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Design of rock support system under rockburst condition

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Abstract: As mining and civil tunneling progresses to depth, 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 zones of loose rock are the main target. Rock support in burst-prone ground needs to resist dynamic loads and large rock dilation due to violent rock failure. After reviewing the rockburst phenomenon, types of rockbursts, damage mechanisms, and rockburst support design principles and acceptability criteria, this paper describes that the support selection process in burst-prone ground is iterative, requiring design verification and modification based on field observations. An interactive design tool for conducting rockburst support design in underground tunnels is introduced to facilitate cost-effective design.

Key words: rockburst; rockburst damage; rock support; design

1 Introduction

As the depth of mining and civil underground construction increases, stress-induced rock fracturing is inevitable and when stored energy is suddenly released, rocks fail violently, leading to seismic events and rockbursts. A rockburst is defined as damage to an excavation that occurs in a sudden or violent manner and is associated with a seismic event (Hedley, 1992; Kaiser et al., 1996). Many hard rock mines in Canada, China, Chile, South Africa, Australia, Sweden, and other countries, and some deep civil tunnels in Switzerland, China, and Peru have experienced rockbursts to various degrees. Two recent civil projects that experienced severe rockburst damage are the Jinping II hydropower intake tunnels in China and the Olmos Trans-Andean tunnel in Peru.

Considerable research effort, at an international scale (e.g. Australia, Canada, South Africa, China), has been devoted to the understanding of the rockburst phenomenon. Micro-seismic monitoring systems are in operation at most burst-prone mines and tunnel construction sites around the world. From the waveform records, the time, location, radiated energy, seismic moment and other source parameters of a seismic event can be obtained. Monitoring of seismic events in mines or along tunnels therefore is a very useful tool for outlining potentially hazardous ground conditions and assisting construction management in effective re-entry decision-making. Advanced three-dimensional (3D) numerical modeling and visualization can identify potentially hazardous areas and assist in planning and design underground structures.

Rockburst risk can often be reduced by selecting appropriate mining or excavation methods and sequences, and by strategically placing developments and other infrastructure. However, due to uncertainties in rock mass properties and boundary conditions (e.g. in-situ stress, fault zone distribution), engineering design will have to rely on ground control measures with burst-resistant rock support as an important line of defense to ensure workplace safety. For this reason, it is imperative to design proper burst-resistant support systems when mining and tunneling at depth. No excavation in burst-prone ground should be advanced without the installation of burst-resistant support systems (Stacey, 2011).

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The design of rock support in burst-prone grounds differs from conventional rock support where controlling gravity-induced rockfalls and managing shallow zones of loose rock are the main target. Rock support in burst-prone ground needs to resist dynamic loads and large deformations due to rock dilation, called bulking, during the violent failure of rock. The term “bulking” is used to describe volume increases of the rock mass near an excavation due to geometric non-fit during the transition from competent to fractured and then to broken rocks. Near excavations, bulking is unidirectional toward the excavation (perpendicular to the wall), a function of the applied tangential strain, and highly dependent on the confining stress. For this purpose of rock support in burst-prone ground, the designers must understand the rockburst damage mechanisms, assess the rock support demands, and be able to select the right support products to fulfill several support functions. Furthermore, the 3D complex geological and geometrical conditions as well as the uncertainty or variability of design input parameters complicate the design. Hence, rock support design becomes an interactive and iterative process of selecting proper support elements to form a rock support system which has enough capacity to meet the expected demands.

Because of these complexities, it becomes quickly evident that such a design process cannot be carried out for all underground excavations in a consistent manner if the design is conducted manually. Tremendous time and effort would be required to manually conduct such design work and costly mistakes could be made if the design engineers do not pay attention to details. Hence, a design guideline which explains the principles and methodologies as well as rock support system capacities is required for design professionals. Furthermore, a rockburst support design tool which helps to streamline the design process and integrate past and current knowledge is needed for the mining and civil construction industries.

In response to industry’s needs, an R&D project is currently on-going at Laurentian University in Canada to produce a concise design guide and to develop an interactive design tool for rock support design in burst-prone grounds. In this paper, after reviewing the rockburst phenomenon, types of rockbursts, damage mechanisms, rockburst support design principles and design acceptability criteria, the design tool which can be used to facilitate a systematic and consistent rock support design in burst-prone grounds is introduced.

2 Rockbursting and rockburst damage

2.1 Rockburst phenomenon

Rockburst is a 20th 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). Rockbursting is the result of sudden and violent failure of rocks. There is a clear linkage between rockburst activities and mining depth. As mining migrates to deeper ground, in-situ stress becomes high relative to the rock strength and the likelihood of rockburst drastically increases. 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 brevity of discussion, we consider here three rockburst types, i.e. strainburst, pillar burst, and fault-slip burst. Rockbursts are either mining-induced by energy release causing damage at the source (e.g. strainburst without significant dynamic stress increase from a remote seismic event) or dynamically-induced rockbursts with damage caused by energy transfer or significant dynamic stress increase from a remote seismic event (e.g. strainburst with dynamic stress increase caused by a remote seismic event).

Rock mass failure occurs when the excavation-induced stress exceeds the peak strength of the rock mass. In many deep underground excavations, strainbursts are the most common rockburst type; they can be mining-induced due to static stress change caused by nearby mining or dynamically-induced due to dynamic stress increase caused by a remote seismic event (called dynamically-induced strainbursts). An example of strainburst damage is shown in Fig. 1.

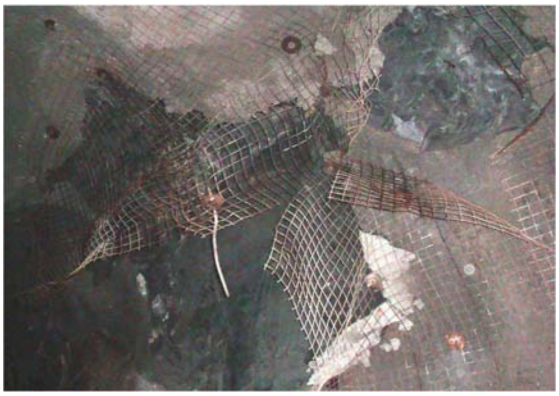


Fig. 1 Example of strainburst damage to a supported excavation.

Two conditions must be met for a strainburst to occur. First, the tangential stress (the maximum principal stress) must be able to build up in the immediate skin of the excavation. Second, the rock mass surrounding the fracturing rock must create a relatively “soft” loading environment such that the rock fails locally in an unstable, violent manner. The energy released by a strainburst comes from the stored elastic strain energy in the failing rock and the surrounding rock mass (not from the seismic source).

During tunnel and shaft construction, strainbursts normally occur within three times the diameter from the advancing face. Such strainbursts can also occur right at the tunnel face and in the floor. In mining, stress changes in the drifts (horizontal tunnels in a mine) may occur after development due to stopping activities; consequently, mining-induced strainbursts can happen during the production stage. Delayed strainbursts occur in situations where the maximum principal stress remains constant but the rock strength degrades over time, or the rock strength reduces due to loss of confinement.

Due to a potentially unstable equilibrium situation near an excavation, strainbursts may be triggered by a small dynamic disturbance, a production blast, a remote pillar burst or fault slip event. For such dynamically-triggered strainbursts, little or none of the released energy stems from the triggering event. Instead, the stored strain energy at the bursting location and the surrounding rock constitutes most of the release energy.

Pillar burst, as the name implies, is defined as a violent failure in the pillar core or the complete collapse of a pillar. Pillar bursts often occur in deep mines when the extraction ratio is high at a later stage of mining. The volume of failed rock and the affected surrounding rock mass is usually larger than that involved in a strainburst and hence the released seismic energy is much greater.

Similar to strainburst, pillar burst can be classified into mining-induced pillar burst and dynamically-induced pillar burst. A mining-induced pillar burst is caused by static stress increase from increased room span or nearby stope extraction. The seismic source is in the confined core of the pillar, and rockburst damage and seismic source are co-located. On the other hand, a dynamically-induced pillar burst is caused by dynamic stress increase from a remote seismic event. In this case, the rockburst damage and the seismic source (i.e. fault-slip event) are not co-located. An example of pillar burst is shown in Fig. 2.

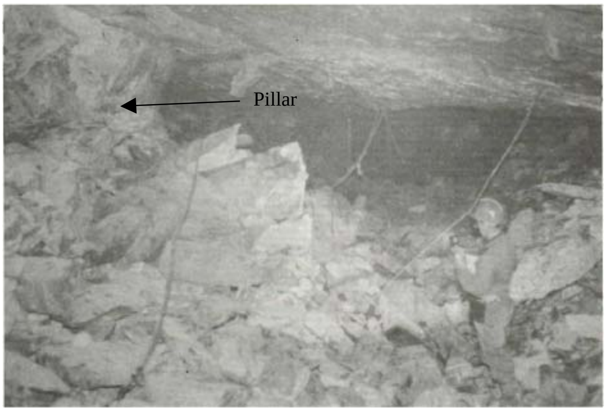


Fig. 2 An example of pillar burst (Hedley, 1992).

A fault-slip burst is caused by the dynamic slippage along a pre-existing fault or along a newly generated shear rupture. A critically stressed fault, with shear stresses exceeding the shear strength, can slip when the degree of freedom is changed as it is intersected by a mine opening. Alternatively, it may slip when the shear strength is reduced due to a drop in clamping stress or water infiltration into the fault. Finally, it may slip when the mining-induced shear stress is increased and exceeds the strength of the fault, which is a function of the normal stress, the coefficient of friction of the fault surface, its waviness or dilation characteristics, and, in the case of fracture propagation, the strength of the rock mass.

Similar to pillar burst, fault-slip rockbursts occur in deep mines when the extraction ratio is high and large closures are allowed to persist over large mining volumes. The most plausible cause of fault-slip along a pre-existing fault is the reduction of normal stress acting on the fault as a result of nearby mining, although an increase in shear stress or a combination of normal stress decrease and shear stress increase can similarly cause a fault to slip. This type of rockburst may release a large amount of seismic energy, coming from the instantaneous relaxation of elastic strain stored in a large volume of highly stressed rock surrounding the slip or rupture area. They may create sufficiently high ground vibrations or ground motions that can cause damage to excavations (dynamically-induced strainbursts), cause shake down of loose or insufficiently supported rock, and/or trigger strainburst and pillar burst at relatively remote locations (hundreds of meters from the seismic source).

Shear rupture type rockbursts have been observed in some mines, particularly in South African mines (Ortlepp, 1997, 2000). Large rockbursts, with Richter magnitude exceeding 3.5, can result from violent propagation of shear fracture through intact rocks. Ortlepp (1997) strongly advocated shear rupture as one of the most important source mechanisms for major rockbursts. There is however a possibility that his bias is in part influenced by the relatively soft mining system stiffness encountered in tabular ore bodies in South Africa.

2.3 Rockburst damage mechanism

Understanding the rockburst source mechanism is critical to deriving 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 rockfall induced by seismic shaking (Fig. 3). Rock bulking due to rock fracturing can be caused by both a remote seismic event and the bursting event itself. Brittle rock fracturing occurs as a result of crack and fracture initiation, propagation, and coalescence (Kaiser et al., 2000; Cai et al., 2004). This leads to the generation of new fracture surfaces in a previously intact or less fractured media and, as a consequence, this rock mass disintegration leads to rock mass bulking. This bulking process is in large part a result of geometric block incompatibilities and thus is much larger than dilation during plastic rock mass yield. Most importantly, it is directional, perpendicular to the excavation wall. During bulking, the broken rock volume increases as it is fractured and fragmented.

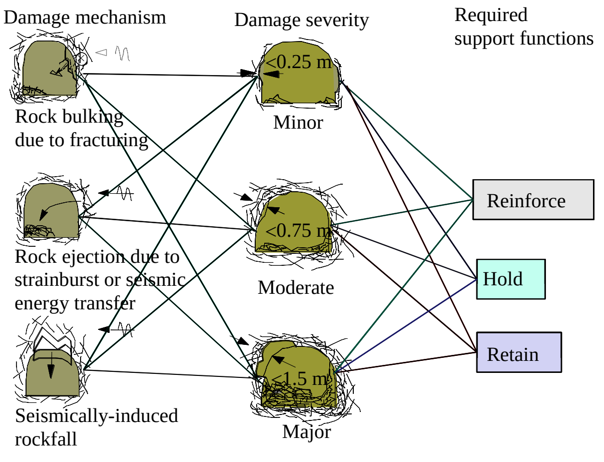


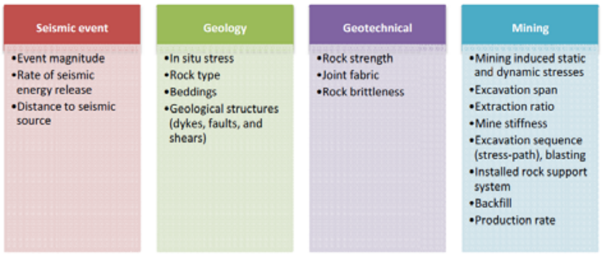
Fig. 3 Rockburst damage mechanism, damage severity, and required support functions (modified from Kaiser et al. (1996)).

Rock ejection can be caused by a strainburst event, a pillar burst event, or by a remote seismic event through dynamic moment transfer. Ejected rock may travel at velocities in excess of 3 m/s; velocities up to 10 m/s were estimated by Ortlepp and Stacey (1994). The upper end of this ejection velocity range cannot be explained by the moment transfer damage mechanism alone. When rock suddenly fractures, part of the stored strain energy in the surrounding rocks can be transferred to blocks in the form of kinetic energy, causing rock ejection. With high strain energy stored in the rock near the excavation, the stress wave from a remote seismic event may add a dynamic stress disturbance and cause a strainburst ("bring the bucket to overflow"). In this case, the ejection velocity is not directly related to the momentum from the seismic source but more closely related to the energy stored in the near-wall rock and how this stored energy is released.

Seismically-induced rockfalls, as the name suggests, are caused by the (low frequency) shaking of ground due to a large remote seismic event, perhaps induced by a pillar burst or a fault-slip rockburst. It occurs when an incoming seismic wave accelerates a volume of rock that was previously stable under static loading conditions, causing forces that overcome the capacity of the support system. Note that it is also possible that the first incoming seismic wave may fracture a volume of rock, and subsequent vibration induced by the seismic waves accelerates the fractured rocks, causing falls of ground. Seismically-induced rockfalls occur frequently at intersections where the span is large and roof rock confinement is low.

2.4 Factors influencing rockburst damage

There are many factors that influence rockburst damage and the severity of the damage (Hedley, 1992; Kaiser et al., 1996; Durrheim et al., 1998; Heal et al., 2006; Cai and Champaigne, 2009). Fig. 4 summarizes the main factors and groups them into four categories, i.e. seismic event, geology, geotechnical, and mining. Factors in the first two groups (seismic event and geology) determine the intensity of



Seismic event	Geology	Geotechnical	Mining
•Event magnitude •Rate of seismic energy release •Distance to seismic source	•In situ stress •Rock type •Beddings •Geological structures (dykes, faults, and shears)	•Rock strength •Joint fabric •Rock brittleness	•Mining induced static and dynamic stresses •Excavation span •Extraction ratio •Mine stiffness •Excavation sequence (stress-path), blasting •Installed rock support system •Backfill •Production rate

Fig. 4 Main factors influencing rockburst damage.

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.

When the size of an opening is large or when multiple openings are created close to each other, the chance of having a rockburst is greatly increased due to a reduction in loading system stiffness. Hence, excavation or yield zone geometry can also influence the rockburst propensity.

When geological weaknesses, such as faults or shear zones, or stress raisers, such as dykes, are nearby, the released energy may often be larger because these geological structures tend to create unfavorable stress and loading system conditions, e.g. by involving large rock volumes in the deformation and failure process.

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, and major) classification can be found in Fig. 3.

It is interesting to note from Fig. 4 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 manageable means to reduce and control rockburst damage potential. There are many methods to achieve this goal, such as changing the mining method, altering the mining sequence, changing drift locations, etc. This is where having a good underground construction strategy will pay off quickly. It should be pointed out that selecting a good construction strategy is necessary but not sufficient to create a safe work environment; a rockburst support plan needs to be implemented in parallel. The importance of having effective rock support systems in bursting ground has been demonstrated by numerous case histories. In the following sections, we discuss rockburst support design principles and methodologies and present a tool for designing rock support systems for highly stressed, burst-prone tunnels.

3 Rockburst support design principles and methodologies

3.1 Rock support functions

The mechanics of rock support is complex, and no models exist that can fully explain the interaction of various support components in a rock support system. Nevertheless, Kaiser et al. (1996) summarized three key support functions as: (1) reinforce the rock mass to strengthen it and to control bulking, (2) retain broken rock to prevent fractured block failure and unraveling, and (3) hold fractured blocks and securely tie back the retaining element(s) to stable ground (Fig. 5).

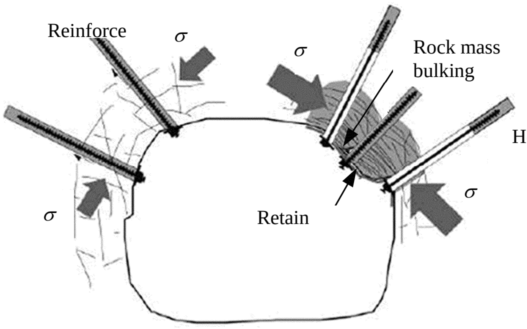


Fig. 5 Three key functions (reinforce, retain, and hold) of rock support (Kaiser et al., 1996).

The goal of reinforcing the rock mass using rock bolts is not only to strengthen it, thus enabling the rock mass to support itself (Hoek and Brown, 1980), but also to control the bulking process, as rock bolts prevent fractures from propagating and opening up. Fully grouted rebars, thread bars, or cable bolts are well-suited for rock reinforcement.

Under high stress conditions, fractured rocks between the reinforcing or 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-place concrete. Shotcrete needs to be reinforced by fiber or mesh to increase its tensile strength and toughness. Mesh-reinforced shotcrete or mesh over shotcrete offers a much superior retaining function under rockburst conditions. In conventional rock support systems, the retaining element is often the weakest link. A chain is only as strong as its weakest link. So, if we want to increase the overall capacity of the rock support system, the problem of weak retaining elements and its connection to the reinforcing or holding elements must be addressed.

When brittle rock fails, it is always associated with large rock mass bulking. When a seismic event occurs, this rock may also be subjected to large impact energy, and when failing in an unstable manner, stored strain energy may be released, leading to rock ejection. Therefore, the installed rock support system must be able to absorb dynamic energy while also accommodating large sudden rock deformations due to rock failure with associated bulking. The holding function is needed to tie retaining elements of the support system and the 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 conebolts and high capacity friction bolts must be used in the support system. The retaining component in a yielding support system must also be able to tolerate large tunnel convergence without "self-destruction" while at the same time absorbing large dynamic energy. A yielding rock support system is a system in harmony with its surrounding, failing rock mass. As a consequence, heavy continuous shotcrete rings are often too stiff as they cannot deform with the bulking rock.

The three support elements providing the reinforcement, retaining, and holding functions do not act independently. Therefore, these rock support elements have to be well connected, forming an integrated rock support system. The connection between the retaining elements and the reinforcing and holding elements deserves special attention to ensure optimal overall capacity of the support system. Fig. 3 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 tools for the construction and for dealing with 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 Champaigne (2009) summarized field experiences into a few simple and easy-to-understand principles (Fig. 6).

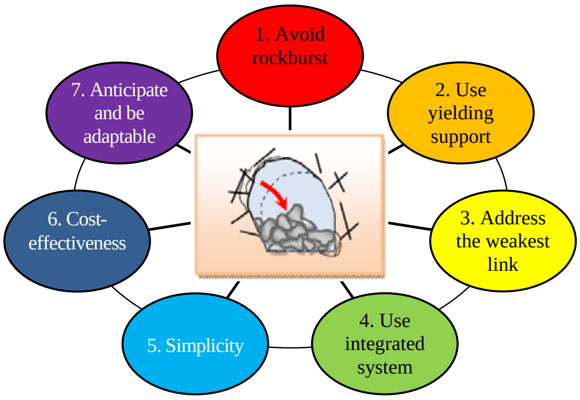


Fig. 6 Summary of seven rockburst support design principles.

The first principle is to avoid rockburst whenever possible. The supreme excellence in rock support in burst-prone ground is to avoid rockburst conditions. 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 tunnel location, use of different excavation shapes, changing the stope size and/or shape, altering mining sequence 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 and may be subjected to large impact energy. Therefore, the installed rock support system must be deformable and able to absorb dynamic energy. It is often un-economical to prevent rockburst damage from happening by increasing the load capacity of rock support. The support behavior must be fundamentally changed to a deformable yielding system that is able to tolerate large tunnel convergence without "self-destruction" while absorbing dynamic energy, thus providing support to ensure safety and serviceability of the tunnel. A yielding rock support system is a system in harmony with its surrounding failing 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 and connection between bolts and screen often fails in large rockburst events. Consequently, the effectiveness of a rock support system comprised of rock bolts and mesh depends on their capacity, but most importantly on the strength and capacity of the connections between the bolts and the mesh. Unfortunately, design procedures for rock support design focus mostly on checking how much load a rock bolt can carry, or how much energy the rock bolt can dissipate. The failure of the 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 and the strength of the connections must be matched with the capacity of the bolts.

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 Fig. 3 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 another. It is essential that various support elements be combined to form an integrated support system. 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 the miner 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.”

Unfortunately, there is still a wide-spread assumption that rockburst-resistant support is expensive for use in highly stressed ground. While mining companies aim at reducing cost in order to stay competitive, they cannot do so at the expense of safety. The consequence of rockburst can be extreme, ranging from damage to underground opening with high rehabilitation costs, damage to mining equipment, loss of production, permanent loss of parts of ore bodies, to injury and fatalities. The cost associated with these items can be extremely high. For example, it is estimated that the rehabilitation cost may be 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. Damage 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. The underground excavation and rock support method therefore must be responsive to a 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 (Fig. 6), the ability to safeguard workers and investment risk can be improved. These core principles must guide rock support design.

3.3 Rockburst support acceptability criteria

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

The classical approach in engineering design assesses the safety margin by the ratio between the capacity (strength or resisting force) of support elements and the demand (stress or disturbing force). Rock support design for burst-prone ground can follow the same approach but the capacities must also be assessed in terms of load, displacement, and energy dissipation capacities. First, the expected loading condition or demand on the support is determined; next, various support elements are dimensioned and then integrated into a support system to achieve a support capacity that exceeds the anticipated demand. The demand is influenced by many factors, such as opening size and shape, rock mass properties, in-situ and mining-induced 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 simultaneously assessed. Not all of them may be critical and thus not all will, in a given case, affect the final support system.

(1) Force criterion

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

$$FS_{\text{Load}}=\frac{\text{Support load capacity}}{\text{Load demand}} \tag{1}$$

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 and movement may be triggered. If this is the case, a deformable support system has to be used to dissipate some of the energy demand until the static demand drops below the support load capacity.

(2) Displacement criterion

Even if an effective rock support system is installed, rock fracturing cannot be prevented if the stress exceeds the rock mass strength. When a rock fractures, as its volume increases, it bulks. Volume increase in the tangential loading direction is restrained and the fractured rocks can only deform in the “radial” direction into the excavation, leading to large bulking deformations near the wall. 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

$$FS_{\text{Disp}}=\frac{\text{Support displacement capacity}}{\text{Displacement demand}} \tag{2}$$

(3) Energy criterion

When a rock block is ejected from the excavation boundary, it possesses kinetic energy, or in the case when 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

$$FS_{\text{Energy}}=\frac{\text{Support energy capacity}}{\text{Energy demand}} \tag{3}$$

When a rock with mass m is ejected from the tunnel roof at an ejection velocity v_{e}, the support system with a large displacement capacity contains the ejected rock after a displacement of d_{s}, the energy demand (Kaiser et al., 1996) is

$$E=\frac{1}{2}mv_{\text{e}}^2+mgd_{\text{s}} \tag{4}$$

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.

(4) System compatibility criterion

The previous three design criteria, i.e. load, displacement, and energy criteria, are intended for the design of reinforcement and support holding elements. However, these elements can only work to achieve their design capacity if the surface support elements are strong and can effectively transfer the loads to the reinforcement and holding elements. 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, as well as the spacing 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 capacities to the fullest. The holding and the surface retaining elements’ capacity of the system must be compatible with rock load and rock deformation, and holding element’s capacity must be compatible with 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 Rockburst support design using BurstSupport

4.1 Design procedure

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 and tunnel 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 varying geological, geometrical, and seismic data considerations. First, the rock mass along a tunnel alignment is typically divided into domains 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, such as in-situ or mining-induced stress, lithology, and rock mass quality (intact rock strength, discontinuity frequency, etc.), are comparable.

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 dominate the design as the expected damage severity controls the demand. 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 made in view of the worst-case scenario (the controlling criterion). Furthermore, it can be assessed whether rock support should be designed to prevent the initiation of damage or whether the rock support system must be designed to control the failure process with related deformations and energy release.

Next, one will have to examine all available rock support elements and pick the best combination of support elements to form an integrated rock support system with the desired support capacities exceeding the anticipated load, displacement, and energy demands previously determined. In recent years, many new support products (Ortlepp and Erasmus, 2005; Varden et al., 2008; Potvin, 2009; Bucher et al., 2010; Cai et al., 2010; Doucet and Gradnik, 2010; Li and Charette, 2010; Cai and Champaigne, 2012) have been developed. This provides an enhanced pallet of support options for the users but also introduces a level of uncertainty as not all new products act in the same manner and have a proven track record. Prudence is advised when considering products as specified performances may not be achievable under field conditions.

Support systems for rockburst conditions are selected on the basis of their load-displacement characteristics and the expected nature and severity of rock mass failure, by combining different holding, reinforcing, and retaining elements and ensuring the overall integrity of the support system. This is achieved by considering compatible support elements to form an integrated rock support system, thereby eliminating the weakest link in the system. A satisfactory design can rarely be achieved in one step, demanding various iterations and comparisons of design options.

4.2 Design tool

Mine geology and infrastructures are complex and three-dimensional in nature. Presently in mining practice, either rockburst support is selected based on site specific or global experience or the design is performed using often simplistic spreadsheet calculations. However, rock support design cannot be carried out in a systematic manner without taking into account geometric (mine excavations) and geological complexities. Furthermore, when performing such time and effort consuming designs manually, costly mistakes may be made if attention is not paid to the interaction of the various influence factors outlined above.

A design tool called BurstSupport is being developed at Laurentian University, Canada, with support from CEMI (Centre for Excellence in Mining Innovation), NSERC (The Natural Sciences and Engineering Research Council of Canada), and several mining companies (see acknowledgements) to address the needs of industry. This tool encapsulates some of the research findings from the Canadian Rockburst Support Handbook (Kaiser et al., 1996) and integrates many recent research outcomes from other investigators. As well, it facilitates the interactive and iterative process of rockburst support design. Parties potentially interested in participating in the further development of the tool are invited to contact the authors to discuss project sponsorship.

BurstSupport is a standalone Windows-based software tool which enables the user to assess load, displacement, and energy demands at multiple drift locations by simultaneously considering anticipated seismic event magnitude and location, in-situ and mining-induced stress conditions, drift orientation, and rock mass quality. Rock support can be selected from a pre-defined support database and assigned to drifts at various locations. Furthermore, 3D mine structures and geological structures can be imported into the tool for easy manipulation (rotation, zoom, pan, etc.). The screenshot presented in Fig. 7 shows the main user interface for effective display 3D geometrical objects for data fusion and integration.

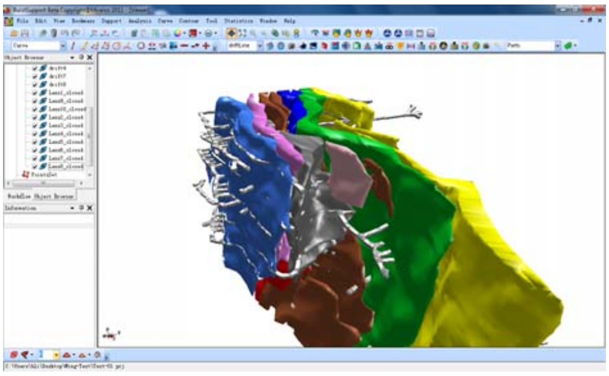


Fig. 7 Main user interface of BurstSupport.

As shown in Fig. 8, the user can specify a design seismic event or multiple seismic events (shown as balls in the figure) which may occur in the mine during operation and calculate resultant peak particle velocities (*ppv*) along the drifts that require rockburst support consideration. The calculation of *ppv* is based on the scaling law given by Kaiser et al. (1996) as

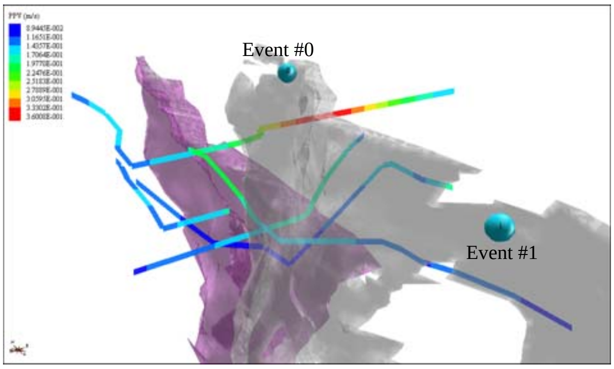


Fig. 8 Calculated *ppv* along the drifts (*ppv*=0.089–0.36 m/s).

$$ppv = C^* \frac{M_0^{a^*}}{R} \tag{5}$$

where M_0 is the seismic moment (GN·m), R is the distance between the drift location and the seismic source (m), and a^* and C^* are empirical constants that should be calibrated for each site. Seismic moment can be related to the event magnitude. Based on the analysis of seismic data from a global database, it was found that a^* in Eq. (5) can be fixed at a^*=0.5 and C^* values are determined from $\lg(Rppv)$-$\lg(M_0\Delta\sigma)$ plots with a reasonable upper-bound limit (e.g. at 95% confidence level), where $\Delta\sigma$ is the stress drop. The values of *ppv* shown in Fig. 8 are calculated using the scaling law with two sequential seismic events whose Richter magnitudes are 3.0 (Event #0) and 2.0 (Event #1), respectively. The maximum value of *ppv* due either event at a drift location is shown in Fig. 8.

Alternatively, the BurstSupport tool allows direct import of ground motion parameters to drift locations, calculated using the synthetic ground motion (SGM) approach. The SGM technique was widely used in earthquake study (Boore, 2003) and has attracted some attention in mining (Hildyard, 2001; Hildyard and Milev, 2001). The SGM approach generates the modeled near-field waveforms by considering fault-slip mechanism, stress drop, slip direction, slip time, and slip amount. The source waves are then propagated in the media by a nonlinear site response analysis using 3D analytical or numerical models which can effectively consider the influence of excavations, geological structures, and mining-induced stress changes on wave propagation. More representative *ppv* and *ppa* values at the drift locations can be obtained from SGM simulations.

In-situ and mining-induced stresses influence the depth of failure and hence the required amount of rock support. Stress analysis can be performed using an external 3D FEM, FDM, or BEM tools, and stress component values on each node along the drift centrelines can be imported into the BurstSupport tool. The maximum tangential stress in a plane perpendicular to the drift axis is found and the depth of failure is estimated using the empirical method described by Kaiser et al. (1996) and Martin et al. (1999). An example of calculated depth of failure is presented in Fig. 9. When calculating the anticipated depth of failure (d_f), the tool takes the rock mass strength, drift orientation, and stress magnitudes into account. By comparison of Figs. 8 and 9, it can be seen that the greater depth of failure in this case is not dominated by the ground motion as deeper damage is predicted at locations of lower *ppv*. In addition to *ppv*, other factors such as stress orientation and rock strength affect the depth of failure at this location.

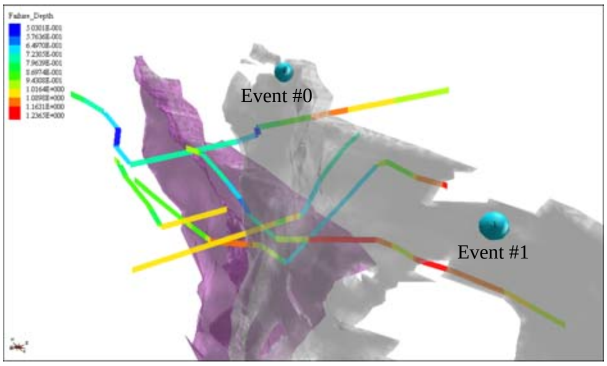
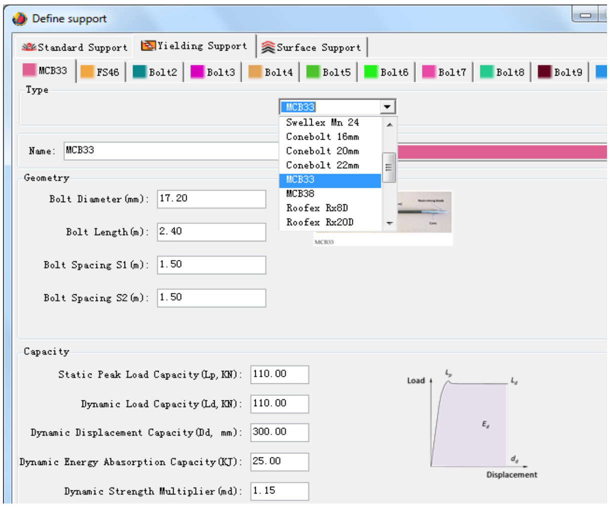


Fig. 9 Calculated depth of failure along the drifts (d_f =0.5–1.2 m).

A convenient feature of the tool is that the user is able to manually select rock support systems with defined support capacities and assign/visualize the rock support pattern to a specific section of the drift. Suggested values of load, displacement, and energy capacities of most commercially available rock bolts are included in the database but the user can also modify or define support properties (Fig. 10). Through an interactive and iterative process of adjusting rock support type and bolt spacing, the factors of safety for load, displacement, and energy can be checked to meet the minimum requirements. One example of calculated factor of safety for the displacement demand is presented in Fig. 11. The result shows that the lowest factor of safety for the displacement demand is 2.65, because high displacement yielding rock bolts (with a displacement capacity of 300 mm) are applied. If rock bolts with a 50 mm displacement capacity were used, the factor of safety would be less than one in some drift sections (not shown). On the other hand, if yielding bolts with 150 mm displacement capacity are used, the minimum factor of safety for the displacement demand is 1.3. For the drifts under consideration, a decision can therefore be made to select rock bolts with a displacement capacity of 150 mm to optimize the design. In this fashion, the rockburst damage problem can be addressed proactively by prescribing cost-effective rock support systems to the mine drifts. Caution should though be exercised as the cumulative effect of various input parameters may lead to large variability in support demand. Sensitivity analyses or parametric studies are advised before a final support system is selected (see below).



Type: MCB33

Name: MCB33

Geometry

Bolt Diameter (mm): 17.20

Bolt Length (m): 2.40

Bolt Spacing S1 (m): 1.50

Bolt Spacing S2 (m): 1.50

Capacity

Static Peak Load Capacity (Lp, KN): 110.00

Dynamic Load Capacity (Ld, KN): 110.00

Dynamic Displacement Capacity (Dd, mm): 300.00

Dynamic Energy Abasorption Capacity (KJ): 25.00

Dynamic Strength Multiplier (md): 1.15

Fig. 10 Screenshot of defining rock support window.

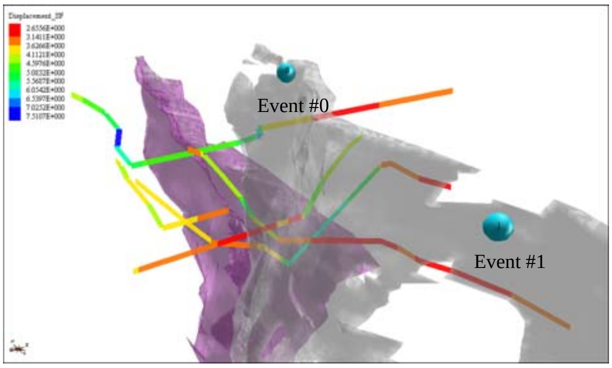


Fig. 11 Factor of safety for displacement demand visualized on mine drifts (*FS* = 2.65–7.51).

As illustrated above, an optimal support design strategy is obtained following an iterative process wherein the tool effectively assists in achieving optimization and verification tasks. Another useful feature of the tool is the statistical analysis of prescribed rock support (by providing statistics of some parameters) for the drifts such as the minimum factors of safety and the total numbers of rock support in one particular section of the drift so as to facilitate mine planning. For example, the total numbers of rock bolts in one mine level can be found easily from the statistical analysis. The total numbers of rock bolts thus calculated consider the bolt pattern and the 3D geometry of the drifts.

4.3 Design verification

Although some model-based design 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 applied, a final design is best arrived at based on an observation design method. This is particularly the case for bursting conditions because of large uncertainties associated with the seismic event magnitude and location, the rock mass strength, local stress, and rock support capacities.

The observational design approach, advocated by Peck (1969), is highly recommended for use in rockburst support design. The fundamental principles of the observational design approach include avoiding difficult ground conditions, letting the rock support itself (Hoek and Brown, 1980), conducting robust design, having an adequate field monitoring plan, having plans for contingency measures, and adjusting construction methods 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 input for feedback loops in 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 or support component connects need modification. The BurstSupport tool can be used by ground control engineers to conduct this design verification. A rational design combined with field observation and monitoring is the key to the success of rockburst support design in burst-prone ground.

5 Conclusions

Rockbursting is a complex mining-induced phenomenon occurring in deep underground construction. Much effort has been put into research to understand why rockburst happens and what the anticipated damage processes are. 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 current deficiencies. As mining progresses to greater depths, violent rock failure cannot be avoided and it will have to be dealt with on a routine basis by implementing rockburst resistant support strategies.

The first step in mastering the science and art of rockburst support design is to understand rockburst mechanisms and identify the main factors that influence rockburst damage. Next, it is imperative to understand the seven principles of rockburst support design and three important functions of rock support, i.e. reinforce, retain, and hold. Most importantly, four design acceptability criteria, i.e. load, displacement, energy, and system compatibility criteria, must be satisfied by any design. 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 ground is iterative, a design tool called BurstSupport is being developed to assist ground control engineers to quickly and systematically evaluate different rockburst support options in a user-friendly manner. The BurstSupport design tool, which considers seismic event and ground motion, as well as rock mass quality and mining-induced stresses, assesses the load, displacement, and energy demands, and provides ground control engineers with a new set of tools for mine planning and geomechanics design. It is envisioned that rockburst risk management can be significantly improved using this tool.

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