Hazards / Risk associated with applied sprayed concrete / shotcrete / fibrecrete (as part of a ground support system)

Wouter Hartman
Principal Geotechnical Engineer

EAGCG Meeting – Shotcrete Workshop
18th – 19th May 2017
Outline

- Background
- Environment
- Mechanisms of shotcrete Failure
- Ground Support System Design
- Ground Support System Application
- Ground Support System(s) Evaluation
- Learning
BACKGROUND

Oct 1993 – High Stress / Seismic Active environment – 72 Level (Vaal Reefs No. 2-Shaft) – 1.8m Mn Seismic Event
BACKGROUND

Nov 1994 – Incident involved with rehabilitation applying Shotcrete in High Stress / Seismic Active environment

I, WOUTER HARTMAN STATE THAT:

I am a Strata Control Officer on the South Mine of Vaal Reefs Exploration and Mining Company Limited, of which No. 2-shaft is a member. Part of my responsibility is to advise management on matters pertaining to Rock Mechanics.

On November 7, 1994, I was informed that a fall of ground on November 05, 1994, in the 7N RAW, had resulted in the death of one contractor employee and injury to another. I visited the scene of the accident in the presence of the Regional Mining Engineer, the Assistant Mine Manager and other production officials responsible for this working place.

The opening-up and rehabilitation of the RAW is currently a priority. The RAW is currently in a high stress environment due to the 72 N 56A pillar +65m above the tunnel. The recommendation stated that the old support installed should be removed and replaced with 75m re-enforced steel-fibre shotcrete, 40 ton 6.0m pre-stressed anchor’s (6 in a row 2m apart, pre-stressed to 20 ton) and meshing and lacing on a 1m diamond pattern.
10 Jan’ 2012 – Local magnitude ML 1.8 seismic event - distance of 50m from the nearest rockburst damage – Mine A.
BACKGROUND

10 Jan’ 2012 – Local magnitude ML 1.8 seismic event - distance of 50m from the nearest rockburst damage – Mine A.

Photographs of damage on 50 and 75L show fibrecrete de-bonding, bulging (hollow behind), and cracking.
BACKGROUND

10 Jan’ 2012 – Local magnitude ML 1.8 seismic event - distance of 50m from the nearest rockburst damage – Mine A.
BACKGROUND

Ground Support Design at Mine A

GSS5S - Stopping ore drives
Stopping support with shotcrete

Specifications (Minimum standards)

<table>
<thead>
<tr>
<th>Posimix Bolts</th>
<th>Fibrecrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>- 2.4m 20mm Posimix Bolts</td>
<td>- Minimum 75mm thick</td>
</tr>
<tr>
<td>- 200 x 200 Plates</td>
<td>- 9kg/m³ poly fibres</td>
</tr>
<tr>
<td>- Installation angle not to be less than 70° from wall</td>
<td>- no access permitted under fibrecrete until bolting complete</td>
</tr>
<tr>
<td>- 1.2m x 1.2m spacing (or half the blasthole ring spacing along drive)</td>
<td>- Fibrecrete to extend from floor to floor</td>
</tr>
<tr>
<td>- bit diameter not more than 38mm</td>
<td></td>
</tr>
</tbody>
</table>

5 GROUND CONTROL

5.1 Minimum Ground Control Requirements

Minimum ground control standards have been developed with regard to:
- Rockmass quality (Q)
- Empirical design techniques
- Previous support performance at Mine A
- Geotechnical Consultant recommendations.

The Ground Support Standards for Mine A in Appendix 1. These standards apply to all underground development.
5. GROUND SUPPORT

The current support systems in the SLC and decline are capable of absorbing a certain amount of dynamic energy caused by seismic events. Ground support and reinforcement in seismic areas is calculated based on the support pressure required to resist the dynamic loading caused by a nominal seismic event occurring 10m from an excavation surface (Reference graphs – eg Potvin and support data eg Kaiser).

The required dynamic support capacity is calculated using the following equation:

\[
\text{Factor of Safety} = \frac{\text{Support Capacity}}{\text{Energy Demand}}
\]

\[
\text{Factor of Safety} = \sum \left( \frac{\text{Load Capacity} \times \text{Displacement Capacity}}{\text{support elements}} \right)
\]

\[
0.5mv^2 + qmgd
\]

Where:
- \( m \) = mass of ejected material
- \( v_e \) = ejection velocity of the block
- \( g \) = acceleration due to gravity
- \( d \) = distance the ejected block has travelled
- \( q \) = 1 for the backs; 0 for the walls

In assessing the dynamic support requirements at Mine A using the above equation, the following assumptions were made:

- Mass of ejected material equal to a continuous rock thickness of 0.5m. This is based on observation of the depth of failure caused by previous rockfalls.
- Velocity of ejection = 3m/s. This value is conservatively valued above the 1.5m/s calculated using the ppv/distance chart (Kaiser et al, 1995) using a maximum event (seismic hazard) magnitude of 2.0.
- Split sets will contribute only 25% of their calculated dynamic support capacity to the total energy absorption capacity of the seismic support system.
- 75mm Fibrecrete will contribute 50% of their calculated dynamic support capacity to the total energy absorption capacity of the seismic support system.
- Mesh will contribute only 25% of their calculated dynamic support capacity to the total energy absorption capacity of the seismic support system.
BACKGROUND

Ground Support Design at Mine A

The spreadsheet shown in Table 1 is used to calculate appropriate bolt spacing in the backs and walls. ‘Energy Balance’ needs to be positive for the dynamic support to resist the dynamic loading with the factor of safety applied.

The support regime currently applied in the SLC drives is as follows:

- 75mm fibrecrete
- 2.4m split sets on a 1.5m spacing
- 2.4m and 3m Gewi Bars installed in at 1.5m spacing

The dynamic support regime may be re-assessed at any time due to increases or decreases in the predicted seismic hazard. Seismic related damage in an unexpected area, or of an unexpected magnitude, may also require a re-assessment of the dynamic support regime.
BACKGROUND

Ground Support Design at Mine A

### Table 1: Dynamic Support Calculation

<table>
<thead>
<tr>
<th>Constants and Assumptions</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth of Failure</td>
<td>0.7</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>2.8</td>
</tr>
<tr>
<td>Mass of ejected block (kg)</td>
<td>1960</td>
</tr>
<tr>
<td>Velocity of ejection backs (m/s)</td>
<td>3</td>
</tr>
<tr>
<td>Velocity of ejection walls (m/s)</td>
<td>3</td>
</tr>
<tr>
<td>Acceleration due to Gravity</td>
<td>0.81</td>
</tr>
<tr>
<td>q Backs</td>
<td>1</td>
</tr>
<tr>
<td>q Walls</td>
<td>0</td>
</tr>
<tr>
<td>Factor of Safety</td>
<td>1.45</td>
</tr>
<tr>
<td>Distance of Travel</td>
<td>0.3</td>
</tr>
</tbody>
</table>

### Support Element Load / Deformation Capacity

<table>
<thead>
<tr>
<th>Support Element</th>
<th>Load Capacity (kN)</th>
<th>Displacement Capacity (mm)</th>
<th>Energy Absorption Capacity (kJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Split Set</td>
<td>60</td>
<td>200</td>
<td>12</td>
</tr>
<tr>
<td>Fibrobrec (to be confirmed)</td>
<td>50</td>
<td>200</td>
<td>50</td>
</tr>
<tr>
<td>Cable Bolt</td>
<td>500</td>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td>Gewi Bar</td>
<td>180</td>
<td>300</td>
<td>48</td>
</tr>
</tbody>
</table>

### Calculated Dynamic Support Requirement

| Required Capacity Backs (kJ/m²) | 21 |
| Required Capacity Walls (kJ/m²) | 13 |

#### Dynamic Support Design Backs

<table>
<thead>
<tr>
<th>Support Element</th>
<th>Spacing (mm)</th>
<th>Percentage Contribution to Support</th>
<th>Energy Absorption Capacity (kJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Split Set</td>
<td>130</td>
<td>25</td>
<td>1.78</td>
</tr>
<tr>
<td>Fibrobrec (to be confirmed)</td>
<td>100</td>
<td>50</td>
<td>25</td>
</tr>
<tr>
<td>Twin Strand Cable Bolt</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>Gewi Bar</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>Energy balance:</td>
<td>0.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Dynamic Support Design Walls

<table>
<thead>
<tr>
<th>Support Element</th>
<th>Spacing (mm)</th>
<th>Percentage Contribution to Support</th>
<th>Energy Absorption Capacity (kJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Split Set</td>
<td>130</td>
<td>25</td>
<td>1.78</td>
</tr>
<tr>
<td>Fibrobrec (to be confirmed)</td>
<td>100</td>
<td>50</td>
<td>25</td>
</tr>
<tr>
<td>Twin Strand Cable Bolt</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>Gewi Bar</td>
<td>1.5</td>
<td>100</td>
<td>21.10</td>
</tr>
<tr>
<td>Energy balance:</td>
<td>0.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Article – *Surface strain burst and bumps (Figure 7).* Small events often mobilise only the skin of the excavation.

“Site personnel, when designing a ground support system, need to consider the interaction between the elements to ensure they are not over engineering one part of the system while neglecting the weakest link.”

BACKGROUND

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 (GAP 709a – SIMRAC Research Report – March 2002).

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 attenuation of the PPV’s in the wall of an underground tunnel (Milev, et al, 2002). 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.
Hedley (1992):
• 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).

The attenuation of the PPV’s in the wall of an underground tunnel (Milev, et al, 2002).
ENVIRONMENT

Studies on **peak particle velocities** and **site response** were conducted

(i) SIMRAC projects, GAP 201 (1998) and GAP 530 (‘Improvement of worker safety through the investigation of site response to rockbursts’ - 1998).

(ii) 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 source.

(iii) Points less than a metre apart show differences in amplitude and phase, which can only be accounted for by large strain across fractures.

The attenuation of the PPV’s in the wall of an underground tunnel (Milev, et al, 2002).
Case Study: WA Mine, Back analysis of the failure concludes that the **failed support system** was ejected from the wall of the excavation with an "**initial calculated velocity of 10.7 m/s**" with a calculated energy demand of "**154.5 kJ**" (Drover & Villaescusa, 2015)

Seismic Event > 2ML – **Distance from Seismic Source unknown**
There are significant uncertainties in the design of ground support from dynamic and rockburst conditions. (Dunn, 2017)

These range from natural and spatial variability for known parameters to significant gaps in our understanding of rockburst mechanisms and PPV at the excavation skin and the associated ejection PPV. (Dunn, 2017)

Need for in situ monitoring of ground support and the rock mass behaviour under dynamic conditions so that laboratory index tests can be calibrated against measured behaviour. (Dunn, 2017)
Punch shear failure is a scenario which requires a high dynamic energy demand. This mechanism is more likely to occur in highly stressed rock masses where the shotcrete is retained by pattern reinforcement. Compressive failure is a common observation in high rock stress environments and may also be referred to as shotcrete spalling. This mode of failure may present in excavations where high stress concentrations are oriented tangential to the excavation surface, such as the roof of excavations subject to high horizontal stress or walls of excavations subject to high vertical loads. Tensile failure of shotcrete is rare in straight-line development. Most often it can be seen in the apex of intersection pillars, where the rock mass is exposed in two directions. It may also be observed in wide span excavations.

Figure 1 - Shotcrete failure mechanisms (modified after Barrett & McCreadh, 1995).
MECHANISM OF FAILURE – SHOTCRETE

- The presenter have been instrumental in the design & manufacturing of a portable shotcrete shear testing equipment for ease of field testing.

- Indications are that fibre reinforced shotcrete has a significantly higher shear value than the theoretical value back calculated from UCS strengths for concrete.
Shotcrete is widely used for isolating fresh rock walls from the atmosphere. This helps to delay the weathering process, which is vital in preventing blocks of rock falling into an excavation.

Being thin and brittle, shotcrete is easily cracked under repeated dynamic loading, potentially allowing rock to be ejected from a damaged section during a seismic event.

Fibrecrete, on the other hand, has a greater tensile strength, which may provide resistance to this problem. Stacey & Ortlepp (2001) pointed out that shotcrete contributed a small amount of energy capacity to the ground support system during a dynamic event.
DESIGN (Considerations)

- Reinforced shotcrete with high toughness and tensile capacity has shown to be an effective support structure. The ideal membrane should consist of following characteristics *Stacey & Ortlepp (2001):*
  - very high stiffness during the early stages of loading to prevent or minimize the deformation of the rock;
  - yielding ability to absorb more energy during dynamic loading without failure;
  - high toughness to resist mechanical damage, and;
  - ability to maintain a high load capacity during rock movement.

However, it is unrealistic to expect all of these characteristics in a single membrane technology. The best solution is to employ multiple technologies to build an integrated membrane system. Diamond mesh, with shotcrete, is the recommended containment support system which has been proven to have sufficient toughness and yield capacity (*Stacy & Ortlepp 2001*).
2.4 Design Considerations for Mining

2.4.1 Design for Strength and Stability

Geotechnical Parameters

The mining industry has traditionally used empirical methods supported by some form of rock-mass classification to design ground support systems. Rock-mass classification systems have been used to group areas of similar geomechanical characteristics, to provide guidelines for stability performance and to select appropriate support. Examples of commonly used systems are:

- Q-system (Grimstad & Barton[17])
- RMR system (Bieniawski[18])
- New Austrian Tunnelling Method (NATM)
- Ground Characteristics Curve Method (Brady and Brown 1985)[19]

Both the Q and RMR classification systems are based on a rating of three principal properties of a rock mass:

- The intact rock strength,
- The frictional properties of discontinuities, and
- The geometry of intact blocks of rock defined by the discontinuities.

The Q system of rock-mass classification was developed for tunnel support in hard rock by Barton et al.[20] and is based on a numerical assessment of the rock mass quality using six parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>RQD</td>
<td>Rock Quality Designation</td>
</tr>
<tr>
<td>Jn</td>
<td>Joint set Number</td>
</tr>
<tr>
<td>Jr</td>
<td>Joint Roughness number</td>
</tr>
<tr>
<td>Ja</td>
<td>Joint Alteration number</td>
</tr>
<tr>
<td>Jw</td>
<td>Joint Water reduction factor</td>
</tr>
<tr>
<td>SRF</td>
<td>Stress Reduction Factor</td>
</tr>
</tbody>
</table>

---

2 Design Considerations

2.1 For Basic Properties

2.2 For Reinforcement

2.3 For Civil Underground Applications

2.4 For Mining
Assumption is to increase the energy absorption capacity with a poorer rockmass and/or behaviour.
**DESIGN (Considerations)**

**Recommended Practice**

**Shotcreting in Australia**

**Second Edition**

### 2 Design Considerations

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1 For Basic Properties</td>
<td>14</td>
</tr>
<tr>
<td>2.2 For Reinforcement</td>
<td>15</td>
</tr>
<tr>
<td>2.3 For Civil Underground Applications</td>
<td>17</td>
</tr>
<tr>
<td>2.4 For Mining</td>
<td>19</td>
</tr>
</tbody>
</table>

**Testing**

In specifying certain testing of the shotcrete, the user should consider the type and frequency of testing in relation to the importance of the opening and availability of test facilities due to specific limitations such as remoteness. This may lead the designer to a more conservative design approach. This will affect the testing specifications (refer to Clause 10.3).

Consideration of systems for ongoing monitoring may be required for long-term openings or excavations predicted to be subjected to large displacements.
Research has shown that, for typical fibre reinforced shotcrete mixes with toughnesses in the range 300 – 500 Joules (ASTM C-1550), the energy absorbed by a given mix in a square EN 14488-5 panel test at 25 mm central deflection is approximately 2.5 times the magnitude of energy absorbed by the same mix in the ASTM C-1550 at 40 mm central deflection (Bernard[59]).
### DESIGN (Considerations)

#### Square-Panel Test Method – EN 14488-5

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>width</td>
<td>0.6</td>
</tr>
<tr>
<td>length</td>
<td>0.6</td>
</tr>
<tr>
<td>M2</td>
<td>0.36</td>
</tr>
<tr>
<td>1m2</td>
<td>1</td>
</tr>
<tr>
<td>m2</td>
<td>2.78</td>
</tr>
<tr>
<td>Joules</td>
<td>500</td>
</tr>
<tr>
<td>kJ</td>
<td>0.5</td>
</tr>
<tr>
<td>kJ/m²</td>
<td>1.4</td>
</tr>
</tbody>
</table>

#### RDP - ASTMC1550

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>diameter</td>
<td>0.8</td>
</tr>
<tr>
<td>radius</td>
<td>0.4</td>
</tr>
<tr>
<td>m²</td>
<td>0.503</td>
</tr>
<tr>
<td>1m²</td>
<td>1</td>
</tr>
<tr>
<td>m²</td>
<td>1.99</td>
</tr>
<tr>
<td>Joules</td>
<td>500</td>
</tr>
<tr>
<td>kJ</td>
<td>0.5</td>
</tr>
<tr>
<td>kJ/m²</td>
<td>1.0</td>
</tr>
</tbody>
</table>
DESIGN (Considerations)

Product Testing
Figure A6.2 – Post-crack load-deflection curves for 800 mm RD panels varying in thickness from 45mm to 95mm and made with a concrete set 1.
\[ W_\gamma = P_\gamma \]  

(3.9)

where \( W_\gamma \) is the post-crack energy absorption of a deflection \( \gamma \) with corresponding average load capacity \( P \), as shown in Figure 14.

Schematic load-displacement diagram of an ASTM C1550 panel test. The energy absorption \( W_\gamma \) can be determined by the deflection \( \gamma \) and the average load capacity \( P \) (from Bernard, 2004).
### DESIGN (Considerations)

Table 2: Load and energy-absorption capacities of reinforcement elements employed in classifying ground support systems. Data compiled from multiple sources

<table>
<thead>
<tr>
<th>Reinforcement elements</th>
<th>Load capacity (kN)</th>
<th>Energy capacity (kJ)</th>
<th>Reinforcement elements</th>
<th>Load capacity (kN)</th>
<th>Energy capacity (kJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical bolt</td>
<td>115</td>
<td>2.2</td>
<td>Swellex Mn12 bolt</td>
<td>110</td>
<td>15</td>
</tr>
<tr>
<td>Resin-grouted rebar</td>
<td>170</td>
<td>14</td>
<td>35 mm friction set</td>
<td>89</td>
<td>5.0</td>
</tr>
<tr>
<td>Modified conebolt</td>
<td>160</td>
<td>30</td>
<td>39 mm friction set</td>
<td>102</td>
<td>7.7</td>
</tr>
<tr>
<td>D-bolt (20 mm)</td>
<td>210</td>
<td>45</td>
<td>46 mm friction set</td>
<td>145</td>
<td>15</td>
</tr>
<tr>
<td>D-bolt (22 mm)</td>
<td>250</td>
<td>56</td>
<td>Plain strand cable</td>
<td>265</td>
<td>18</td>
</tr>
<tr>
<td>Swellex PM12 bolt</td>
<td>110</td>
<td>4.6</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The development of a ground support design strategy for deep mines subjected to dynamic-loading conditions

P Morissette  Agnico Eagle Mines Limited, Canada
J Hadjigeorgiou  University of Toronto, Canada

2017
The development of a ground support design strategy for deep mines subjected to dynamic-loading conditions

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2017
### Table 4: PPV-performance threshold of detailed ground support systems installed in the walls

<table>
<thead>
<tr>
<th>Ground support systems</th>
<th>Conceptual reinforcement capacity Load (kN/m²)</th>
<th>Energy (kJ/m²)</th>
<th>PPV-performance thresholds (mm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>σr/UCS</strong></td>
<td><strong>Reinforcement</strong></td>
<td><strong>Surface support</strong></td>
<td></td>
</tr>
<tr>
<td>0.2–0.4</td>
<td>Mechanical bolts</td>
<td>Welded-wire mesh (W1)</td>
<td>110–124</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mesh-reinforced shotcrete (W1s)</td>
<td>110–124</td>
</tr>
<tr>
<td></td>
<td>FS-35/39</td>
<td>Welded-wire mesh (W2)</td>
<td>96–110</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mesh-reinforced shotcrete (W2s)</td>
<td>96–110</td>
</tr>
<tr>
<td></td>
<td>FS-46</td>
<td>Welded-wire mesh (W4)</td>
<td>156</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mesh-reinforced shotcrete (W4s)</td>
<td>156</td>
</tr>
<tr>
<td></td>
<td>FS-39 and Swellex Mn12</td>
<td>Mesh over fibercrete (W5s)</td>
<td>168</td>
</tr>
<tr>
<td></td>
<td>1st pass FS-46 2nd pass MCB</td>
<td>Mesh-reinforced shotcrete (W9s)</td>
<td>230–240</td>
</tr>
<tr>
<td></td>
<td>FS-35/39</td>
<td>Welded-wire mesh (W2)</td>
<td>96–110</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mesh-reinforced shotcrete (W2s)</td>
<td>96–110</td>
</tr>
<tr>
<td></td>
<td>FS-46</td>
<td>Welded-wire mesh (W4)</td>
<td>156</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mesh-reinforced shotcrete (W4s)</td>
<td>156</td>
</tr>
<tr>
<td></td>
<td>1st pass FS-46 2nd pass MCB or cables</td>
<td>Welded-wire mesh (W8/W9)</td>
<td>228–270</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mesh-reinforced shotcrete (W8s/W9s)</td>
<td>228–270</td>
</tr>
</tbody>
</table>

MCB = modified cone bolt

---

**The development of a ground support design strategy for deep mines subjected to dynamic-loading conditions**

P. Morissette, Agnico Eagle Mines Limited, Canada

J. Hadjiyorgiou, University of Toronto, Canada
Kaiser et al. (1996) define three main failure mechanisms and provides a method to cater for these. The three failure mechanisms are as follows:

- **Strainbursts** — seismically triggered (initiated by mining-induced stress change) and dynamically loaded (a remote seismic event triggers and adds energy to the strainburst); these are also referred to as self and remotely triggered strainbursts, respectively.
- Seismic shakedown.
- Seismic ejection.

The energy absorption requirement \( E_a \) in units of \( kJ/m^2 \) of ground support under dynamic loading is calculated as follows:

\[
E_a = \frac{1}{2} m v^2 + q \times m \times g \times d
\]

where:

- \( m \) = Mass of potentially ejected rock.
- \( v \) = Ejection velocity.
- \( g \) = Acceleration due to gravity.
- \( q \) = Direction factor.
- \( d \) = Stopping distance.
• Calculations use the square of ejection velocity, so errors in the value of velocity are compounded; the actual ejection velocity is usually unknown.

• The method suggests that wall support requirements will be less than backs, as the potential energy change for wall ejection is zero.

• The method is dependent on assumptions for size and thickness of failure.

• The method does not account for damage mechanisms other than pure ejection e.g. assumes axial loading and does not consider shear.

• Momentum change should also be included. Momentum change equates arithmetically to the product of the component load and the impulse duration. A rigid scheme with shorter impulse duration will need to withstand a higher load to meet the momentum demand.

• Common practice has been to assume, as an input for this method, the displacement (d) of the block that is ejected, then calculate energy changes and select a ground support scheme that will survive those energy changes. However, this approach is incorrect as d should be an output resulting from the interaction of the ground support scheme with the damaging excitation.

• Interaction of the scheme with the rock will change the kinetic energy demand. To illustrate this, consider that as movement develops during an event, some support types (e.g. fibrecrete) apply restraint at small displacement while others (e.g. mesh) do not respond to the displacement until it has become substantial.

Mikula, 2012
Recently, Kaiser and Cai (2013a, 2013b) suggested that it was time to rethink some of the assumptions when designing ground support for burst-prone ground. They noted four main areas that needed attention:

- The assumed direct relationship between ground motion (ejection energy) and yielding support demand is overly simplistic. Overstressed and highly strained, brittle rock breaks into cohesionless blocky ground; it can bulk gradually or suddenly, resulting in large deformations. While the solution may be the same, i.e. a need for yielding bolts, the design criterion is not energy demand but strain or displacement demand.

- Damage in mining excavations is mainly due to seismically triggered strainbursts or falls of ground; the load or deformation demand should be independent of the source characteristics but entirely dependent on the locally releasable energy. Hence it is more important to maintain a Factor of Safety (FS) that influence strainbursts (stress level, mining system stiffness, depth of stress fracturing or depth of failure) and factors that influence falls of ground (geological structures, extent of rock mass fracturing, etc.). The effect of ground motions with respect to support design and energy demand requirements may be overrated.

- Only for excavations very close to a large fault-slip event will the dynamic loading impact dominate over the demand from locally stored energy. In this case, damage will be affected by the dynamic load imposed by the event as well as by the energy transferred from the event, and the commonly adopted relationships between ground motion intensity and support energy capacity are applicable.

- Actual and design ground motions are not identical; the former are affected by radiation patterns and wave transmission modifiers and are needed for forensic analyses, whilst the latter are needed for design, i.e. it is necessary to estimate ground motions that could damage an excavation.
DESIGN (Considerations)

Perhaps we should go back to basics...

When a mass is accelerated, where does its kinetic energy come from? Does it come from the force applied to the mass in order to accelerate it? If so, is there any mean to connect newton with joules i.e. 1N of force increment a 1kg mass' kinetic energy by X joules/sec?

When a force is applied to an object, that object's momentum changes its kinetic energy.

At low speeds and energies, all of the forces acting on an object equal that object's mass times its acceleration (Newton's 2nd law). The relationship between force and energy can be derived from the 2nd law:

\[ F = ma \] (Newton's 2nd law) where \( F \) is force, \( m \) is mass, and \( a \) is acceleration. \( F \) has magnitude and direction. i.e \( F = (\frac{dp}{dt}) \) where \( p \) is momentum and \( \frac{dp}{dt} \) implies a change in momentum with respect to a change in time. Momentum, \( p \), however, is related to kinetic energy, \( KE \), by the equation \( KE = \frac{p^2}{2m} \). So a change in momentum corresponds to a change in kinetic energy.

The essence of Newton's second law: Applying a force to a mass changes the momentum of that mass. An acceleration just represents this change in momentum for an object that has a constant mass.
DESIGN (Considerations)

Perhaps we should go back to basics or look at other disciplines...

The units **newtons and joules** can be connected directly. For a mass under a constant force, \( F \times \Delta d = \Delta KE \) where the \( \Delta \) is the symbol for change and the "\( x \)" means that only the part of \( F \) that is in the same direction as \( d \) should be multiplied.

Thus moving an object a distance \( d \) with a force \( F \) changes the kinetic energy in a mathematically direct fashion.

Q. Do we really think we can stop displacement...?
DESIGN (Considerations)

Perhaps we should go back to basics or look at other disciplines...

It is now well known that during an earthquake, high-frequency seismic waves cause major damage because the resonance frequency of most man-made structures — homes, bridges, roads — falls within their frequency range.

Resonance frequency is the tendency to naturally oscillate at certain frequencies.

Extent of Cracking – Concrete Flooring Design:
Cracking reduces floor stiffness and, consequently, lowers its natural frequency. For conventionally reinforced concrete it is important to allow for cracking. Otherwise, the results are likely to be on the un-conservative side. For conventionally reinforced flat slab construction with span to depth ratio of 30 or larger, a 30% reduction in stiffness is reasonable. (Prof. Bijan O Aalami (Professor Emeritus, San Francisco State University; Principal, ADAPT Corporation)
DESIGN (Considerations)

Perhaps we should go back to basics or look at other disciplines...

DETERMINATION OF VIBRATION CHARACTERISTICS OF A RE-INFORCED CONCRETE FLOOR

Determining vibration characteristics requires finding
(i) the natural frequency of a floor system and
(ii) the associated peak acceleration.

First Mode Shapes and Deflection of Simple and Continuous Spans
APPLICATION

Site preparation – Mine C
APPLICATION

Shotcrete applied in boxcut – poor wall preparation - Mine D
APPLICATION
Fibrecrete applied on Sidewalls – Was any standard followed..? - Mine E
APPLICATION

Shotcrete applied on Bullnoses – severe cracking – no cover mesh – only strapped at base to provide containment - Mine F
APPLICATION

Steel Fibre Shotcrete applied on Sidewall – shotcrete ejected from sidewall - Mine F
APPLICATION

Fibrecrete applied at Drawpoints – Shakedown fall of fibrecrete – no mesh – Mine F
APPLICATION

Mesh over shotcrete vs No mesh - Shakedown fall of shotcrete Mine F
APPLICATION

Ejection of shotcrete - Mine F
APPLICATION
Shotcrete applied on Sidewall – severe shotcrete cracking and ejection from sidewall - Mine F
APPLICATION

Aggressive groundwater: Fibrecrete and mesh adversely affected – Mine G
Shotcrete have been applied: Mesh not yet secured: A 0.8 magnitude event on face – Mine H: GS15S_B, the highest form of *dynamic support* was used.
GROUND SUPPORT STANDARD EVALUATION FOR DYNAMIC GROUND MOTION – Mine H

GS15S_B

GS15S_B (FACE SUPPORT TO BE USED)

5m x 1m Sheet of Mesh vary centre sheet side according to actual drive width

90 mm Fibrecrate Pass 2

80 mm Fibrecrate Pass 1

90 mm Fibrecrate Pass 2

90 mm Fibrecrate Pass 1

GARFORD BOLTS

GARFORD BOLTS

Bolt must be perpendicular to surface with +/- 15 degrees variance, to compensate for boom length

GROUND CONTROL:
- BACKS: 1.2 m spacing, 1.5 m between rows
- WALLS: Dose 5 on 0.75 x 0.75 spacing

FIBRECRETE SPECIFICATIONS:
- Thickness mm: 100
- Reinforcement: 4.0
- Grade: P100 to P150
- Roughness Factor: 1.6
- Quantity: 0.53 m³ (Pass 1 & 2)

DO NOT SPRAY BUTTS - withstand by 300 - 500 mm

3.0 m FRICTION BOLTS TO BE USED ON OVERLAP

REINFORCEMENT SPECIFICATIONS:
- Garford Dynamic Bolt
  - Diameter: 27 mm
  - Length: 2.4 m
  - Bit Size: 45 – 45 mm
  - Hole depth: 2.4 m

- Number of Garford bolts per cut = 42 (34 on first cut)
- Plate Specifications
- Garford bolt: Central Plate with 10 mm dome plate
- Friction bolt: Garford, Central plate, 300 mm x 280 mm x 1.9 mm

1 x 30 mm 1200 mm cartridge
- Fast set resin
- Used for the resin

QUALITY CONTROL:
- Random pull tests will be carried out. Refer to Pull Test Guidelines
- Pull rings to be installed on 1% bolts (20)

MESH SPECIFICATIONS:
- Mesh: Galvanised
  - Size: 5 mm x 100 mm
- Wire Size: 5 mm
- Mesh sheet dimensions must be suitable to cover specified area
- - shown picture is guide only
- Mesh overlap 300 mm, bolt through the centre square
- Where mesh is used, reinforce pillars with the jacking up the mesh must not overlap
- Mesh to face, across the backs and down the shoulders
- Mesh must have adequate running across the backs closest to the surface to minimise blast damage

NOTES:
- Additional support may be required to maintain minimum standards with variations in design
- 1.5 m spacing to the previous grade support
- 0.9 m bolts to be used for the hanging mesh
- Min. 1% of bolts are variable and DO NOT form part of the support pattern

SIGN OFF
- Senior Geotechnical Engineer
- Underground Superintendent
- Tech Services Superintendent

SIGNATURE & DATE

FILE NAME: T.Techdata/1KM5/Mine Plans/Level Plans/GS15S_B.pdf

DESIGNED BY: GEOTECH
DRAWN BY: G.E.O.H.A.R.T. LTD
10. RECOMMENDATIONS

- X to investigate ways to reduce the risk of operators going in front of the jumbo.
- Ground awareness training
- Investigate and trial de-stress blasting
- For the 9145 FW Dr E a detailed document will be produced that will include the following:
  - Fire only at end of day shift
  - 12 hours exclusion zone
  - Geotechs to review seismicity and give permission on a daily basis to enter the heading, this will be done using JDi and MSRAP
  - Review possibility of shotcreting the face before meshing. This will give additional confinement, possibly reducing fly rock potential.
Shotcrete & Mesh have been applied: Areas where mesh was damaged the shotcrete ejected: 2.0 Mn event which occurred in close proximity to the drawpoint: Mine H: GS15S_B, the highest form of dynamic support was used.
GROUND SUPPORT STANDARD EVALUATION FOR DYNAMIC GROUND MOTION – Mine H
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 a desired ground support system for dynamic ground behaviour.
GROUND SUPPORT STANDARD EVALUATION FOR DYNAMIC GROUND MOTION – Mine H

- 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 experienced 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) seems to show some damage.
No damage is likely for PPV’s below 39mm/sec. This is slightly different to 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).
GROUND SUPPORT STANDARD EVALUATION FOR DYNAMIC GROUND MOTION – Mine H

- The *surface support fibrecrete* 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**.
LEARNINGS

- There appears to be a disconnect between the energy absorption capacity obtain via static testing for the dynamic behaviour of the rockmass and the fibrecrete response.

- Shotcrete and/or Fibrecrete implemented as a standalone containment support in an underground mine subject to quasi-static and/or dynamic ground behaviour poses a significant **Health and Safety Risk**.

- Applied shotcrete/fibrecrete covered or assisted with yieldable mesh in conjunction with yieldable straps and yieldable reinforcement elements appears to be a reasonable containment strategy for an underground mine subject to quasi-static and/or dynamic ground behaviour.
LEARNINGS

• Perhaps new thinking required related to design considerations for applied sprayed concrete, shotcrete and/or fibrecrete for underground mine tunnels subject to quasi-static and dynamic ground motions – PPV > 39mm/s

• Need to explore other areas / disciplines and how that may assist us in our understanding of ground support and in particular shotcrete behaviour and related damage e.g. Site response, shotcrete peak response acceleration, natural frequency etc..