EVALUATION OF A GROUND SUPPORT SYSTEM AGAINST EXPECTED ROCKBURSTS

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ABSTRACT:
This paper describes the process of evaluating ground support systems which are expected to perform and endure the effects of violent ground motion. The paper will highlight a case study in Australia and the ground engineering principles will emphasize the important underlying factors when a ground support system is designed or selected. The paper highlights the characteristics of ground support elements integrated with a yieldable containment system allowing energy to be absorbed whilst it arrests the displacement of rock within tolerable limits during seismic induced Peak Particle Velocity (PPV). The invaluable importance of ground support system installation quality cannot be more emphasized. Support performance is only as good as the quality of its materials and installation. Continuous quality control during the selection and installation processes of rock re-inforcement and surface support elements is the responsibility of the end user. Therefore, support design assumes and relies on the control of the quality of its implementation and installation. Throughout this paper, it will show that assessing the energy capacity of ground support systems, still plays an important role in determining whether a specific surface support and reinforcement system is able to withstand the energy demand that the rock mass could exert for a seismic source at a specified location, deformation, velocity and displacement. The paper further touches on the importance of mining layout and production sequence as the primary prevention of rockbursts risk (e.g. stress concentrations, large seismicity close to workings and poor site response). The role of mining layout design is considered primary and critical to the control of seismic energy releases and the prime aim is to have a ground support design targeting the control of the residual condition following the optimisation of a mine layout design.

Key words: ground support systems; yieldable containment system; energy; Peak Particle Velocity (PPV); seismicity.

1 WHY DYNAMIC GROUND SUPPORT IS CONSIDERED
Dynamic support design has attracted years of research study by many specialized institutions as well as by mine geotechnical departments. Literature addresses both the demand and capacity aspects of design in seismological research and support product development.

The control of rock at the skin of a mining excavation impacted by seismic induced PPV involves the design of dynamic support. The intent is for the dynamic support to arrest the induced ground displacements within practical limits to retain the functions of excavations, maintain the integrity of the support systems and provide safe continuous access and production.

Design of dynamic support requires knowledge of the demands from likely seismic activity as well as the capacities of support options. From a demand perspective seismic activity is recorded with seismic networks sensitive to the level of the seismic monitoring strategy. The seismicity is correlated with occurrences and intensities of damage. Damage is correlated with PPV as the distanced scaled parameter relating to the magnitude of a seismic event. From a capacity perspective the load, deformation, yield and failure characteristics of support units as well as those of combinations of support types into systems are required to assess their energy absorption potential.

The most widely used support design criterion for rockburst-prone mines is based on work of Wagner in 1984, which takes into account the kinetic and gravitational potential energy of the key blocks. The criterion for effective rockburst-resistant support systems is to absorb the kinetic and potential energy associated with the hangingwall moving with an initial velocity of 3 m/s. Previously it was assumed that during a rockburst the hangingwall must be brought to rest within 0.2 m of downward movement (GAP 709a – SIMRAC Research Report).
The energy-absorption requirements of a support system are linearly related to the downward hangingwall displacement, and are a function of the square of the peak particle velocity (PPV). Therefore, a comparatively small decrease in peak particle velocity results in a large decrease in the energy-absorption requirements of a rockburst-resistant support system. For example, if the velocity criterion is decreased from 3 m/s to 2 m/s, the energy-absorption requirement is decreased from 20.93 kJ/m² to 12.83 kJ/m² (assuming a maximum allowable displacement of 0.2 m and a fallout height of 1.2 m). As a result, a decrease in peak particle velocities would allow for considerably lower energy-absorption demands on rockburst-resistant support systems (MILEVE et al 2002, GAP 709a – SIMRAC Research Report).

A number of studies on peak particle velocities and site response were conducted in two previous SIMRAC projects, GAP 201 and GAP 530 (Improvement of worker safety through the investigation of site response to rockbursts). Many important results were obtained. For example, it was found that the ppv on the skin of the excavation may be larger by four to ten times than the PPV at a point in solid rock at a similar distance from the energy source. One of the main objectives of Milev’s study was to create a large volume data set of PPV’s measured in different geotechnical areas that can be used to re-evaluate the velocity criterion. Extensive underground seismic measurements at Carbon Leader Reef and Ventersdorp Contact Reef sites were carried out. A total number of 41 sites located at TauTona, Kloof, Mponeng and East Driefontein gold mines were monitored. The PPV’s measured at each mine were categorized in three statistical groups:

- PPV’s less than 100 mm/s;
- PPV’s greater than 100 mm/s; and
- PPV’s greater than 800 mm/s.

The last group of seismic events was considered as damaging. The values of 100 mm/s and 800 mm/s used for definition of these groups were based on the observations obtained from the simulated rockburst experiment made under the SIMRAC project GAP 530 and published by Milev et al. 2001. Figure 1 illustrates the PPVs generated by the simulated rockburst on the wall of an underground tunnel.

The PPVs measured on the blasting wall were related to the rockburst damage. Figure 1 indicates the areas of high and low intensity damage followed by an area where no visible damage was observed. A PPV of 800 mm/s was measured in the transition from low intensity to no rockburst damage. The value of 100 mm/s was subjectively chosen to separate the events with noticeable PPV’s from the rest of the events which have an insignificant effect on the support system. However, in some isolated cases damage was observed at PPV’s in the range of 100 mm/s (Mponeng gold mine).

Hedley (1992) proposed no damage should be encountered at a ppv less than 50 mm/s, falls of loose rock occur at 50 mm/s < ppv < 300 mm/s, falls of ground are encountered for 300 mm/s < ppv < 600 mm/s and severe damages are expected to occur at ppv > 600 mm/s (Kaiser, Tannant, McCreath & Jesenak, 1992).

2 THE CONTROL OF SEISMIC ENERGY RELEASE

Ground support cannot repair or make up for poor mine layout design. Mining layout controls the rates of stress distributions, locations of stress concentrations, the magnitude of stress levels, and the integration of these with the geological structures, discontinuities and tectonics of the host and orebody rock masses. Mining excavation shape, size and orientation relative to geological structure determine its behaviour in response to its own force fields and those imposed by other excavations in its vicinity.

It is imperative that the role of mining layout design is considered primary and critical to the control of seismic energy releases. Support design is aimed at controlling the residual condition after mining layout design had been optimised (see Figure 2 – Example of a good mining layout).

3 ROCKBURST MECHANISMS

The local magnitude at the source, the rock mass conditions en route, and the distance to mining excavations
determine how energy is radiated and attenuated, and what effect it may have on excavations. It follows that not all excavations are equally vulnerable or stable.

Sympathetic seismic events near or at excavations may be triggered by the seismic waves derived from remote events. All of the damage mechanisms may be encountered in these occurrences (See Figure 3 and 4 below). The primary control is mining layout design.

If an excavation is within the source radius of a large seismic event it may be completely crushed over some distance, whereas a similar excavation subject to a minor seismic event may result in a face burst. A much smaller seismic event may cause strain bursting or potentially loose rock spalling off and falling out. The closer the excavations are to the source of an event, the more violent the rockmass response and associated damage. It is likely that the zone of intact rock may be significantly affected (e.g. additional fracturing). Current practices and underlying design is less likely to cater for these occurrences. They require mining layout design and perhaps preconditioning to control the amount of energy likely to be released before support could be designed for the residual condition.

4 CHARACTERISTIC OF DYNAMIC GROUND SUPPORT

Ground dynamic support must be able to yield and absorb energy whilst it arrests the displacement of rock within tolerable limits during seismic induced PPV. Dynamic support systems consist of yielding support elements combined to form a yielding resistance to ground displacement. Examples of yielding support elements are Cone bolts, Garford dynamic bolts, Garford dynamic cables, fibre reinforced shotcrete with wire mesh and straps. Some of these elements are usually combined to create reinforcement and suspension support as well as surface support cover between tendons e.g. a combination of friction bolts, cable bolts and mesh.

5 QUALITY CONTROL OF SUPPORT PRODUCTS AND INSTALLATION

Support performance is only as good as the quality of its materials and installation. Ensuring the manufacturing quality of support elements is an important continuous process in factories, but it requires occasional scrutiny by the end user. However, the installation of support units and combinations of these are the continuous quality control responsibility of the end user. Therefore, support design assumes and relies on the control of the quality of its implementation and installation.

6 DESIGN METHODOLOGY

For Mine X the highest ejected material, for the August 2011 seismic event (1.9 Mn), where up to 2m of material being ejected from the backs with the fibrecrete and mesh severely damaged and Garford bolts exposed but not failed.

There is a number of factors to account for when determining dynamically capable support and reinforcement. The more favourable approach is to take into account the energy capacity at which the rock mass will hold or exhibit. When energy considerations are based on seismic activity, the support and reinforcement should at least be able to withstand the potential energy that the rock mass could exert, for a specified location, deformation, velocity and displacement.

An article by Scott et al (2008) following the Beaconsfield Mine tragedy suggests that the following approaches
could be considered (based on the Canadian Rockburst Handbook):

- Strain burst support requirement assessment method which includes (i) Self triggered strainburst and (ii) Remotely triggered strainburst
- Seismic shakedown support requirement assessment

Due to the seismicity characteristic (Fault Slip mechanism and shakedown) of Mine X it was found appropriate to highlight the following ground support assessment approach.

Seismically-induced falls of ground are caused when a seismic wave passes around a drive, causing additional stress fracturing and adding a seismic acceleration increment to the gravitational acceleration (static weight) of failed material. How much ground motion a supported rock mass can survive is dependent on the static factor of safety for survival ($SF_{surv}$) defined in the following equation:

\[
SF_{surv} = \frac{1}{d_{ult}(m)} \left[ \frac{(n \cdot ppv)^2}{2gd_{ult}} \right] + 1
\] (5)

Where,

- $d_{ult}(m)$ is the remaining displacement capacity of the support (i.e. after prestress or after other deformations imposed on the support)
- $m_d$ is the multiplier on the support element strength (i.e. steel strength) when loaded dynamically, typically between 1.1 and 1.4 (suggested value of 1.25)
- $n$ is the ejection velocity ratio, conservatively assumed to be unity (1).

At this static safety factor for survival, the actual SF during the event would be one. Hence, to achieve a real safety margin, the design $SF_{design}$ must be greater than $SF_{surv}$, e.g. $SF_{design}(load) = SF_{surv} \times 1.5$.

Hence the steps involved in the assessment of support requirements against seismic shakedown are detailed in the following:

**For far-field situations**, PPV can be calculated using

\[
ppv = \frac{10^{0.5 \times (ML + 1.5 \times 2 \log(C^*))}}{R}
\] (6)

Where,

- $C^*$ = an empirically determined constant (0.25 m$^2$/s).

The actual pressure on the support $p_s$ is determined from the total (static plus dynamic) depth of fracture defined in the equation below:

\[
d_f \sim \sqrt{wN2 \times (1.25 \cdot (\sigma_{max} + \Delta \sigma_{max})/UCS) - C}
\] (7)

From the calculated depths of fracture, the corresponding load (t/m$^2$) is:

\[
p_s = d_f \times Y
\] (8)

Where,

- $Y = \text{density of rock (t/m}^3\text{)}$

The support load demand for the amount of failed rock, the selected design event and the chosen displacement capacity can now be determined by multiplying $p_s$ by $SF_{design}(load)$.

### 7 CASE STUDY

Some of the information prepared for the seismic database report had significant relevance in reviewing the proposed seismic ground support standard for Mine X. Figure 5 (below) shows the percentage of reported failure mechanisms for events recorded in the seismic damage database. It clearly shows that nearly 80% of all excavation failure mechanism indicates fault slip as the source mechanism.

![Seismic source mechanism associated with excavation failure at Mine X.](image)

Figures 6 to 8 below plot the local magnitude (ML) versus Affected Area, Mass of rock fall and Depth of Damage respectively. The graphs show no real trend, which may suggest that it is likely that the distance between seismic event location and location damage would have an overriding significant effect.

To determine if there is a relationship between event size, distance to event and affected area it will be necessary to determine X, Y, Z of the damaged areas, plot it in 3D spatial analysis software program like Surpac and obtain a direct distance to the event location. Furthermore, the relation between specific site stress levels, rock type (strength and structure), geological discontinuities, excavation wall height and span, interacting excavations, and effectiveness of support systems all affect the extent of damage and depth of failure involved with site response to seismicity.
Fig. 6 Magnitude vs. Affected area.

Fig. 7 Magnitude vs. Mass of Fall.

Fig. 8 Magnitude vs. Depth of Damage.

An additional graph was created to visualise the excavations where seismic damage is likely to occur. Figure 9 below outlines, based on historical data, the majority of excavations likely to incur some kind of damage during a seismic event are the footwall drives (25%), ore drives (27%) and other (30% e.g. Vent Raise). Crosscuts are 50% less likely to be damaged during a seismic event.

It would further appear that the damaging seismic events are loosely associated with the mine’s blasting times (see Figure 10 below):

- 6-7 am : 7 damaging events
- 6-7 pm : 6 damaging events

However, damaging seismic events are not limited to these time zones only.

7.1 Ground support damage history

Ground support damage information was available for the 47 damaging events since January 2006. The seismic damage database revealed twelve different combinations of rock reinforcement and surface support systems (ground support standards) that were damaged between January 2006 and September 2011 (see Figure 11).

Following on from the damaged ground support database, an assessment of the distance from the seismic source to damaged location distance data has been provided by Mine X and it was accepted as valid. According to Mine X Geotechnical Department the seismic network had been previously calibrated. Assumptions and support calculations were made using...
the available data and must be viewed within the limits of the integrity of the data.

We used the provided seismic source to damage location data for each of the damaged ground support standards to see if there was any correlation between PPV, local magnitude and damaged ground support standard. The check was conducted using Kaiser et al (1996) PPV formulation:

$$PPV = 1.4 \times 10^{\frac{(0.5+ML)}{R}}$$

(10)

Where,

PPV = is the estimate peak particle velocity (m/s) at a location of damage
ML = Local magnitude scale
R = Distance (m) from the seismic source event to the location of damage

The PPVs vs Distance from seismic source (Figure 11) are plotted against damaged ground support standards e.g. Splitsets and mesh, Friction bolt/mesh & fibrecrete, CT Bolts & Mesh, Friction bolts/CT bolts/mesh & fibrecrete, Fibrecrete/mesh & CT bolts, GS9S, GS9S & GS11S, GS9S (+Garford Bolts), GS11S (+Garford Bolts), GS11S_B, GS11S (Cable Bolts in Backs) and Garford Bolts/Cable Bolts/fibrecrete & mesh.

The PPVs versus distance away from seismic source plot (Figure 11) above indicates the following:

- The power plot shows a reasonable correlation between PPV and distance from the seismic source for different damaged ground support standards and local magnitude. A trend line equation was derived from the data for use in the design or evaluation of damaged ground support standards.

$$PPV = 1.4481 \times R^{-0.529}$$

(11)

Where, PPV is the peak particle velocity measured in m/s and R is the distance away from the seismic source to the damaged location. It must be noted that care must be taken when using the formulation (Milev et al, 2002). The correlated formulation may only cater for a small percentage of the data. The PPVs were calculated and not measured PPVs (i.e. PPV is amplified at the skin of excavations due to relative loosening of the rock due to fracturing and jointing) close to the surface of the excavation.

7.2 Demand on Roof Support (Rock Reinforcement and surface support)

Assuming an estimated block ejection thickness of maximum 2m based on the seismic event that occurred on 22nd August 2011 and which had resulted in a fall of ground 40m down the length of the footwall drive 2m thick (from the roof). Thus based on this 2m thick block, and a calculated maximum PPV of 1.25m/s, the energy absorption requirement $E_k$ (kJ/m$^2$) of the support system is $E_k = 31.84$ kJ/m$^2$ (Rock Reinforcement). For the surface support the mass of the unit of rock for surface support assessment is based on the cone between the overlapping compressive zones and $E_k$ was evaluated to be 3.98 kJ/m$^2$.

When critically examining the ground support system as presented (P01-G_1 Support and Reinforcement), the view was taken that the ground support system could not be considered as a continuum. This was confirmed when the photographs from the 52 rockburst damage reports were reviewed. The actual behaviour of the ground support system appears to presents itself as discontinuous elements, subject to dynamic ground motion. This is likely because of the mixture of contrasting yield versus stiff components in the ground support system. This in itself presented a serious problem when assessing the ground support system with regards to the energy absorption criteria.

It would appear as if the yielding rock reinforcement elements (Garford Dynamic Bolt) on average do not have the necessary capacity (average energy absorption capacity 28.5 kJ) to withstand a single seismic event with a PPV of 1.25m/s (i.e. based on the calculated PPV) at a distance of 10m for a seismic event with a local magnitude of 1.9. However if the maximum energy absorption capacity for the Garford bolt is considered then the rock reinforcement is likely to withstand 1.6 seismic events with a PPV of 1.25m/s (i.e. based on the calculated PPV) at a distance of 10m for a seismic event with a local magnitude of 1.9.

Mesh and shotcrete is not considered to be subject to the same thickness of rock in the ground support demand calculation. The tendons must be capable in absorbing energy for the whole potential rock ejection thickness, but the surface elements must contain the cones or pyramids between bolts where the bolt “tributary area” actions do not overlap. It obviously depends on the bolt spacing and an assumed 45deg inclusion zone between collar and toe per bolt. This assumption reduces the demand on surface support and probably is proven because otherwise everything should fall off or shoot off. Hence the capacity (mesh and shotcrete) for the surface support 3.24 kJ should be theoretically capable to withstand a seismic event with a PPV of 1.25m/s (i.e. based on the calculated PPV) at a distance of 10m for a seismic event with a local magnitude of 1.9.

The surface support fibrecete (non-yielding) when assessed as a separate unit would not have the energy capacity to withstand a seismic event with a PPV of 1.25m/s (i.e. based on the calculated PPV) at a distance of 10m for a seismic event with a local magnitude of 1.9.

The surface support mesh (yielding) when assessed as a separate unit would not have the energy capacity to withstand one seismic event with a PPV of 1.25m/s (i.e. based on the calculated PPV) at a distance of 10m for a seismic event with a local magnitude of 1.9.

Therefore, even with a dynamic bolt capable of withstanding PPV’s of 1.25m/s, the system will still fail when the surface support cannot withstand the 1.25m/s ground motion.
When assessing all the failures associated with dynamic ground motion the following can be concluded:

- The ground support system acted as separate elements and not as one unit. This was quite obvious from almost every photo within the rockburst damage reports. Following these rockburst events, the fibrecrete was lying on the floor or in the mesh as separate panels with smaller rock fragments scattered or in one heap and mesh failed at overlap areas.

Three Garford Dynamic Bolts failed and it would appear as if one of the bolts only extended to 100mm instead of a full 300mm as per bolt specification (October 2010). The bolt also showed signs of a bending and shearing combination mechanism.

8 CONCLUSION

It can thus be concluded that that the expected energy demand on the ground support system will exceed the individual components of the ground support system up to 75m away from the seismic source (should conditions be similar to what have been experienced to date at Mine X. The ground surface support individual entities will likely fail up to 250m away from the seismic source. Note that the equation developed was used to determine calculated PPV. Care should be taken in using the formulation as the PPV’s used to develop the equation for the back analysis is not measured at the excavation surface. Thus it can be concluded that:

- Mesh and 2.4m long splitsets (GS9 – Ground Support Standard) are not the desired seismic ground support system for dynamic ground behaviour.

- 75mm Fibrecrete, mesh and 2.4m long splitsets (GS9S – Ground Support Standard) are not the desired ground support system for dynamic ground behaviour.

- 100mm Fibrecrete, mesh and 2.4m long Garford Dynamic Bolts (GS15S_B – Ground Support Standard) seems to show no damage when subject to a seismic source 75m and further away. The damaged ground support standard was subjected to peak particle velocity range of 0.09 – 1.25m/s. This specific standard had experience a range of seismic events with magnitudes that ranged from $M_L=0.1$ to $2.1$ (i.e. Fault slip or crush burst type events).

- Where the seismic source is closer than 70m, 100mm Fibrecrete, mesh and 2.4m long Garford Dynamic Bolts (GS15S_B – Ground Support Standard) had some damage.

- No damage is likely for PPV’s below 39mm/sec. This is in conflict with Hedley’s (1992) comments that no damage should be encountered at a PPV less than 50mm/sec (i.e. that is assuming the source parameter calculations are consistent for different databases).

- 70% of locations where ground support damage occurred had a calculated PPV between 39mm/sec and 300mm/sec.

- 14% of locations where ground support damage occurred had a calculated PPV between 300mm/sec and 600mm/sec.

- 16% of locations (seven in total) where ground support damage occurred had a calculated PPV above 600mm/sec of which two occurred closer than 10m away from the seismic source.

- For the 22nd August 2011 seismic event ($M_L=1.9$) up to 2m of material were ejected from the backs with the fibrecrete and mesh severely damaged and Garford bolts exposed but not failed.

The surface support fibrecrete (non-yielding) when assessed as a separate unit would not have the energy capacity to withstand a seismic event with a PPV of 1.25m/s (i.e. based on the calculated PPV at a distance of 10m for a seismic event with a local magnitude of 1.9).

The surface support mesh (yielding) when assessed as
a separate unit would not have the energy capacity to withstand one seismic event with a PPV of 1.25m/s (i.e. based on the calculated PPV) at a distance of 10m for a seismic event with a local magnitude of 1.9.

Therefore, even with a dynamic bolt capable of withstanding PPV's of 1.25m/s, the system will still fail when the surface support cannot withstand the 1.25m/s ground motion.

Further to the above it is the author’s belief that the weakest link for all seismically damaged locations is the combination of fibrecrete and welded mesh possibly due to the contrasting stiff ground surface support versus the axial yielding rock reinforcement elements at the overlapping zones.

It would seem that the highest risk for seismic damage does occur in the strike orientated ore and footwall drives. Most of the ground support damage was related to seismicity occurring on geological structures traversing the ore and footwall drives either perpendicular or at an acute angle. The emphasis to enhance the High Risk Seismic Ground Support Standard should be focused around these areas or look into the feasibility of transverse mining (if orebody size lower down the mine will allow).

It has been found that certain areas e.g. ore drives have been subject to face bursts. The ground support system evaluated (P01-G_1) does not have a general rule where temporary mesh is used to prevent rock being ejected from the working face. It would seem appropriate to use temporary mesh in high risk areas (e.g. high stress and geological structures intersecting areas and when approaching geo-structures (e.g. GS15S_B) in addition to current pre-conditioning being evaluated.

9 ACKNOWLEDGMENT

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10 REFERENCES

2. GAP 709a – SIMRAC Research Report.