Strategies and tactics to control seismic risks in mines

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Transaction Paper

Synopsis

The risk associated with mining induced seismicity is one of the major threats to the safety and sustainability of deep underground mines. This paper describes techniques that allow site practitioners to efficiently control such risks in mines. The proposed approaches rely on ground support to strategically control seismic risk and re-entry time to tactically control this risk. The strategic approach is based on the detailed understanding of past seismicity to ascertain the seismic hazard of individual sources throughout the mine. This approach also relies on assessing the potential damage that these sources can induce on nearby excavations using the excavation vulnerability potential (EVP) and rockburst damage potential (RDP) concepts proposed by Heal *et al.* (2006). It is then possible to investigate how to reduce the risk of experiencing damaging seismicity in mine drives by locally enhancing the ground support system. The tactical approach relies on a proposed methodology to estimate reliable re-entry times or exclusion periods based on the seismic decay following blasting. Some examples of how these techniques have been applied in Australian mines are given.

Introduction

Mine seismicity has become a widespread problem in the global mining industry. Major mining countries such as Canada, Australia, South Africa, Chile and the USA, amongst others, have deep mines experiencing different levels of seismicity. South Africa is arguably the country facing the strongest seismic hazards having at least six mines deeper than 3 000 m (Potvin *et al.*, 2007). Seismic events exceeding Richter magnitude 2 happen on a regular basis in these operations and magnitude 3 events also occur occasionally. The mining practices in the deep South African gold mines remain labour intensive as limited mechanization has been implemented to date. A significant number of miners are working at the face where the probability of experiencing large seismic events can be high. Adding to the seismic risk is the fact that in the spatially confined gold mine stopes, there is no real opportunity to install adequate ground support to control the consequence of large seismic events. The combination of high hazard, limited opportunity to control the hazard and high personnel exposure necessarily translates in a high risk from mine induced seismicity. The statistics on the annual number of fatalities due to rockbursts in South African mines tends to confirm the above discussion, with an average of more than 20 fatal events per annum in recent years (from SAMRASS database).

Notwithstanding that the context is often very different, many mines in the world, including some operations in South Africa, have been managing seismic risks very successfully, even in operations experiencing high seismic hazards (frequent large magnitude seismic events). The Australian mining industry experienced a period in the late 1990s where seismic hazard was on the rise due to intense mining activities at depth. It is thought that the seismic risks at that time were not particularly well managed. The Western Australian mining industry, which was relatively small at the time, suffered at least three rockburst fatalities between 1996 and 1998 (Potvin *et al.*, 2000). The situation has changed in recent years. With the implementation of better strategic and tactical seismic risk management techniques, since 2000, despite continued expansion of mining activities at depth, there was only one rockburst related fatality in Australian mines, the highly publicized Beaconsfield event that occurred Anzac Day 2006.

Seismic hazard cannot be totally removed, although it can be reduced when sound strategic planning and design are implemented. Well-known design and planning strategies such as avoiding shrinking pillars, not mining towards faults, stress

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shadowing and others have shown to be efficient in reducing seismic hazard. These types of strategic mine planning techniques are discussed in Mikula (2005) and will not be covered here. This paper will focus on two specific approaches. First, a strategic approach based on the detailed understanding of past seismicity to ascertain the seismic hazard of individual sources throughout the mine, which is then used to assess the potential damage that these sources can induce on surrounding excavations using the excavation vulnerability potential (EVP) and rockburst damage potential (RDP) concepts proposed by Heal *et al.* (2006). The second approach is tactical and relies on a proposed methodology to estimate a safe re-entry time based on the seismic decay following blasting.

A strategic approach to dynamic support

There is a wide variety of ground support methods, including rockbolts, cable bolts, mesh and shotcrete. Some reinforcement and surface support elements have been specifically designed to resist dynamic loading. These dynamic support elements can be expensive and the installation of such support systems can be slow and costly, especially if the design is to cater for strong ground motion. As such it is not necessarily practical to use dynamic resistant ground support systems throughout the mine. A four-step methodology is proposed to assist with the selection of an appropriate level of dynamic support resistant systems as well as the relevant installation locations.

- The first step of the strategic approach to dynamic support is to identify areas where seismic sources are active and have a significant likelihood of producing large seismic events. The largest probable event to be expected from each of these sources, which is defined as the seismic hazard, is then assessed.
- The second step is to assess the magnitude of the ground motion (or shockwave), in terms of peak particle velocity (PPV), that can be generated at the surface of the surrounding excavations, if the largest expected event was to occur.
- The third step is to estimate the capacity of excavations located near the seismic source to resist the largest probable PPV defined in the previous step, assuming a given ground support system. This is expressed in terms of excavation vulnerability potential.
- The last step is to assess the rockburst damage potential considering the largest probable PPV and excavation vulnerability. By changing the ground support design, the reduction of rockburst damage potential (seismic risk) can be assessed.

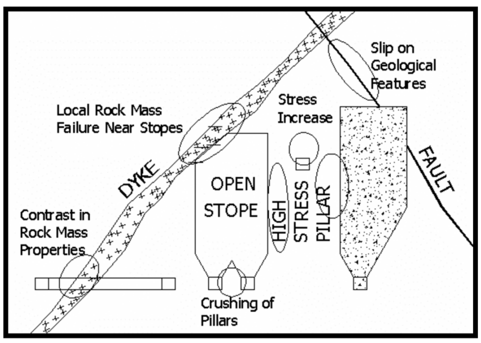
Step 1—Assessing the seismic hazard

Mine seismicity is not a random phenomenon. It is the product of a local and sudden failure within the rock mass. This definition is valid for very small to very large seismic events, and for all failure mechanisms. The energy released by the failure determines the size of the event and severity of the seismic hazard. Large events represent high seismic hazard as they release a large amount of energy, which, in some cases, can be destructive.

Seismic events tend to cluster spatially delineating areas within the rock mass experiencing failures. Rock mass failure is better described as a process rather than as a discrete event. During the rock mass failure process, a number of localized failures will produce seismic activity in the form of a series of events located within a volume of rock mass. This grouping of events (often called clusters) may be used to define a seismic source. For example, the physical location of the cluster of events defines the location where the failure process is happening, and the seismic signatures of the group of events (waveforms, as recorded by seismic monitoring systems) provide valuable information on the dominant failure mechanisms as well as the hazard associated with this seismic source. Hudyma *et al.* (2003) describes typical mine induced seismic sources, which are often the result of stress change due to mining, combined with geological or geometric features within the rock mass such as faults, dykes, geological contacts, pillars, abutments, sharp corners, etc. (Figure 1).

When a mine has collected enough high quality seismic data, it becomes possible to identify the main seismic sources currently active in a mine, using filtering and clustering techniques (Hudyma, 2008). Once the seismic sources have been identified, the seismic hazard associated with each of these sources can be assessed.

If we define seismic hazard as the largest probable event that can occur from a given seismic source (or cluster), one of the key relationships used to assess the hazard is the Guttenberg-Richter frequency-magnitude relationship (Figure 2). In particular, the x-intercept of the frequency



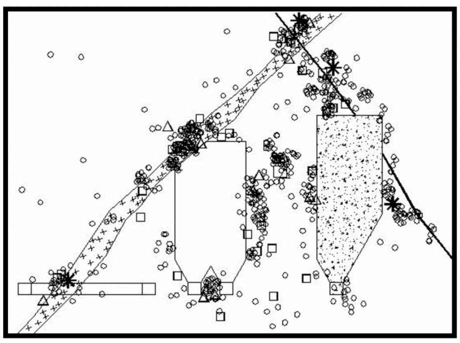


Figure 1—Diagrams showing generic seismic failure mechanisms (on the left) associated with open stope mining. The resulting seismic events cluster where the rock mass failure occurs, as shown in the diagram on the right (after Hudyma *et al.*, 2003)

magnitude plot of well confined seismic datasets (i.e. cases where clusters represent single seismic sources), has been shown to reliably represent the largest probable seismic event that could be produced by this source, at a certain point in time (Hudyma and Potvin, 2006). It is therefore possible to assign a seismic hazard or define the largest probable seismic event for each active seismic source, provided that the seismic dataset is well clustered and that individual clusters have sufficient accurate data to produce a well behaved frequency-magnitude relationship. A well behaved frequency-magnitude relationship will approach linearity over several orders of magnitudes events (Figure 2). Figure 3 shows a seismic dataset where clusters have been colour-coded according to the largest probable event expected from the seismic source at a given point in time, using the MS-RAP software.

Step 2—Assessing the largest potential ground motion at the surrounding excavation

Seismic shockwaves attenuate as they travel away from the source, through the rock mass. Kaiser *et al.* (1996) proposed the following relationship to assess the peak particle velocity (PPV) as a function of the distance from the source of a seismic event.

$$PPV = 1.4 \times \frac{10^{MR/2}}{r}$$

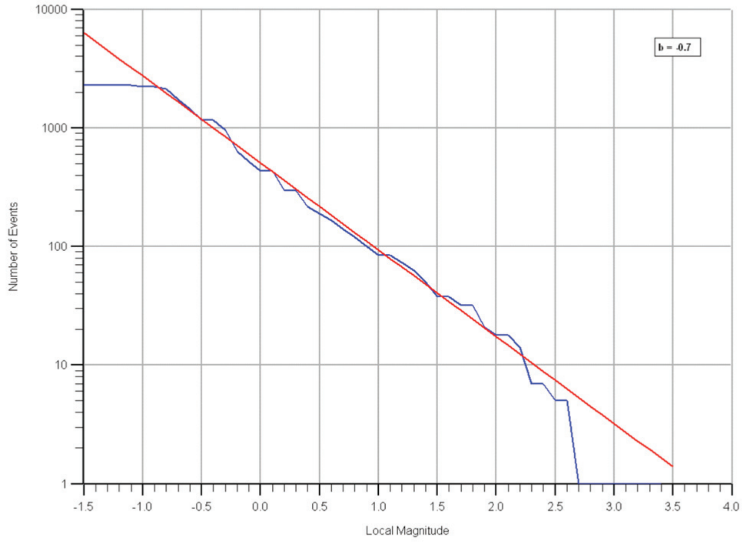


Figure 2—Gutentberg-Richter magnitude-frequency relationship. The b-value is given by the slope of the line and the x-intercept is the maximum probable event to be expected from this dataset

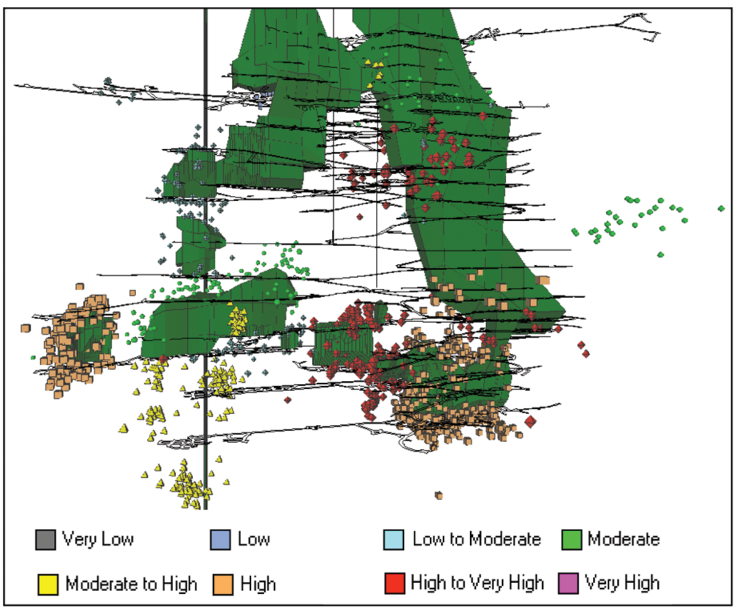


Figure 3—A seismic dataset from an open stope mine organized by clusters which have been colour-coded by seismic hazard (the largest expect seismic event magnitude)

where:

- *PPV* is the peak particle velocity (in m/s) at a distance *r* from the source of the seismic event.
- *MR* is the magnitude of the seismic event on the Richter scale.
- *r* is the distance (in meters) from the seismic event to the location where the *PPV* is to be estimated.

As the largest probable seismic event from active seismic sources can be estimated using the methodology outlined in the previous section, the potential ground motion expressed as PPV can be calculated at every location neighbouring active seismic sources. Figure 4 is plot of potential PPV generated by the largest probable seismic events from the seismic sources identified in Figure 3, which would be transmitted to the surrounding excavations.

Step 3: Assessing the excavation vulnerability potential (EVP)

The amount of damage produced by any given seismic event can vary enormously. For example, a Richter 2 event at a given distance can produce no associated damage or can result in the total destruction of a drive. The scaled distance-relationship described in the previous section accounts for some of this variation, because further events typically produce less damage. Other factors will also influence the outcome of a seismic event. Whilst identifying that there are a multitude of factors which may influence the occurrence or otherwise of rockburst damage, Heal *et al.* (2006) identified four primary factors which, depending on their characteristics, make an excavation more or less vulnerable to rockburst damage. These factors are:

- Stress condition factor (E_1): the ratio of static stress condition to rockmass strength around the excavation prior to the seismic event; the higher this factor is the more vulnerable the excavation may be to rockburst damage.
- Ground support capacity (E_2): the capacity of the ground support system to absorb the dynamic loading; the lower capacity will make the excavation more vulnerable.
- Excavation span (E_3): the larger span will make the excavation more vulnerable.
- Geological structure (E_4): the presence of seismically active structures such as faults in contact with an excavation will make it more vulnerable.

Heal *et al.* (2006) produced methods and tables to quantify each of the above four factors (see Appendix 1), which can then be fed into an empirically calibrated methodology to assess rockburst damage potential. The four factors have been regrouped into a single parameter called the excavation vulnerability potential (EVP).

$$\mathrm{EVP} = \frac{\text{Stress Condition Factor}\left(E_1\right)}{\text{Ground Support Capacity}\left(E_2\right)} \times \frac{\text{Excavation Span}\left(E_3\right)}{\text{Geological Structure}\left(E_4\right)}$$

Step 4—Assessing the rockburst damage potential (RDP)

A rockburst damage scale (RDS) similar to the one proposed by Kaiser *et al.* (1992) has been adopted as a qualitative assessment of rockburst damage (Table I).

Heal *et al.* (2006), from the back analysis of 254 cases of rockburst damage, developed an empirical chart (Figure 5) relating the RDS as a function of the largest probable PPV and the excavation vulnerability potential (EVP). The methodology allows for identification of the seismic sources throughout the mine, assessment of the largest probable seismic event that each of the sources can generate at a given point in time, and calculation of the largest probable radiating

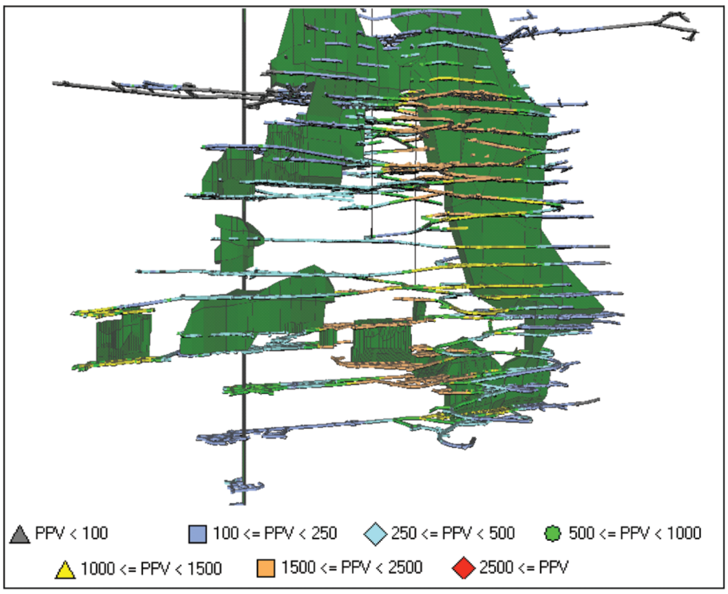


Figure 4—A plot of maximum expected PPV (mm/s) projected from cluster identified in seismic data, projected onto mine development of an open stope mine

Table I

Rockburst damage scale adapted from Kaiser *et al*., 1992

Rockburst damage scale	Rock mass damage	Support damage
R1	No damage, minor loose	No damage
R2	Minor damage, less than 1 t displaced	Support system is loaded, loose in mesh, plates deformed
R3	1–10 t displaced	Some broken bolts
R4	10–100 t displaced	Major damage to support system
R5	100+ t displaced	Complete failure of support system

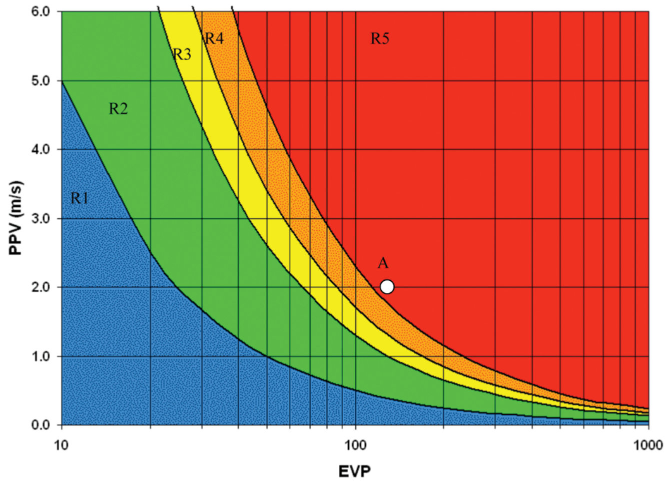


Figure 5—Empirical chart relating the largest probable ground motion (PPV) to the excavation vulnerability potential to assess the potential rockburst damage (R1 to R5)

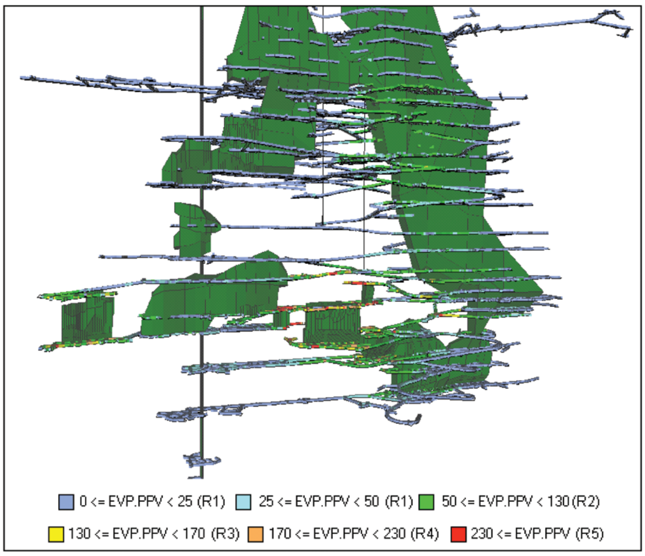


Figure 6—A plot of rockburst damage potential (EVP x PPV) of an open stope mine

ground motion (PPV) on the surrounding excavations. The rockburst damage potential can then be assessed using Figure 5, combining the largest probable ground motion and the EVP. For example, point A in Figure 5 has a PPV of 2 m/s and an EVP of 110, resulting in a potential R5 damage. This suggests that a complete failure of the support system is likely if the largest expected event magnitude were to occur.

This methodology has been programmed into the MS-RAP software and the rockburst damage potential can be automatically assessed at any time at all excavations throughout the mine. An example of rockburst damage potential is given in Figure 6.

The seismic risk at sections of the mine which are prone to high damage potential (R4 orange and R5 red) can be mitigated by increasing ground support capacity. This is shown in Figure 7, where a point originally plotting in the R5 region of the graph (total destruction of the ground support system) can be moved to R3 zone by adding cable bolts (reducing EVP), and to R2 by adding further heavy duty dynamic resistant support elements. The cost of mitigating the risk by increasing the support system locally, where the rockburst damage potential was originally high, can be calculated. The methodology allows for strategic planning, including the cost of mitigating seismic risk. This methodology can also be used in a tactical approach, whereby management can decide to manage the risk by limiting the exposure of people to high rockburst damage potential areas.

Tactical approach—re-entry time

Seismic risks due to local stress changes following blasts are often tactically managed by limiting personnel exposure, and by delaying the access to the nearby area for some time after the blast. The blast could be a production or a development mining blast. The delay before resuming activities is often referred to as 'safe re-entry time'. By studying the post-blast decay pattern of seismicity, it is often possible to develop some temporary exclusion rules, whereby seismicity would have subsided to a safe level before personnel are allowed to regain access to their workplace. Omori charts (Figure 8) are particularly useful in investigating the seismic decay after blasting.

These principles are simple, well known to the mining industry and commonly applied, albeit often in quite different ways. There is no accepted methodology on how to develop these re-entry rules. Some operations look at the decay in the number of events and derive a single re-entry rule to be applied in the entire operation. Other mines look at more sophisticated parameters and develop localized rules for different mine areas. It is suggested that the latter, more refined approach is often required to achieve safe re-entry rules, as the seismic behaviour is rarely uniform throughout the mine and many important details must be considered to achieve unbiased and reliable sets of rules.

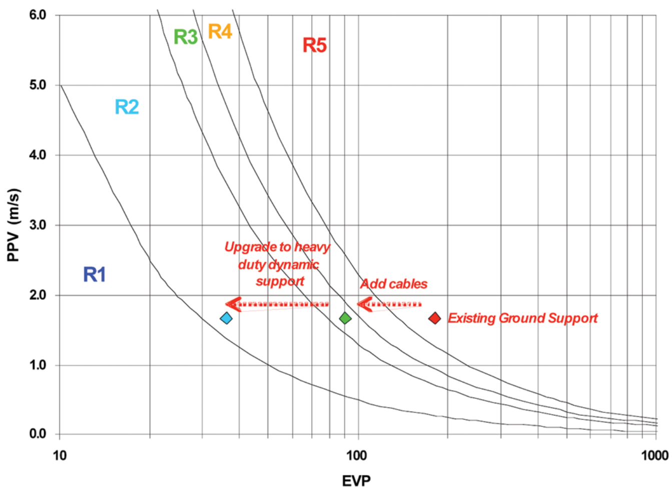


Figure 7—Example of a reduction of rockburst damage potential (seismic risk) by adding ground support capacity (after Heal, 2007)

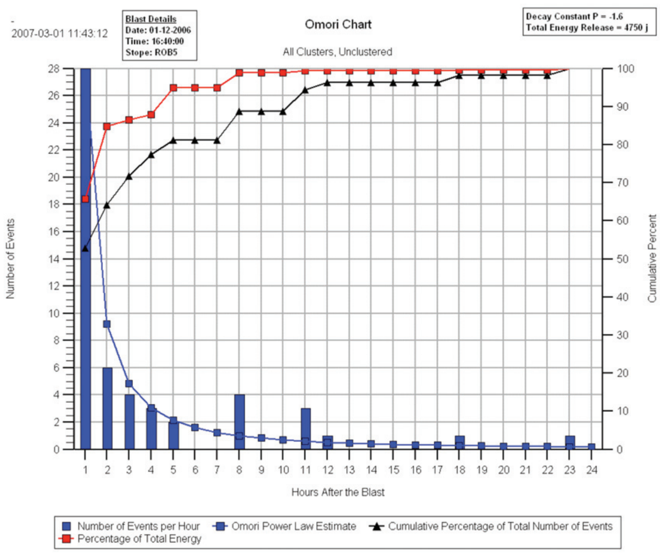


Figure 8—Example of an Omori chart showing the decay of seismicity following a blast

One important consideration is the sensitivity of the microseismic monitoring system. The sensitivity of the system is directly related to the spatial arrangement of sensors within the array. Unless an array is uniform and totally surrounds the mine, there will be areas of the mine with closer sensor spacing than others, and therefore the accuracy in recording seismic events will be better in some areas compared to others. As the frequency-magnitude of seismic events often follows a power law, areas where the system cannot record the smaller events will miss a large proportion of the events. On the other hand, the very small events missed in areas where the system is less sensitive carry less energy and therefore may not be as important to consider in terms of seismic hazard assessment. If the seismic data is to be compared from different areas of the mine for the purpose of studying seismic decay and re-entry time, then the variation in accuracy of the monitoring system in different areas of the mine must be understood and accounted for.

The seismic hazard related to a blast is often due to the local stress readjustment from geometry change and is therefore confined to an area in close proximity to the blast. This seismic hazard is also confined to a certain period of time after the blast. This is not to say that a blast cannot trigger an event far away from its own location, which has often been observed in the case of fault-slip related seismic events. However, these types of events often exhibit no obvious relationship to the location and timing of mine blasting, and must be managed using techniques other than re-entry time.

Criterion for re-entry

Looking again at the Omori chart in Figure 8, recorded seismicity is presented as a bar chart, showing the number of events occurring each hour following the blast. The black line (defined by triangular points) represents the cumulative number of events, while the red line (defined by the square points) represents the cumulative energy dissipated by seismicity after the blast. Looking at the number of events, or cumulative number of events, as a criterion can be misleading as a small event would then count for as much as a larger event. Also, the variation in system sensitivity in areas of the mine could become a more serious issue with such a criterion.

It is proposed that the cumulative energy release provides a more robust criterion. Many mines in Western Australia are using 90% of the cumulative energy dissipated (T90) as a re-entry rule. This is a completely arbitrary rule. The underlying assumption is that once 90% of the total energy has been released, the rock mass can be considered to have readjusted to the new state of stress and is unlikely to produce a significant event. It is interesting to note in Figure 8 that 90% of energy in this example was released within 4.5 hours after the blast while 90% of the cumulative events took almost 11 hours to occur. This implies that the events occurring in the later hours after the blast contain only small amounts of energy, which tends to validate the proposed arbitrary energy based criterion of T90.

Another important parameter to account for is the total amount of energy released by a blast. A blast may take a long time to dissipate 90% of its energy but if the energy levels are low, then there is no reason to delay the re-entry. Figure 9 shows the relation between the local event magnitude and the seismic energy at a certain mine. Despite the scatter, in general, events under 100 J are roughly under magnitude -1 and are in most cases, unlikely to cause rockburst damage. Therefore, another arbitrarily rule at this mine could be if the total energy release is under 100 J, no re-entry delay is required.

Re-entry times at different mine locations

When studying re-entry times at different mine locations and considering the discussion above, it is suggested that one needs to define four basic parameters before undertaking the study:

- ➤ The analysis duration is typically 12 to 24 hours.
- ➤ The volume of blast influence, in terms of the seismic hazard being potentially heightened by the blast, will define the maximum blast-to-event distance to be included in the study.
- ➤ Re-entry criterion; it is proposed to use 90% of the cumulative energy recorded within the volume of influence defined above.
- ➤ Minimum total seismic energy > 100 J.

Using the previous four parameters, the back analysis of a large number of blasts (25 to 100) distributed throughout the mine can be used to develop localized re-entry times for

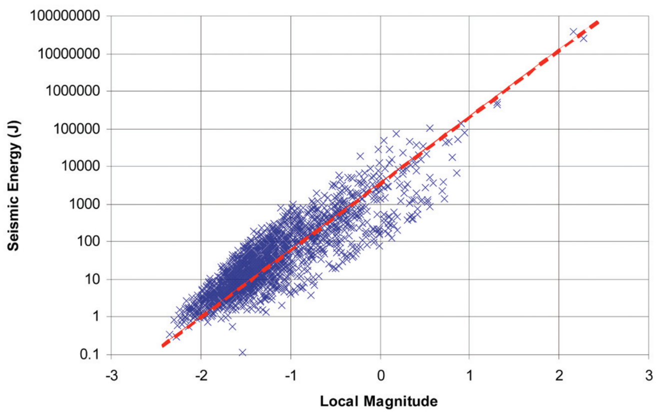


Figure 9—Relationship between local magnitude and seismic energy of seismic events recorded by an ISS system at a given mine (Heal, 2007)

different areas of the mine. For example, the plot of re-entry times for a number of blasts within a certain area can provide a strong basis for understanding the seismic response and seismic hazard within a given area. Figure 10 shows four different re-entry plots representing four different areas of a mine. In Figure 10 (a), all re-entry times are zero hours. This may be because the seismic system has only limited coverage in this area of the mine or alternatively, the area may have low stress or, no nearby seismically active geological structures and generate only a few low energy seismic events. Figure 10 (b) shows several zero hour re-entry times but also a distribution of blasts which had between 4 and 10 hours re-entry. In this area, several seismic sources may be present, some being excited by specific blasts. The size of the blast may also have an influence on the re-entry time in this case. It would be prudent for this area to use the maximum re-entry time measured of 10 hours. Figures 10(c) and (d) have limited data but show similar outcomes, which is a spread of re-entry times. In both cases seismic sources are taking some time to dissipate the energy and again, the maximum re-entry time measured at each location should be considered until more data becomes available.

These tools become more useful and accurate as more data are included in the analysis and the trends for local re-entry times become better defined.

Conclusion

An increasing number of mines around the world are operating in seismically active conditions and in some cases in high seismic hazard areas. The key to safe and successful mining in such conditions is to manage the seismic risks using both strategic and tactical approaches. Tools currently exist to assess the seismic risks and assist in the planning for efficient mitigation measures. In this paper, a strategic approach was described to assess the mitigation of seismic risk using dynamic resistant support and a tactical approach based on limiting personnel exposure by defining area specific re-entry time, based on the study of the decay of seismicity following blasting. These tools are currently used by sponsors of the Australian Centre for Geomechanics Mine Seismicity and Rockburst Risk Management Project.

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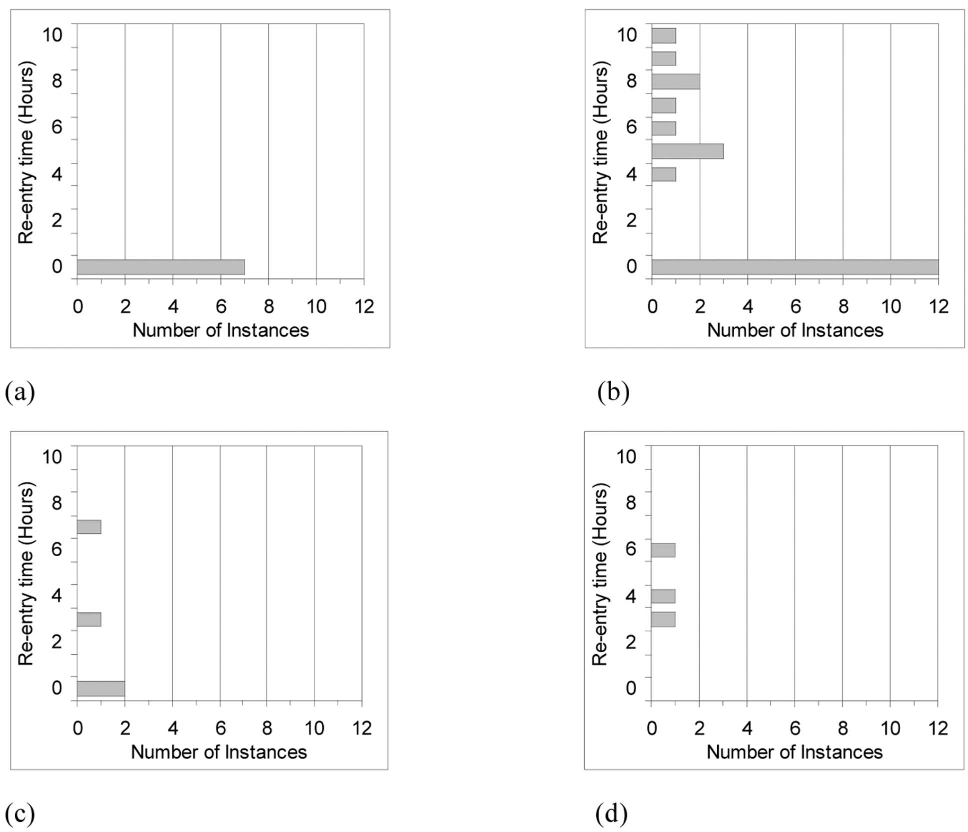

Figure 10—Re-entry time distributions established based on 90% energy dissipated after blasting, in four areas of a mine

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Appendix 1

The factors used in the excavation vulnerability potential (EVP) calculation (Heal *et al.*, 2006).

Stress condition factor (E_1):

$$\text{Stress Condition}\left(E_1\right)=\frac{100\text{x}\sigma_{1M}}{UCS}$$

where:

- σ_{1M} = the mining induced maximum principal stress (MPa) at the location of interest (not necessarily the seismic event location), and
- UCS = the intact unconfined compressive strength (MPa) of the rock at the location of interest.

Ground support capacity (E_2)

Ground support capacity ($E2$) are discussed in Table II.

Excavation span (E_3)

The excavation span factor is defined simply as being the diameter (in metres) of the largest circle that can be drawn within an excavation as shown in Figure 11.

Geological Structure (E_4)

Geological Strucute (E_4) are being discussed in Table III ◆

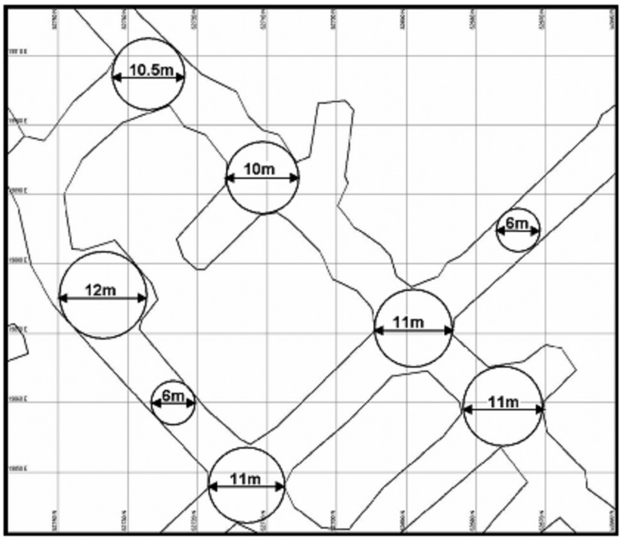

Figure 11—Excavation span

Table II

Ground support capacity—*E*2

Classification	Surface support	Reinforcement	E2 rating	Example
Low	None	Sport bolting (spacing > 1.5 m)	2	Spot bolting with split sets or solid bar bolts, minimal surface support
Moderate	Mesh or fibrecrete	Pattern bolting (spacing 1–1.5 m)	5	Pattern bolting with split sets or solid bar reinforcement, with mesh or 50 mm fibrecrete
Extra bolting	Mesh or fibrecrete	Pattern bolting with a second pass of pattern bolting (overall spacing < 1 m)	8	Pattern bolting with split sets with mesh or 50 mm fibrecrete. Plus an additional pass of pattern reinforcement, such as solid bar bolts
High static strength	Mesh or fibrecrete	Pattern bolting and pattern cablebolts	10	Pattern bolting with split sets or solid bar reinforcement, with mesh or 50 mm fibrecrete. Plus pattern cablebolting
Very high dynamic capacity	Dynamic surface support	Pattern dynamic support	25	Pattern bolting with dynamic ground reinforcement such as conebolts, with a dynamic resistant surface support system

Table III

Goelogical Structure (E_4)

E4	Description
0.5	*Seismically active major structure* Major structural features such as faults, shears or discrete contacts intersect the location and act as a potential failure surface promoting rock mass failure. *Example:* The rock mass fails back or along a major fault, increasing the depth of failure considerably more than would otherwise occur in the rock mass.
1	*Unfavourable rock mass/no major structure.* The orientation of the rock mass discontinuity fabric may promote or enhance rock mass failure. Generally, this factor is applied when there are local cases in which the rock mass discontinuities promoted falls of ground much larger than would be expected. *Example:* A heavily jointed, blocky rock mass with kinematically unstable rock mass blocks. The rock mass is prone to deeper than normal gravity driven failure mechanisms.
1.5	*Massive rock mass/no major structure.* The rock mass is essentially massive, or non-persistent rock mass discontinuities may exist; including possible minor blast related fracturing. There are no major structures such as faults or shears, which may promote or enhance rock mass failure.