Managing rockburst risk in D&B tunnels

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ABSTRACT
Deep mining and tunnelling share the challenge of dealing with overstressed rock and rockmasses. Managing rockburst risk in a tunnelling operation has some fundamental differences compared to mining. Rockburst mechanics and character differ as does the range of options for controlling the potential for the rockburst hazard. Due to limited operational options in tunnelling, the emphasis for risk management must shift to impact mitigation. This paper presents a number of common rockburst mechanisms and outlines a strategy for risk management in deep tunnels.

RÉSUMÉ
Les mines et tunnels industries les deux connaissent les défis découlant de fortes contraintes dans la roche et rockmasses fragile. La gestion du risque des coups de toit efficace en tunnel présente des différences importantes par rapport à l’exploitation minière. Les mécanismes de rupture sismique diffèrent dans un environnement de tunnel isolé. Le caractère du danger diffère aussi fait le choix d'options pour contrôler le danger potentiel de rafales. Avec les options opérationnelles limitées disponibles dans un projet de tunnel qui est déjà en cours, l’accent devrait passer à la gestion du risque pour atténuer les impacts. Ce document présente un certain nombre de mécanismes communs des coups de toit et définit une stratégie pour la gestion des risques dans les tunnels profonds.

1 INTRODUCTION
Rockbursts are explosive failures of rock which occur when high stress concentrations are induced around underground openings (Hoek 2006) in brittle rock or rockmasses with brittle structure. In mining, there are many different mechanisms that lead to rockbursts. Pillar failure can be very violent if the pillar core reaches capacity and the mine geometry is such that instantaneous deformations (system unloading) are large. Large stress changes associated with large scale mining can result in fault slip distant from the drift or shaft but capable of inducing sympathetic strain bursts (due to stress wave propagation) or seismically induced ground falls. In tunnelling, however, the most important mechanism is strain bursting of walls and the tunnel face, with or without structural control and as a result of the complex stress path within the near-field rock as the tunnel advances (Diederichs et al 2013).

Compared to squeezing and other forms of tunnel instability, there have been relatively few experiences in Europe with brittle failure in hard more massive rockmasses (Rojat et al 2009, Hagedorn et al 2008, Vuilleumier and Aeschbach 2004). With large power projects under construction in China, there have been numerous recent rockburst challenges (Zhu et al 2010) that have highlighted the dangers of rockbursting in tunnels. There has been a great deal of experience with rockbursts in the South African, North American and Australian mining industries (Blake and Hedley 2004, Ortlepp and Stacey 1994, and many others). More recently, deep tunnelling in the Andes of South America has resulted in case examples of brittle or violent rockbursting (Diederichs et al 2013, Abadia Abanon 2007).
resulting in an instantaneous and violent bulking (or explosive ejection if not supported properly). This type of rockburst hazard can be prevented by stiff reinforcement preserving rock strength but may also require support with high displacement capacity at significant load mobilization that does not impact the final load capacity. This type of burst is referred to a strain burst. In this case the energy of ejection comes from the rock surrounding the failing volume. Peak particle velocity measured from a seismic event is not relevant in this case as a measure of intensity although the peak velocity of ejection is an important indicator of the hazard.

The second mechanism is the violent ejection of a mass or block of rock due to an incoming seismic wave from a more distant seismic event. Peak particle velocity is a relevant measure of intensity. This type of rockburst damage requires energy absorption capacity. In mining the seismic energy can come from any number of mechanisms associated with mining in the vicinity. In a single tunnel development, there is less chance of a major event located distal from the tunnel (unless the span is large and the advance round large). Normally distal events can come from faults and structures within a few tunnel diameters of the tunnel wall or face. Changes in rockmass strength and stiffness (dykes or geological contacts for example) can be sources of distal events as well as initiating events at the tunnel perimeter.

The final category refers to ground that may be already unstable and is finally taken to failure by the disturbance due to a remote seismic event. Again peak particle velocity and frequency are important parameters for the initiating event and the impact on the unstable ground. It is implied that this rockmass is already adequately supported for static loading. This static support is then overloaded by a short lived reduction in natural supporting capacity within the rockmass. This mechanism does not require any special support beyond the normal static support (rebars, shotcrete, etc) although additional excess capacity is required if such events are anticipated. This definition of rockburst is not intended to apply to unsupported ground that is inherently unstable.

Such a groundfall in unstable ground could be triggered by machinery, blasting or any other mild disturbance and can only be considered a rockburst if the correct specified static support has been installed and the disturbance is a true seismic event such as a fault slip some distance from the tunnel or a strain burst in another location along the tunnel. It is also important to note that large groundfalls or collapses due to structure or chimney/caving failure can be sudden and create a loud noise and air blast similar to a rockburst. The important difference is that the driver in these cases is gravity without dynamic excess energy release.

Table 1, extracted from the Canadian Rockburst Handbook lists the various mechanisms and qualitative intensity levels. Note that these levels were developed for mining and may not be appropriate for some tunnelling operations depending on the span, excavation method and operational environment. Examples are shown in Figure 2.

<table>
<thead>
<tr>
<th>Damage mechanism</th>
<th>Damage severity</th>
<th>Case of rockburst damage</th>
<th>Thickness [m]</th>
<th>Weight [kN/m²]</th>
<th>Closure* [mm]</th>
<th>v_p [m/s]</th>
<th>Energy [kJ/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulking from ejection</td>
<td>Minor</td>
<td>highly stressed rock</td>
<td>&lt; 0.25</td>
<td>&lt; 7</td>
<td>&lt; 1.5</td>
<td>&lt; 1.5</td>
<td>not critical</td>
</tr>
<tr>
<td>Major</td>
<td>stored strain energy</td>
<td>1.5</td>
<td>50</td>
<td>60</td>
<td>1.5</td>
<td>not critical</td>
<td></td>
</tr>
<tr>
<td>Bulking</td>
<td>Minor</td>
<td>highly stressed rock</td>
<td>&lt; 0.25</td>
<td>&lt; 7</td>
<td>&lt; 1.5</td>
<td>&lt; 1.5</td>
<td>not critical</td>
</tr>
<tr>
<td>Major</td>
<td>with significant</td>
<td>&gt; 0.75</td>
<td>20</td>
<td>30</td>
<td>1.5</td>
<td>10</td>
<td>not critical</td>
</tr>
<tr>
<td>Major</td>
<td>excess strain energy</td>
<td>1.5</td>
<td>50</td>
<td>100</td>
<td>1.5</td>
<td>25</td>
<td>30</td>
</tr>
<tr>
<td>Ejection by remote seismic event</td>
<td>Minor</td>
<td>seismic energy</td>
<td>&lt; 0.25</td>
<td>&lt; 7</td>
<td>&lt; 1.5</td>
<td>&lt; 1.5</td>
<td>3 to 10</td>
</tr>
<tr>
<td>Moderate</td>
<td>transfer to</td>
<td>&gt; 20</td>
<td>300</td>
<td>3</td>
<td>10</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Major</td>
<td>joint or broken rock</td>
<td>&gt; 1.5</td>
<td>50</td>
<td>&gt; 300</td>
<td>&gt; 3</td>
<td>20</td>
<td>50</td>
</tr>
</tbody>
</table>

v_p is the velocity of displaced or ejected rock; a and g are seismic and gravitational accelerations
* closure expected with an effective support system

Figure 2: Examples of (top) minor, (middle) intermediate to severe, (bottom) very severe strain bursts in tunnels
Most of the discussions on rockburst damage in mining environments has been based on the primary mechanism of a remote seismic event, triggered by large scale mine stoping, on a tunnel within the mine infrastructure. For tunnelling not associated with mining, the primary source of seismicity is the rockmass around the tunnel itself. It is possible for the stress changes and blasting associated with an isolated tunnel to generate structural seismicity some distance away from the active heading. Far more common is the strainburst at or near the active tunnel face (bulking with ejection in Table 1). Examples of strain bursts of increasing intensity are shown in Fig 2.

2 STRAINBURST MECHANICS

In terms of understanding and likelihood assessment, it is important to understand the mechanics of rockbursting in terms of the components:
- Stress Concentration
- Deconfinement
- Brittle failure
- Energy storage
- Energy release
- Volume of failure

2.1 Stress Concentration

Stress concentrations arise at the tunnel boundary away from the advancing face according to the classic formula for maximum wall stress in terms of the principal stresses within the plane of the tunnel section:

\[ \sigma_{\text{max}} = 3\sigma_1 - \sigma_3 \]  

(1)

Non-circular geometries, of course, serve to locally increase and decrease the stresses predicted by this simple equation. In addition, the stress component axial to the tunnel is not considered by this equation.

Three dimensional stress concentrations around an advancing tunnel face can be determined using numerical models. Oblique orientations of principal stress can cause complex concentrations at the face. High axial stresses create a collar of elevated stresses around the face perimeter while relaxing the face. This can lead to enhanced burst potential (Figure 3).

Contrasting stiffnesses within or near the tunnel face can lead to enhanced concentration as well as enhanced local energy release. Stiffer units will attract stresses and fail prematurely while the softer units nearby provide an energy reservoir for ejection.

2.2 Deconfinement

Brittle fracturing is very sensitive to confinement. The loss of confinement (normal to the tunnel boundary) enhances the brittle failure caused by stress concentrations parallel to the tunnel surface creating the potential for violent buckling or sudden asperity rupture and shear as rockburst mechanisms. Deconfinement of sub-parallel structure with coplanar stress elevation during excavation can lead to sudden failure as small interlocking asperities are nullified by small amounts of dilation.

2.3 Brittle Failure

For massive or moderately jointed rock with a high ratio of compressive to tensile strength (Table 2), there is ample evidence that brittle spalling damage initiates in tunnel walls at an unconfined stress of around 40-60% of the intact laboratory strength.

![Table 2: Transition between shearing rockmass behavior and brittle fracture/spall behavior based on rockmass quality (GSI) and ratio of compressive to tensile strength.](image)

Table 2: Transition between shearing rockmass behavior and brittle fracture/spall behavior based on rockmass quality (GSI) and ratio of compressive to tensile strength.

<table>
<thead>
<tr>
<th>Strength Ratio</th>
<th>GSI &lt; 55</th>
<th>GSI 55 to 65</th>
<th>GSI 65 to 80</th>
<th>GSI &gt; 80</th>
</tr>
</thead>
<tbody>
<tr>
<td>UCS T ≤ 8</td>
<td>shear</td>
<td>shear</td>
<td>shear</td>
<td>shear</td>
</tr>
<tr>
<td>UCS T ≥ 9 to 15</td>
<td>shear</td>
<td>shear</td>
<td>shear/spall</td>
<td>shear/spall</td>
</tr>
<tr>
<td>UCS T ≥ 15 to 20</td>
<td>shear/spall</td>
<td>shear/spall</td>
<td>shear/spall</td>
<td>shear/spall</td>
</tr>
<tr>
<td>UCS T ≥ 20</td>
<td>shear/spall</td>
<td>shear/spall</td>
<td>shear/spall</td>
<td>shear/spall</td>
</tr>
</tbody>
</table>

![Figure 3: Three-dimensional analysis of the Olmos tunnel, Peru. On the left, higher stresses axial to the tunnel creates a significant concentration of stress around the tunnel perimeter and increased face relaxation leading to extreme bursting in the face and heading perimeter. (compared to a section of the tunnel with lower axial stress shown at right – here nonviolent spalling in the roof dominated behaviour). See Diederichs et al 2013 for details.](image)
This same limit applied to deviatoric stress can be used as an in situ damage threshold up to a spalling limit defined by confinement (as per Hoek 1968 and Diederichs 2003) as shown in Figure 4. While spalling is not bursting the parallel fractures create potential for buckling or other sudden release.

Figure 3: Spalling strength criteria described in detail in Diederichs 2003 and 2007.

2.4 Energy Storage

In order to release energy, rocks must store energy. Energy storage is related to strength and stiffness of the failing rock although UCS alone can provide the simplest indicator of energy storage. Combining UCS with the UCS/T ratio as an indicator of brittleness, Figure 4 gives a reasonable predictor of rockburst potential. If a strong stiff rock unit is bounded by a rockmass with a low unloading modulus or if the excavation geometry is such that large closure displacements are likely after local rock failure, then the burst potential increases due to a larger energy reserve in the surrounding system.

Figure 4: Rockburst failure mode potential indicator (Diederichs 2007)

In addition the stress path within the rock from in situ to tunnel wall or face conditions can determine the sequence and intensity of energy storage and release. Rock that is stressed at high confinement and then deconfined stores more strain energy and has a greater potential for bursting than a rockmass that is generally deconfined prior to directional loading (Figure 5).

Figure 5: Burst potential based on energy storage and release according to stress path (Diederichs et al 2013).

Closely spaced fractures with random orientations oblique to the tunnel face and wall results in a weaker material that is likely to yield through shear before energy can be stored. By contrast structure parallel to the tunnel wall or induced boundary parallel stress fracturing can store energy through loading parallel to the fracture surfaces – energy that can be released violently through buckling. So-called “destress” blasting in front of the face (drilling and charging holes ahead of the face) acts by creating random fracture networks incapable of storing energy as the tunnel advances.

Alternatively, continuous fractures at high angles to the tunnel walls can focus and channel spall fracturing to greater depths than would normally occur. This creates a situation where brittle fractures prone to buckling near the tunnel wall are loaded by a stack of dilating fractures with a great deal of stored energy. Diederichs et al. 2013 describe this phenomenon in detail as a driver of extreme rockbursting in the Olmos tunnel in Peru.

2.5 Rapid energy release

Brittle failure is the result of a high unloading modulus (rapid release of strain energy and stress). Most of the ejection energy, however, comes from the rockmass around the failing volume. A circular tunnel boundary represents a stiff system and yields less available energy for ejection. Flat tunnel faces or walls, for example are less stiff as the post yield displacement is greater, imparting more energy to the fracturing rock leading to strain burst potential.

One of the greatest contributors to rockburst potential in tunnelling is the act of overscaling and the loss of the arched or circular profile. This practice creates very “soft” system geometries and confinement loss. This
combination increases the potential for stress induced fracturing and enhanced burst potential when yield occurs. It is important to remember that the practice of scaling predates the use of shotcrete for surface support and retention and is based on shallower structurally controlled gravity failure. It is important to remove loose and unstable blocks from the work area but uncontrolled scaling such that the stable tunnel profile is lost is to be avoided. (Note that while the use of mechanical scaling often leads to overaggressive scaling, manual scaling bars are not to be used in burst prone ground due to the risk of exposure for the workers).

2.6 Volume and total energy release

Figure 6 is a now classic predictor for the maximum volume of rock around a tunnel available for release in a rockburst.

![Figure 6: Depth of damage (rock available for bursting) around a tunnel. (Diederichs 2010 and Martin et al 1999)](image)

Large tunnels will generate more rockburst volume than smaller tunnels if the failure happens after final profile is reached (independent of the staging). Slower staged excavation creates more numerous, smaller disturbances. This radiated energy can outstrip the rocks time-dependent redistribution of stress and strain causing unexpected internal failure (fault slip, for example).

Persistent geological structure can connect large volumes of rock and provide a connection for simultaneous rapid energy release in the event of failure.

3 ROCKBURST RISK MANAGEMENT

Unlike mining where there are often numerous sequencing options available to control and modify the stress path around at-risk excavations, no such luxury exists for tunnelling. Therefore, the hazard of brittle rock failure and some level of sudden energy release must be accepted as unavoidable in many tunnelling conditions. The following section deals with strategies and philosophies for rockburst risk management in tunnels.

It is important to understand the aspects of Risk before proceeding with the discussion. The following definitions are offered for clarity within this report and for further discussion:

Rockburst Triggers: Any number of mechanisms such as stress, structure, geometry and others that act individually or with other mechanisms to create the potential for a rockburst hazard.

Rockburst Hazard: A seismic event resulting from brittle rockmass rupture, with energy release, and with the potential to damage the tunnel profile, harm personnel, impede tunnel progress, or damage equipment and infrastructure, initiated:

1) at or near the tunnel boundary through fracture in brittle rock, or through structurally controlled slip or buckling, with energy release and rock ejection.

2) at some distance from the tunnel (within the rock mass) typically on structural features where the energy released creates ejection of material at the tunnel boundary or where vibration causes a rockfall in a rockmass that has been properly supported for static conditions..

This likelihood can be ranked as low, medium or high based solely on geological, stress and operational factors (such as advance rate, powder factor, orientation, overscaling and other "triggers"). The impact on safety, progress and equipment (and costs) can be assessed as low, medium or high. It is critical to analyze the hazard through visual (video) and seismic monitoring in order to control the likelihood or manage the impact appropriately.

Rockburst Likelihood: The potential for a rockburst hazard to occur (including frequency and magnitude). The total hazard potential should be classified by considering both the magnitude of the event (Seismic Magnitude, PPV, Volume or thickness of Ejected material, Energy required to arrest the failure and ejection). A smaller event magnitude normally has a higher frequency or potential in a tunnel.

In a mine, this hazard can be controlled by sequencing, mining rate and other mine planning activities. In a tunnel the options are limited for hazard control but include tunnelling advance round length, installation of immediate temporary reinforcement into the face and exposed advance round side walls and roof, blast control, profile control, preconditioning through advance blasting.

Rockburst Impact: The real consequence of a rockburst event in an operating tunnel to workers (safety and lost time), tunnelling progress such as support costs, delays and advance (round length reduction) rate reduction and equipment damage (downtime and repair costs). The highest priority is, of course, safety. Serious injury or fatality cannot be accepted but even minor injury due to rockbursting will most likely result in a very lengthy shutdown due to project, mine and government safety investigations. The second priority for risk reduction (through hazard control or impact management) is the tunnel progress.
Damage to equipment is to be avoided but is an acceptable sacrifice, if necessary to maintain safety and progress.

In addition to the moral imperative to prevent injury, it is important to understand that injury to workers or undue exposure to a hazard (a “near miss” without protection) can result in an extended multi-month shutdown of a tunnelling project. The impact of a rockburst hazard event can be reduced and managed through reentry delays, controlled access to the face, temporary or permanent support with displacement and energy capacity, restricted access, robotic equipment to replace manual tasks at the face, protective enclosures for workers, and communication.

Rockburst Risk: The product of rockburst hazard potential (likelihood or frequency), and the real cost of each event. Low likelihood events with high impact can be managed through worker protection and restricted access to the face. Higher likelihood events with moderate to major impact require active measures such as face support or modified excavation procedures (advance rate, blast control, reentry restrictions, preconditioning, et cetera). Risk is defined as the total impact or cost of a single hazardous event or series of hazardous events.

The most dangerous form of rockburst that impacts tunnels outside of active mining operation is the face burst. This is an explosive release of material from the face or the partially or unsupported round adjoining the face. In tunnelling this poses a construction challenge and poses a severe safety challenge for drill and blast operations. Examples are shown in Figures 8 thru 10.
Figure 9: Video analysis of minor rockbursting showing association of the initial strain burst (left with estimation of ejection velocity from frame analysis) and the subsequent gravity fall of rock in the heading due to undercutting by the burst (right with video estimation of acceleration).

Figure 10: A frame by frame sequence of a major burst at a tunnel face (Maule project after Abadia Anadón 2007). 1) face immediately prior to event; 2) event nucleation; 3) propagation of diagonal release fracture; 4) ejection begins; 5,6) rockburst. Total time =1 second Ejected thickness 0.5-0.1m

For this hazard of face-bursting, there are few support options that can be taken since the activity occurs in the unsupported heading. This differs from mining where seismic events remote from the drift impact the excavation sometime after construction is complete. Risk management measures that can be taken understand the mechanics, to either control the likelihood, or manage the impact are summarized here:

A) Seismic, Video and Probe Mole Monitoring to understand mechanisms and geological change:
- Correlation between blast energy, round length advance rate, span and seismic release
- Seismic decay rates for safe re-entry
- Ejected and gravity fall volumes for support design
- Tunnel moving from soft to stiff or vice versa
- Laminated structure parallel to roof or walls
- Heterogeneous rockmass (stiff and soft elements)
- Fracture with persistent steep structure
- Massive face in brittle homogenous rock

B) Energy management to remove energy from the face and tunnel perimeter that could be released during a tunnel-induced rockburst event:
- Modify tunnel geometry if the bursting is exploiting flat surfaces or corners.
- Manage round length and reduce if needed to control rock behavior
- Do not leave face and round unsupported over time since energy storage through creep and rock weakening through degradation can occur
- Monitor induced seismicity to understand the nature of energy buildup and release
- Preconditioning (advance destress blasting holes) if needed to remove stored energy from face
- Preconditioning hole angled out to fragment the future wall rock and create stress shadow

C) Maintain Tunnel Profile since a complete, continuous, arched and as-designed tunnel profile reduces surface instability and reduces the potential volume of release during failure:
- Mechanical but gentle scaling (do not overscale)
- Manage Overbreak (manage blasting)
- Stiff grouted support early to preserve rock strength
- Swellex provide immediate reinforcement as well as energy/displacement capacity.
- Manage explosive use to

C) Rockburst Impact and Risk Management to reduce the impacts of rockbursting, in order of priority, on 1) safety, 2) advance and, if possible, 3) on equipment:
- Re-entry protocol - Manage cycle to minimize risk
- Monitor exposure – Safety Zone
- Robotic installation of first support (Figure 11)
- Worker protection for manual jobs such as support installation, blast hole loading and wiring (Figure 12)
- Eliminate Manual Scaling
- Ensure early dynamic (high displacement) support
- Training and Communication

Figure 11: A robotic Swellex installation attachment for installing immediate support with load, energy and displacement capacity at the face and around the perimeter of a tunnel prior to permanent support and other activities such as drilling and blast loading.
4 CONCLUSIONS

In summary, rockbursting in tunnel operations is significantly different from the hazards and risks normally associated in mining operations. The rockburst stress trigger and energy release is very much a function of the tunnel itself, the advance, the excavation methodology and the immediate geology. Most tunnel bursting occurs at the face or immediately behind. Only a few, structurally influenced rockburst events have been observed significantly behind the face in tunnelling.

It is important not to confuse the event or the hazard with the overall risk in this case. Far too often the spectre of rockburst activity causes long term delays and reluctance to continue with valuable tunnelling operations.

A sensible risk management strategy is one that accepts that rockburst hazard can be controlled but only to a limited extent and focusses on impact management placing the risk to human safety, the risk of tunnel delay or stoppage, and the risk to equipment and other infrastructure in that specific order of priority. Reasonable reductions in advance rate are acceptable to maintain safety. Equipment may be sacrificed to maintain worker safety and to continue tunnelling in a timely fashion. Most important in all of this strategy is communication.

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