rock support system comprised of rockbolts and mesh depend on their capacity, but most importantly on the strength and capacity of the mesh and the connection between the bolts and the mesh. Unfortunately, design procedures for rock support design in underground construction focus mostly on checking how much load a rockbolt can support, or how much energy the rockbolt can dissipate. The failure of rock mass between the bolts and the impact of this failure on the rock support system is often not considered in design. The selection of surface support elements is often based on experience or empirical design method. Further research is needed to develop a rational design methodology for the surface support...
component in combination with the design of the holding element.

As a fundamental requirement, holding elements need to be combined with reinforcing elements such as rebars and surface support elements such as mesh and shotcrete to form a rock support system. There is no such thing as a “super” bolt or “super” liner that can be used alone to combat rockburst problems. Quite often, we need a rock support system that is comprised of different rock support components, because as indicated in Figure 1 all three support functions (reinforce, retain, and hold) are needed to form an effective rock support system. Some support components have multiple roles but may be strong in one aspect and weak in the others. It is essential that various support elements be combined to form an integrated support system so as to maximize their capabilities for support in burst-prone grounds. This is the principle of using an integrated system.

The fifth principle is the simplicity principle. Simplicity is powerful. Rock support elements should be relatively easy to be manufactured, installed, and maintained. Regardless of how effective it is, if a rock support element is complicated to manufacture and the cost is high, operators will be reluctant to use it. If it is difficult to install and production is adversely affected, its acceptance by the mine operators and workers will suffer. When it comes to rock support in burst-prone ground, it is always beneficial to follow Albert Einstein’s advice – “Make everything as simple as possible, but not simpler.”

There is still a misconception (i.e., rockburst-resistant support is expensive and it costs extra money) in the mining industry on the use of rockburst support in highly stressed ground. While mining companies aim at reducing cost in order to make profit, they cannot do so at the expense of safety. The consequence of rockburst can be extreme, ranging from damage to underground opening which requires rehabilitation, damage to mining equipment, loss of production, permanent loss of orebodies, to injury and fatalities. The cost associated with those items can be extremely high. For example, it is estimated that the rehabilitation cost is 10 to 20 times higher than the initial development cost in underground hard rock mines. A major rockburst may shut down mine production or tunneling operations for an extended period of time. In other words, if the price tag for rockburst damage is high, the cost of preventing it in the first place, using a rockburst resistant rock support system, can be remarkably low. Many accidents have told us that prevention and control in burst-prone ground is most cost-effective.

The last principle advocates the ability to anticipate and to adapt. Burst-prone ground conditions and rockburst damage severity potential change constantly, and it is unrealistic to have a fixed design that cannot be changed. Let the underground excavation and rock support method be responsive to the variety of ground conditions that can be encountered. The art of rock support in burst-prone ground is not to rely on the low likelihood of unexpected ground behaviors, but on the readiness to manage them with an effective rock support system that is unbeatable.

By understanding the seven principles (Figure 3), the ability to safeguard workers and company property can be increased. These core principles must guide support design.

3.3 Design acceptability criteria

Rock support in burst-prone ground differs from conventional rock support where controlling gravity induced rockfalls and managing shallow loosing zones is the main concern. In addition to these design issues, rock support in burst-prone grounds needs to resist dynamic loading and large rock dilation due to violent rock failure.

The classical approach used in engineering design considers the relationship between the capacity (strength or resisting force) of the element and the demand (stress or disturbing force). Rock support design for burst-prone ground can follow the same approach but capacity must also be defined in terms of displacement and energy dissipation capacity. First, the expected loading condition or demand on the support is determined and, second, the various elements are dimensioned and then integrated into a support system to achieve a support capacity that exceeds the demand. The demand is influenced by many factors, such as opening size and shape, rock mass properties, in-situ stress level and orientation, seismic source type and characteristics, stress wave magnification, support conditions and properties, etc. In burst-prone ground, the following four design acceptance criteria need to be considered.

3.3.1 Force criterion

The load factor of safety (FS_{Load}) is defined by:

$$FS_{Load} = \frac{\text{Support Load Capacity}}{\text{Load Demand}}$$  \(1\)

In general, the force criterion covers the design for both static and dynamic loads. Under dynamic loading conditions, the dynamic acceleration will increase the load demand significantly and a yielding support system has to be used to reduce the demand to realistic load capacities.

3.3.2 Displacement criterion

Even when rock support systems are installed, rock fracturing cannot be prevented when the stress is high. When a rock fractures, it significantly increases its volume as it bulks. Near the excavation boundary, volume increase in the tangential direction is restrained and the fractured rocks can only deform in the radial direction, leading to large radial bulking deformations. Hence, the installed rock support system must have sufficient displacement capacity to meet or exceed the displacement demand. The displacement factor of safety (FS_{Disp}) is defined by:

$$FS_{Disp} = \frac{\text{Support Displacement Capacity}}{\text{Displacement Demand}}$$  \(2\)

3.3.3 Energy criterion

When a rock block is ejected from the excavation boundary, it possesses kinetic energy. If a rockfall is triggered, the energy demand is increased by the change in potential energy. Hence, the designed energy absorption capacity of the support system must meet or exceed the energy demand. The energy factor of safety (FS_{Energy}) is defined by:

$$FS_{Energy} = \frac{\text{Support Energy Capacity}}{\text{Energy Demand}}$$  \(3\)

When a rock with mass \(m\) is ejected from the tunnel roof at an ejection velocity \(v_e\), the support system with large displacement capacity contains the ejected rock after a displacement capacity of \(d_f\), the energy demand is (Kaiser et al., 1996):

$$E = \frac{1}{2}mv^2_e + mgd_f$$  \(4\)
where \( g \) is the gravitational acceleration. Hence, the support system for rock failing in the roof must be able to absorb this amount of kinetic energy.

### 3.3.4 System compatibility criterion
The previous three design criteria, i.e., load, displacement, and energy criteria, are intended for the design of reinforcement and holding elements. However, these elements can only work to achieve their design capacity if the surface support elements are strong and can transfer the related force, displacement or energy demands. There is a strong interaction between the reinforcement/holding elements and the surface support elements; i.e., the capacity of the reinforcement/holding elements depends on the capacity of the surface support elements, and the capacity of the surface support elements also depends on the capacity of the reinforcement/holding elements.

An optimal rock support system is one with compatible and balanced support elements where all support elements work in harmony to contribute their capacity to the fullest. The holding and the surface retaining element’s capacity of the system must be compatible to rock load and rock deformation, and holding element’s capacity must be compatible to the surface retaining element’s capacity. In design, it is difficult to calculate the demand for surface support elements. Hence, empirical design methods are often used but it is important to ensure that the load, displacement, and energy capacities of surface support are compatible to those of the reinforcement/holding elements.

### 4 ROCK SUPPORT DESIGN AND VERIFICATION

#### 4.1 Rockburst support design procedure and tools

As explained above, rockburst support design is to meet the load, displacement, and energy demands with appropriate support capacities, under given ground and excavation conditions.

Geological and geotechnical data are the foundation for all mine design. Because rock mass behavior can vary drastically in a mine or along a tunnel, it is necessary to establish rock mass domains according to geological, geometrical, and seismic data. First, rock mass zones (or blocks) are typically domain based on seismic activities, which is mostly influenced by mining activities. Next, within each domain, sub-zones are identified within which the key engineering design parameters are comparable. The most common parameters are likely to be lithology, intact rock strength, discontinuity frequency, and rock mass quality.

In each design domain, one needs to estimate the anticipated seismic event magnitude and event location as well as potential rockburst damage mechanisms, and calculate the load, displacement, and energy demands on the rock support for the dominant rockburst damage mechanism. It is often difficult to know in advance which type of rockburst damage mechanism is likely to occur and the expected damage severity of that damage mechanism. Hence, all three rockburst damage mechanisms need to be analyzed separately before the critical support demand can be identified. Then, the best decision on rock support system selection can be conducted in view of the worst-case scenario. An evaluation can be made on whether rock support can be designed to prevent the initiation of damage or whether the rock support system must be designed to control the failure process.

Next, one will have to examine all available rock support elements and pick the best combination of the support elements to form an integrated rock support system with the desired support capacities exceeding the load, displacement, and energy demands previously determined. Support selection for rockburst conditions is based on the load–displacement characteristics of the support system and the expected nature and severity of rockmass failure, by combining different holding, reinforcing, and retaining elements and ensuring the integrity of the support system. This is achieved by considering compatible support elements to form an integrated rock support system, and eliminate the weakest link in the system. A satisfactory design can rarely be achieved in one step, demanding various iterations and comparisons of design options.

Such designs cannot be carried out manually and in a consistent manner for all mine excavations. Also, when conducting such time and effort consuming designs manually, costly mistakes can be made if attention is not paid to details.

A design tool, called BurstSupport, is currently under development at Laurentian University, Canada, with support from CEMI (Centre for Excellence in Mining Innovation) and several mining companies. This tool will facilitate the interactive process of rockburst support design. BurstSupport will enable the user to assess load, displacement, and energy demands at multiple drifts by considering anticipated event magnitude and location, in-situ stress, drift location and orientation, rock mass quality. The user will be able to specify rock support systems with defined support capacities to meet the anticipated demands and, in this fashion, will be able to address the rockburst damage problem proactively by using an effective rock support system. As indicated above, an optimal design is obtained in an iterative process and the tool will assist to achieve optimization and verification tasks.

#### 4.2 Design verification

Although some rational design methods and numerical methods are used, rock support system design for underground excavations is largely dependent on empirical methods and practical experience. Whatever design method is used, the design needs to be assisted by the observational design method.

The observational design approach, advocated by Peck (1969), is recommended for use in rockburst support design as well. The fundamental principles of the observational design approach include avoiding difficult ground conditions, letting the rock support itself, conducting robust design, having an adequate field monitoring plan, having plans for contingency measures, and adjusting construction method according to exposed condition. Observational methods utilize monitoring as an integral part in the rock support system design process. The underlying logic is that a design is not complete until the design assumptions have been verified and the structure’s performance has been matched with performance predictions.

Field monitoring provides feedback loops to the design process. Analysis of microseismic monitoring may indicate that the design seismic magnitude and location needs adjustment; analysis of convergence data and depth of failure data may suggest that the adopted rock mass properties or even the in-situ stress field needs modification; observation of rock support system performance may show that the selected support system needs modification. The BurstSupport tool can be used by ground control engineers to conduct this design verification. Hence, a rationale design combined with field observation and monitoring is the key to the success of rockburst support design in burst-prone grounds.
5 CONCLUSION

Rockbursts are complex natural and mining-induced phenomena occurring in deep underground construction. Much effort has been put into research to understand why it happens and to anticipate where it will happen. Unfortunately, due to the complexity of rock mass and the boundary conditions, we still do not have great confidence in predictive means and reality repeatedly reminds us of deficiencies. As mining progresses to deeper ground, violent rock failure cannot be avoided and it will have to be dealt with on a routine basis by implementing rockburst resistant support strategies.

Rockburst support is not a mystery nor a skill that only few can master. The first important step that leads to mastering the science and art of rockburst support design is to understand rockburst mechanisms and to identify major factors that influence rockburst damage. Next, it is imperative to understand the three important functions of rock support—reinforce, retain, and hold. In addition, there are a few design principles, as outlined in this paper, which need to be understood and practiced.

Four design acceptability criteria, load, displacement, energy, and system compatibility criteria, must be satisfied. By following these design acceptability criteria, a clear distinction between the rockburst support design and conventional rock support design is made.

Finally, realizing that the design procedure for rock support design in burst-prone grounds is iterative, a design tool is under development to quickly and systematically evaluate different rockburst support options in a user-friendly manner.

REFERENCES


