Deep Mining 2010 — M. Van Sint Jan and Y. Potvin (eds)
© 2010 Australian Centre for Geomechanics, Perth, ISBN 978-0-9806154-5-6

An interpretation of ground support capacity submitted to dynamic loading

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Abstract

Rockburst risk is an increasing problem in underground mining worldwide, as the general trend is for mines to operate in deeper environments. In most mines affected by seismicity, the first line of defence to mitigate the potential consequences of rockburst is to install dynamic resistant ground support systems. The assessment of ground support capacity when submitted to dynamic loading has been the subject of intensive research over the last two decades. In particular, drop tests were developed to investigate the capacity of support elements while the performance of various support systems was examined by simulating rockbursts with carefully designed blasts.

The above research has yet to yield an accepted method to determine the dynamic capacity of ground support. In this paper, the published results from many of the above tests are compiled and practical observations are made regarding the dynamic capacity of ground support systems.

1 Introduction

The trend towards exploiting deeper mineral resources is a natural evolution of underground mining worldwide, as near surface reserves become progressively depleted. Notably, South Africa has several mines operating between 3 and 4 km below surface while some Canadian mines are operating at a depth exceeding 2 km (Potvin et al., 2007). The challenges associated with deep mines are numerous but perhaps the prime risk and concern in many of these mines is rockbursting. However, rockbursting is not confined to deep mines. Relatively shallow mines, for example in Western Australia, can also experience high stress (Lee et al., 2006) and must address the risks associated with rockbursts. Rockbursting is undoubtedly an increasing problem in the mining industry.

There are a number of measures that can be implemented to mitigate rockburst risks, including reducing exposure of personnel and changes to mine design, layout and extraction sequences. However, the most common line of defence in mines is the implementation of a dynamic resistant ground support system. A mine which experiences significant seismicity, to the extent where rockburst damage is caused to underground workings, must implement ground support designs which account for the possibility of dynamic loading. This is an area where rock engineering science is still developing. More specifically, the dynamic capacity of ground support has been the object of significant research during the last two decades.

Some of this work has focused on ‘drop testing’ using gravity to either directly deliver kinetic energy to isolated ground support elements (Yi and Kaiser, 1994; Kaiser et al., 1996; Ortlepp and Stacey, 1997, 1998; Ortlepp et al., 1999; Stacey and Ortlepp, 1999; Ortlepp and Swart, 2002; Gaudreau et al., 2004; Plouffe et al., 2008) while others have used a load transfer mechanism from decelerating a support sample attached to a load (Player et al., 2004, 2008a, 2008b, 2009; Villaescusa et al., 2005). A third category of testing reported on in literature is the use of blasting to simulate the dynamic load on complete support systems installed in situ (Tannant et al., 1993, 1994; Hagan et al., 2001; Hildyard and Milev, 2001; Reddy and Spottiswoode, 2001; Espley et al., 2002; Archibald et al., 2003; Heal, 2005; Andrieux et al., 2005; Heal and Potvin, 2007).

In addition to simulated rockburst testing of complete ground support systems, back calculation of support capacity from a large database of case histories has also been performed by Heal (2010).

Despite this significant body of research, there is still no accepted method for the design of ground support submitted to dynamic loading. At the same time, practitioners operating in rockbursting conditions are required to use 'best practice' to design ground support capable of mitigating the consequences of seismic events. This paper will attempt to synthesise previous research and provide some guidance on the significance and limitations of these results to facilitate their use for ground support design.

2 Ground support submitted to dynamic loading; design principles

Some general rock engineering design principles relevant to the specific case of dynamic loading of ground support are described in this section. But before considering the design itself, it is important to realise that dynamic loading occurs as a result of mine induced seismicity, which consists of repeatedly occurring discrete events of different magnitude and location. In between seismic events and in addition to dynamic loading, the ground support system must also fulfill its role of maintaining the integrity of the excavation and will be submitted to static loading. Therefore, the design of the support system under dynamic loads does not replace the design for static loads, but must rather be done as an additional process. This paper is concerned with the dynamic design process.

2.1 Factor of safety (FOS) approach to dynamic support design

As is often the case in structural and rock engineering design, an approach based on the factor of safety (FOS) where the structural capacity of a system is compared to the actual load acting on the system (or demand), can be applied to the problem of support design for dynamic loading. In this case, the dynamic loading is a result of the seismic wave interacting with the excavations and comes from individual seismic event shockwaves.

Expressed in terms of kinetic energy, the demand is a function of the mass in motion and the velocity at which the mass is moving. The ejection velocity is a function of the magnitude of the event and the attenuation of the peak particle velocity with distance from the event source. The implication here is that when conducting forward analysis, the designer must assume a certain seismic event of a certain magnitude will occur at a certain location, possibly away from the area being designed, in order to assess the demand.

A methodology to assess such events based on seismic hazard maps is provided in Heal (2005), Potvin (2008) and in Hudyma and Potvin (2009). The ground motion velocity induced by this 'design event' from the hazard maps (the anticipated maximum magnitude event) can then be scaled for distance between the event and the design location using Figure 1 The ppv-magnitude-distance relationship presented in Figure 1 is based on the original far-field relationship presented by Kaiser et al (1995) with the introduction of a term related to the source size to saturate the ppv in the near-filed. The relationship can be presented as:

$$ppv = \frac{C \cdot 10^{\frac{1}{2}(m_L + 1.5)}}{R + R_0}$$

Where:

C = 0.2–0.3 is recommended for design purposes.

R = the distance.

Ro = the source radius (Ro) estimated as (Kaiser et al., 1995).

$$R_0 = \alpha \cdot 10^{\frac{1}{3}(m_L + 1.5)}$$

Where:

α = 0.53–1.14.

Similar approaches were taken by Campbell (1981) and Mendecki (2009).

The energy demand on ground support can be estimated from the product of the scaled velocity and an estimate of the moving mass. It is reasonable to base the moving mass assessment on the loosened zone observed around excavations, or on observed rockburst damage from past events.

Kaiser et al. (1996) propose the following equation to assess the energy demand based on the kinetic energy (plus a gravity component) experienced by the support system during rockburst ejection of a rock mass:

$$E = \frac{1}{2} \cdot m \cdot v^2 + q \cdot m \cdot g \cdot d \tag{1}$$

where:

m = the ejected mass (kg) (can be assumed as the loosened zone).

v = the ejection velocity of the mass (m/s) (scaled velocity from seismic event, can be obtained from Figure 1).

g = acceleration due to gravity (m/s^2).

d = distance travelled by the ejected mass (m) (assume a value of < or = of displacement capacity of surface support for design purposes).

q = constant; 1, 0 or -1 for ejection from the back, wall or floor respectively.

The value of the ejection velocity is related to the ppv and is sometimes assumed to be the same. Amplification of the ppv may however occur at the surface of the excavation. Although several mechanisms have been proposed for PPV amplification in this fractured zone, it is still poorly understood. The degree of amplification appears to be partly dependent on the frequency of the incident seismic wave and the thickness of the broken zone around the excavation and the reflection of the wave from the excavation (McGarr et al. 1981; Milev et al. 1999; Kaiser et al., 1995). The site effect varies strongly from site to site and is difficult to quantify (Webber, 2000). The phenomenon is more typical of deep South African and Canadian mines where the stress fracturing surrounding stopes may extend for a few to several metres. In Western Australian mines, this fracture zone is more likely to be less than a metre and rarely more than two metres. As such, a quantitative value for the site effect in Western Australian mines is more likely to be two or less. Kaiser et al. (1995) is of the opinion that ejection velocities of greater than the ppv is likely to occur for only small ejected blocks but concede that the ejection velocity could be higher due to stored strain energy around the opening also being transferred to the ejected rock and suggest an amplification factor of between 1 and 4.

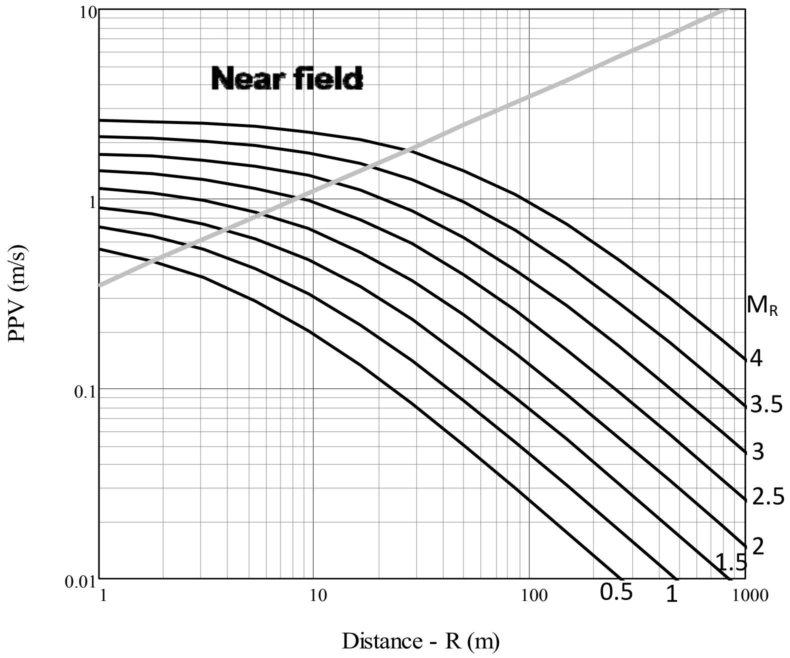


Figure 1 **Scaled-distance relationship between an event of a given magnitude and the velocity generated at a certain distance from the source**

The above process involves multiple assumptions to assess the parameters in Equation 1, and this introduces uncertainty into the calculation and may affect the confidence in the estimation of the energy demand from dynamic loading induced by a seismic event.

The FOS approach also requires the evaluation of the capacity of the ground support system to resist dynamic loading. Recent research has focused on drop testing and simulated blast experiments to quantify capacity, and this is further examined below.

3 Dynamic capacity of ground support systems

In mechanised mining, most ground support systems are comprised of reinforcement elements such as rockbolts as well as surface support which is, most commonly, mesh or fibre-reinforced shotcrete (FRS).

Under static conditions, many authors have suggested different mechanisms to explain the reinforcing action of rockbolts. Some have proposed that a compression arch is formed (Stillborg, 1994), others have suggested that a beam is created by tying layers of rock together (Panek, 1964). The simplest approach, and perhaps the most commonly used in mines, is the one that considers that reinforcement supports the dead weight of rock (Charette and Hadjigeorgiou, 1999). Each of these explanations can be relevant, depending on the prevailing conditions.

The surface support is installed on the surface of the rock and its primary aim is to contain the rock mass in between the reinforcement elements or prevent unravelling of the skin of the excavation. It is interesting to note that under static conditions, the functions of the reinforcement and surface support are distinct from each other and the need for them to work in unison as a system is minimal. In fact, shotcrete is sometimes applied over the reinforcement resulting in little interaction between the surface support and reinforcement. This is often reflected in the static design process where the demand is matched to the capacity of the reinforcement alone, with little consideration in the calculations given for the contribution of the surface support.

3.1 The weakest link

Typically, load is transferred from the rockmass to the surface support during the processes of rock fracturing and ejection brought about by a seismic event. This transfer will occur via the plate and terminating arrangements (split set ring, nuts, etc.) of each reinforcing element. When the surface support or the plate or the terminating arrangement fails, the load is no longer transmitted to the reinforcement, and the rock will likely be ejected from in-between the bolts. In this scenario, the reinforcement will only be submitted to a fraction of its dynamic load capacity.

Therefore, to withstand the dynamic loading generated during a seismic event, the ground support must work as an integrated system and will only be as strong as its weakest link. This was described by Simser (2007) in the Sudbury mines. This is also evident in work done by Heal et al. (2006), who have also demonstrated this principle with the study of 254 cases of rockburst damage showing that the weakest link in the ground support systems used in mines was often the surface support or connection between the surface support and reinforcing elements (plate and terminating arrangement). Only 30% of the rockburst damage cases from this database were due to reinforcement failure (Figure 2). The implication for estimating the ground support capacity under dynamic loading is that the capacity must be assessed as a system rather than as individual support elements. Using the dynamic capacity of the reinforcement alone for design purposes would likely over-estimate the capacity of the system as Heal et al. (2006) have shown through their database that surface support and connections often fail before the reinforcement capacity is mobilised.

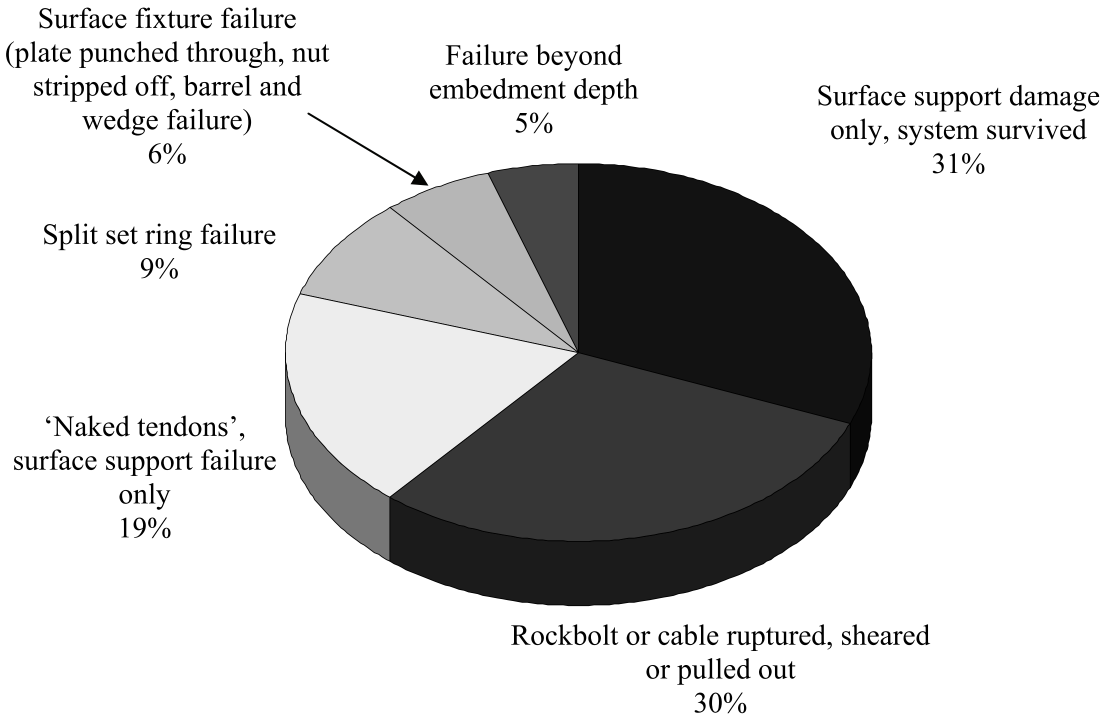


Figure 2 Breakdown of the components of ground support system failures from 254 rockburst damage observations (after Heal et al., 2006)

3.2 Dynamic capacity of ground support estimated from drop tests

The use of a controlled laboratory facility to test and understand the behaviour of ground support elements when submitted to dynamic loading is desirable from the point of view of the repeatability of the tests and relatively low cost of testing once the rig is constructed. For the last fifteen years, a number of test facilities have been constructed in South Africa, Canada and, more recently, in Australia. All facilities rely on gravity (or weight) drops to generate energy to be applied to ground support. However, all testing facilities have significant differences which make the comparison of their results somewhat difficult. This is discussed further later in this section. A comprehensive review of the testing rigs is available in Hadjigeorgiou and Potvin (2008) and the specifications of each test rig are summarised in Table 1.

The Western Australian School of Mines (WASM) rig, which is the most recent and best instrumented facility, relies on a drop weight deceleration of the support element being tested, also known as the momentum transfer mechanism (Player et al., 2004), whilst the other rigs use the kinetic energy from the impact of the falling weight onto the support element itself. When testing surface support, the SRK and SIMRAC rigs distribute (and also attenuate) the impact by dropping the weight on a pyramid of bricks laid over the support system whilst the GRC and the MIRARCO rigs drop the weight directly onto the surface support tested. The GRC and Mirarco systems are extremely stiff as the surface support is mounted directly on steel/concrete pillars sitting on a concrete floor. Presumably, a higher proportion of the energy is transferred to the floor through these stiff pillars.

Table 1 Comparison of the dynamic load simulation methods used for each trial (after Hadjigeorgiou and Potvin, 2008)

Rig #	Common Name	Support Element Tested	Support Systems (panels)	Props	Max. Drop Weight (kg)	Maximum Height of Drop (m)	Maximum Energy Available (kJ)	Maximum Impact Velocity (m/s)
1	Terratek	Short bolts up to 1.6 m	N/A	Props up to 1.6 m		0.6		3
2a	SRK drop weight test facility Set-Up 1	Integrated support system; bolts and surface support	1.6 × 1.6 m		1,048 (2,706)	4 4	41.12 (81.5)	8.8 (7.3)
2b	SRK drop weight test facility Set-Up 2	Rockbolts and cable bolts	N/A		1,048 (2,706)	4		20
3	SIMRAC dynamic stope test facility	Props	3 × 3 m	Props up to 2 m (with extensions)	10,000	3	300	7.7
4	GRC-Laurentian	Steel rod 2.44 m long	N/A	N/A	48.494	0.3	0.14	2.43
5	GRC-Creighton	Surface support	1.2 × 1.2 m diamond patterns; shotcrete panels 1.5 × 2.75 m	N/A	565	4	21.9	8.8
6a	NTC	Bolts up to 1.7 m long	N/A	N/A	1,000	2	20	1.5
6b	NTC-CANMET	Bolts up to 1.7 m long	N/A	N/A	3,000	2	58.86	6.26
7	WASM	Bolts and cables up to 2.4 m long. Surface support	1 × 1 m	N/A	4,500	6	225	10
8	Wedge-block loading device	Bolts and cables up to 5.5 m long	No	No	10,000	4	390	8.9
9	MIRARCO	Surface support	1.5 × 2.7 m screen	N/A	565	3	16.63	7.67

Only the SRK drop weight test facility configured in set-up 1 (Rig #2a in Table 1) is capable of testing a complete support system (rockbolts and mesh or FRS together). However, published results (Ortlepp et al., 1999) from this rig (set-up 1) focus on the capacity of surface support only, rather than support systems.

They also use the input energy into the system rather than trying to calculate the portion of energy distributed between the pyramid of bricks, the surface support and the bolting arrangement. Ortlepp and Stacey (1998) have also published results from reinforcement only, tested using the same rig configured in set-up 2. The WASM rig can also test both reinforcing elements and surface support, but at this stage cannot test them together as an integrated support system (see third column, Table 1). Most other rigs can only test either reinforcement or surface support.

It is noted that the ASTM organisation has adopted the NTC-CANMET rig and methodology (Plouffe et al., 2008) as a standard method for laboratory determination of rock anchor capacity by drop tests (ASTM D 7401–08).

3.2.1 Compilation of published results from drop testing

Given the high cost of constructing, commissioning and running drop testing facilities, it follows that researchers working on individual facilities have not published significant bodies of test results, and most of the rigs are no longer active, except for the SIMRAC prop testing, the NTC/CANMET, and the WASM facilities. As the SIMRAC rig is not designed to test bolts, mesh or shotcrete, the WASM and the NTC/CANMET rigs appear to be the only facilities currently contributing to growing the public database of dynamic tests. Given that there are a wide variety of ground support systems used in mines, and the fact that practitioners are frequently required to design dynamic resistant support systems, there is an incentive to compile all results from the different rigs such that the status of the current knowledge from the various drop testing campaigns can be assessed.

An attempt is made here to compile the results from as many published tests as possible. However, as mentioned before, there are difficulties in comparing the results obtained from the different rigs due to their different testing arrangements and protocols. It is noted that a very small percentage of 'abnormal' test results from the various published sources of data were ignored, when explanations for the deviation could not be found.

3.2.1.1 Reinforcement results

Figure 3 is a compilation of drop tests results for reinforcement elements from the work of Ortlepp and Stacey on the SRK rigs in the 1990s, Ortlepp and Stacey (1998) and the WASM publications by Player et al. (2008a, 2009). The total energy absorbed is plotted as a function of the displacement.

Amongst the testing not included are the results from the Terrateck and SIMRAC rigs which are not directly relevant to this article as they are mainly used to test props. The testing done by Yi and Kaiser (1994) are also not included as they applied only small impact loads of less than 0.15 kJ. The tests performed by Gaudreau (2004) on the original NTC rig and by Falmagne et al. (2005) and others (Doucet, 2010, written comm.) on the NTC/Canmet rig are shown later in this section as they use a different testing protocol based on repeated impacts rather than the single 'blow' used in other tests. Other rigs were only capable to test surface support (Table 1).

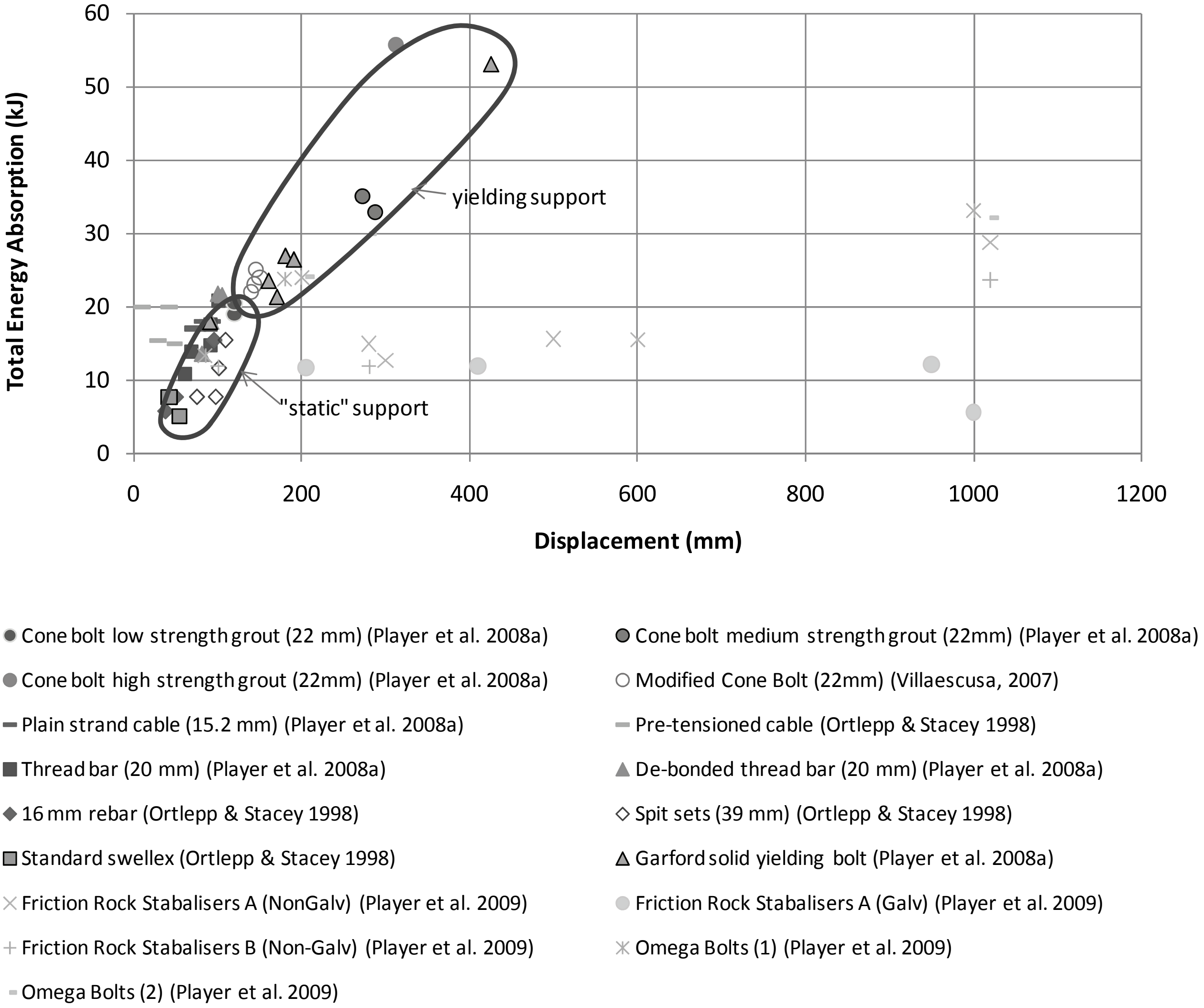


Figure 3 **Compilation of drop tests performed on various reinforcement elements and reported by the following authors; Ortlepp and Stacey (1998); Player et al. (2008a, 2009)**

Figure 3 includes results from 70 tests grouped under 17 datasets, represented by different symbols. Each dataset represents a different reinforcement element or a variation in the size of the bolt, the grout or the embedment length.

Considering that a wide variety of bolts was tested using two different rigs, the compiled datasets show a very clear ‘quasi-linear’ trend. A large cloud of data plots in the area defined between 7 and 27 kJ of total energy absorption and between 25 and 200 mm displacement. The trend of energy increasing with displacement is to be expected as the energy is a product of the force and displacement. The bottom half of the cloud (say, energy between 7 and 18 kJ and displacement between 25 and 100 mm) is dominated by reinforcement commonly used in mines dealing with mostly static loading conditions whilst the top half of the cloud (say, energy between 18 and 27 kJ and displacement between 100 and 200 mm) is dominated by yielding bolts.

The energy absorption for encapsulated (fully grouted or partly de-bonded) bars is generally dissipated mainly by bolt elongation combined with gradual breaking of the bolt/grout bond and limited slippage in the case of grouted solid bars. Cone bolts generally allow for more displacement and energy absorption as the energy is dissipated by a combination of steel elongation and friction generated by the bolt ploughing through the grout. Some of the more recently developed yielding bolts allow for extended elongation through mechanisms other than steel stretching.

Generally, thicker bars and yielding bars provide better energy absorption and displacement capacities as they stretch more and offer more resistance than thin bars. This is reflected in the data in Figure 3. There are four higher energy absorption data points, all from yielding bolts. These exceptional performances seem to be isolated cases. These points follow the general energy displacement trend, however, with very high values of energy absorption and displacement.

In a laboratory environment, it could be difficult to replicate the friction bond between friction bolts and the rock. Most of the datasets on friction bolts published in Player et al. (2009), plotted as light grey (X, + and ●) in Figure 3, do not follow the quasi-linear increasing trend from other tests. They show a very flat trend instead, which means that there is virtually no increase in energy absorption once a certain energy and displacement has been reached. The laboratory response observed by Player et al. (2009) shows that an initial frictional resistance to movement dissipates most of the energy. The very flat trend in the energy absorption with displacement suggests that there is a reduction in the friction resistance with displacement.

Reinforcement in general can dissipate energy through bond breaking, steel deformation, friction or a combination of the above. The bi-modal behaviour depicted in Figure 3 can be interpreted as most reinforcement systems appear to dissipate energy by bond breaking and steel stretching and as such follow the quasi-linear increasing trend. The friction bolts, however, absorb most of its energy by overcoming the original frictional resistance and then slide without dissipating much energy, producing the flat trend on the energy displacement graph.

Most of the omega (inflatable) bolt results (Player et al., 2009) also fit the general quasi-linear increasing trend. Although they use a friction bond, the mechanism involved when inflatable bolts are submitted to dynamic loads is more akin to grouted bolts and this is reflected by the test results.

Finally, for the pre-tensioned cable data (Ortlepp and Stacey, 1998) are somewhat deviating from the general trend, showing stiffer behaviour, as one would expect.

The results from Gaudreau (2004) and Falmagne et al. (2005) and others (Doucet, C., written comm., 2010) are shown in Figure 4. The multiple drops on the same specimen from individual tests are connected with thin solid lines. The thick solid lines define an envelope of these test results representing 10, 50 and 90 percentiles of the results. The following observations are made:

- The ultimate strength and displacement results for the elements tested using multiple drops on the specimen cannot be compared with the ultimate strength of the samples from the tests which were submitted to a single drop shown in Figure 3. This was also recognised by Player et al. (2008c).
- Some of the variability in the Falmagne et al. (2005) series of tests is likely due to the fact that different ‘borehole’ diameters as well as cone geometries were tested.
- The second series of results showed less variability and this may be because the test procedure was kept consistent (no variation in the ‘borehole’ size).
- Gaudreau (2004) results generally agree with the Canmet results.

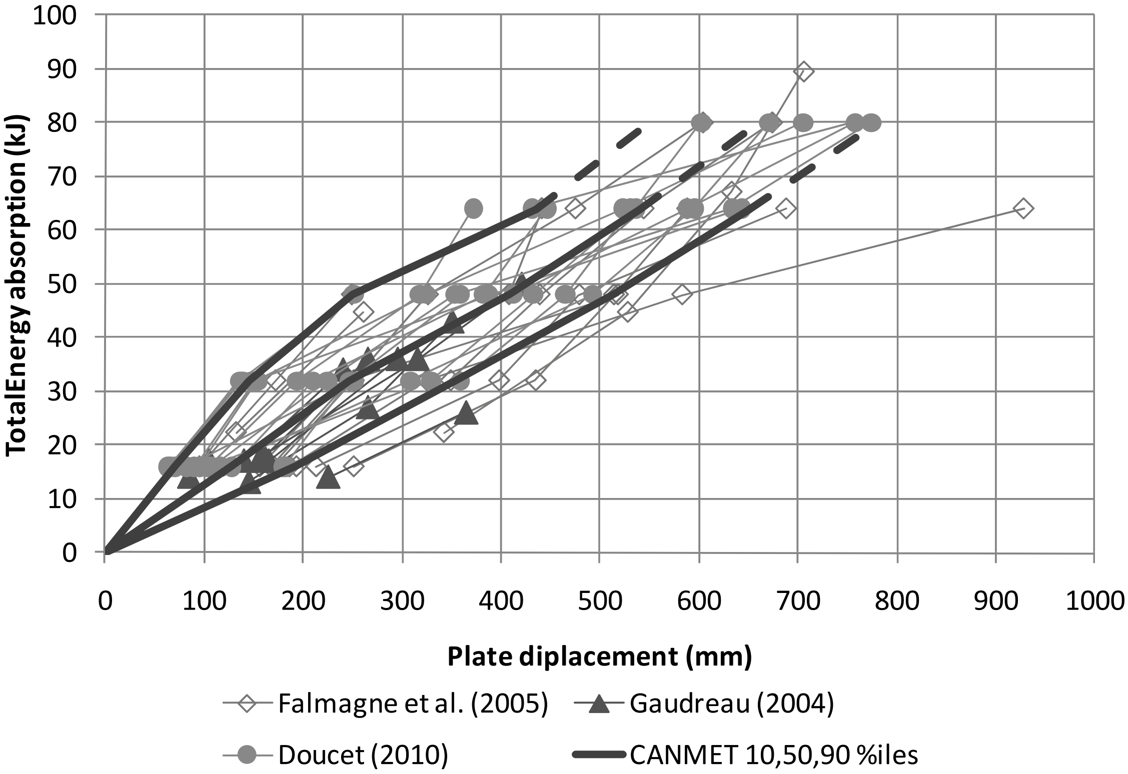


Figure 4 **Compilation of drop tests (using multiple drops) performed on various reinforcement elements and reported by the following authors; Gaudreau (2004) and Falmagne et al. (2005) and others (Doucet, C., written comm., 2010)**

The combined results from all tests on reinforcement (Figure 3 combined with Figure 4) are shown in Figure 5. An important observation is that, except from the previously discussed friction bolt test series (Player et al., 2009) the relationship between energy absorption and displacement from results of different bolts tested on different rigs using different protocols are surprisingly consistent. Most results fit within the 10, 50 and 90 percentiles of Canmet repeated tests shown in Figure 4 and redrawn as dashed lines in Figure 5.

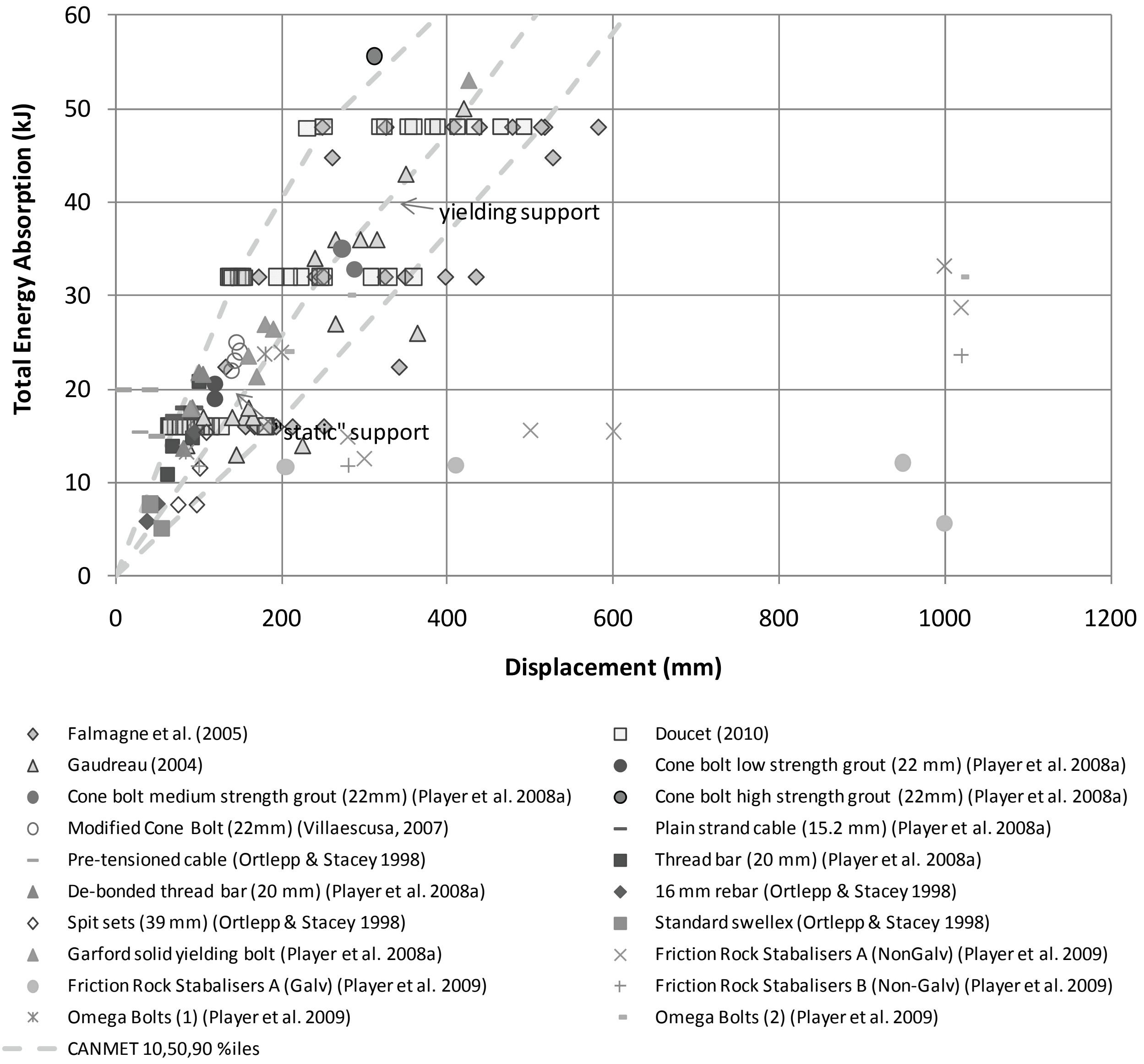


Figure 5 **Compilation of all drop tests performed on various reinforcement elements and reported by the following authors; Ortlepp and Stacey (1998); Player et al. (2008a, 2009); Gaudreau (2004); Falmagne et al. (2005) and others (Doucet, C., written comm., 2010)**

3.2.1.2 Surface support results

Figure 6 is a compilation of surface support results from drop tests, where the total energy absorbed is plotted as a function of the displacement. The compilation includes tests from three different rigs and was sourced from Kaiser et al. (1996); Ortlepp and Stacey (1997); Player et al. (2008b).

It is noted that the surface support energy results published by Ortlepp and Stacey (1997) are input energy, and a significant part of this input energy was dissipated in the brick pyramid, with the remainder transmitted to the surface support element tested. The fraction of the energy absorbed by the bricks is unknown and the tests were originally intended for use as a comparative assessment of the performance. To enable comparison to other tests we will assume that about half of the input energy is lost due to the brick arrangement. This is based on an estimation by Human (2004) for the SIMRAC test facility. Although simplistic, this assumption yields results which are comparable to other tests.

Sixty-five test results from sixteen datasets are shown in Figure 6. The data is relatively scattered, but when regrouped according to individual surface support elements (areas delineated by the blue lines), the relative performance of the different surface support methods becomes evident. The expected general trend of increasing energy with displacement can be observed. The lowest performing surface support against dynamic loading is plain shotcrete, which is expected due to its low tensile strength and deformation capacity in addition to its very low post-peak strength. The best performance was from surface support involving cable-lacing, which exhibits a high deformability and high energy absorption capacity. Other surface support systems (with no lacing) generally have energy absorption capacities under 10 kJ. According to Figure 6, FRS and chain link mesh have similar energy absorption capacity but the mesh exhibits larger deformability. The weld-mesh alone has only achieved energy absorption capacity of up to 5 kJ.

Even when looking at the results for individual surface support elements, significant scatter exists within each dataset. This is a reflection of the variety of the products tested. For example, it is noted from Figure 6 that thinner wire-mesh (which varies from 3.2 to 5.6 mm wire) and wider aperture (100 × 100 mm) generally have lower energy absorption and displacement capacity. Thicker wire-rope lacing and high-tensile chain-link mesh also perform in the upper region of their respective group. These results are all according to expectations and largely explain the scatter within each type of surface support.

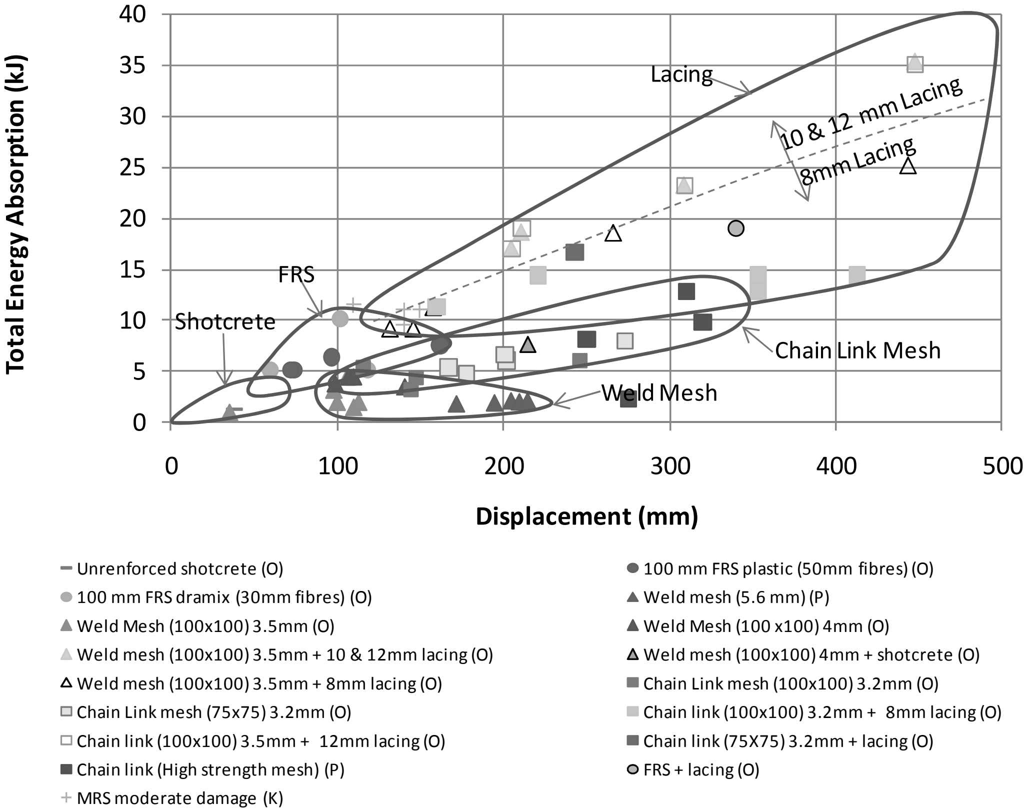


Figure 6 **Compilation of drop tests performed on various surface support elements and reported by the following authors; Kaiser et al. (1996) (K); Ortlepp and Stacey (1997) (O); Player et al. (2008b) (P)**

One group of data deviating from the general trend is the weld-mesh, which does not show an increase in energy absorption with increasing displacement. One apparent inconsistency seems to arise from the comparison of the test results performed on the WASM rig on 5.6 mm weld-mesh (Player et al., 2008b) which absorbed less energy than the smaller wire mesh (3.5 and 4 mm) results tested by Ortlepp and Stacey (1997). This could possibly be explained by the different mesh testing procedures of Player et al. (2008b) and Ortlepp and Stacey (1997). Player et al. (2008b) attach every square of mesh on the periphery of the sheet to the testing frame, whilst the procedures adopted by Ortlepp and Stacey (1997) attempt to replicate the bolting pattern and attach the mesh in the four corners of a one meter square, providing more freedom for the mesh to deform. The WASM procedure results in a much stiffer mesh response, when compared to the other testing methods. If this is the case, it is also possible that the high tensile chain-link mesh reported in Player et al. (2008b) are lower than they would have been, if tested with a configuration equivalent to that of Ortlepp and Stacey (1997).

As a general conclusion on the overall database, unless rope lacing or other high energy absorption surface support elements such as heavy gauge mesh straps or high tensile strength mesh are utilised, the weakest link will likely be the surface support and the overall support system will likely fail at energy levels lower than 10 kJ, which is at the lower end of the reinforcement capacity results (Figure 3). Under this scenario, the full capacity of most commonly used reinforcing elements would not be engaged during dynamic loading, resulting in surface support failure with only low loading applied to the reinforcing elements. Historically, this has been a common occurrence in seismically active mines, based on the case history data described in Heal (2010) and Heal et al. (2006) (Figure 2).

3.2.2 Practical use of drop test results

The factor of safety (FOS) approach, which compares the energy demand on ground support with its energy absorption capacity, is not easily applied. The assumptions required to determine the energy demand were mentioned in Section 2.1, and they are a source of inaccuracy and uncertainty in the FOS design method. The determination of energy capacity of a support system using drop test results will also require some interpretation, as the tests have limitations. Given the mechanisms typically resulting in ground support failure under dynamic loading conditions in underground mines (e.g. Figure 2), the tests are not necessarily a true representation of reality. Some of these tests were originally designed as a relative comparison test while others focused on repeatability. Player et al. (2008a) in references to their results warns that:

> *'Companies using the results must make their own determination on underground installation quality and the suitability of the loading mechanism, potential energy release from a seismic source as to how the performance of their reinforcement system would change at a particular site.'*

Indeed, users of the drop test results must keep in mind that the quality control issues can have a strong influence on the results. Also, the interaction between the rock mass and the ground support is not simulated in drop testing. Undoubtedly the rock mass characteristics have a significant influence on the performance of support system installed in a mine. Furthermore, as seen in Section 3.2.1.2, test protocols can have a serious influence on the results.

But, more importantly, the drop tests perhaps provide results from individual support elements that somehow need to be combined for the purpose of designing a complete support system. As an initial step, it is useful to take the results from the reinforcement (Figure 5) and the surface support (Figure 6) and compile them on the same graph (Figure 7).

Three shaded zones are delineated; the top zone is an approximation of the quasi-linear trend from testing reinforcement elements, the bottom zone includes most surface support results excluding rope lacing, which are re-grouped in the middle zone of the graph. It is readily apparent from this that the weakest link will be the surface support, which has only a fraction of the energy capacity of the reinforcement.

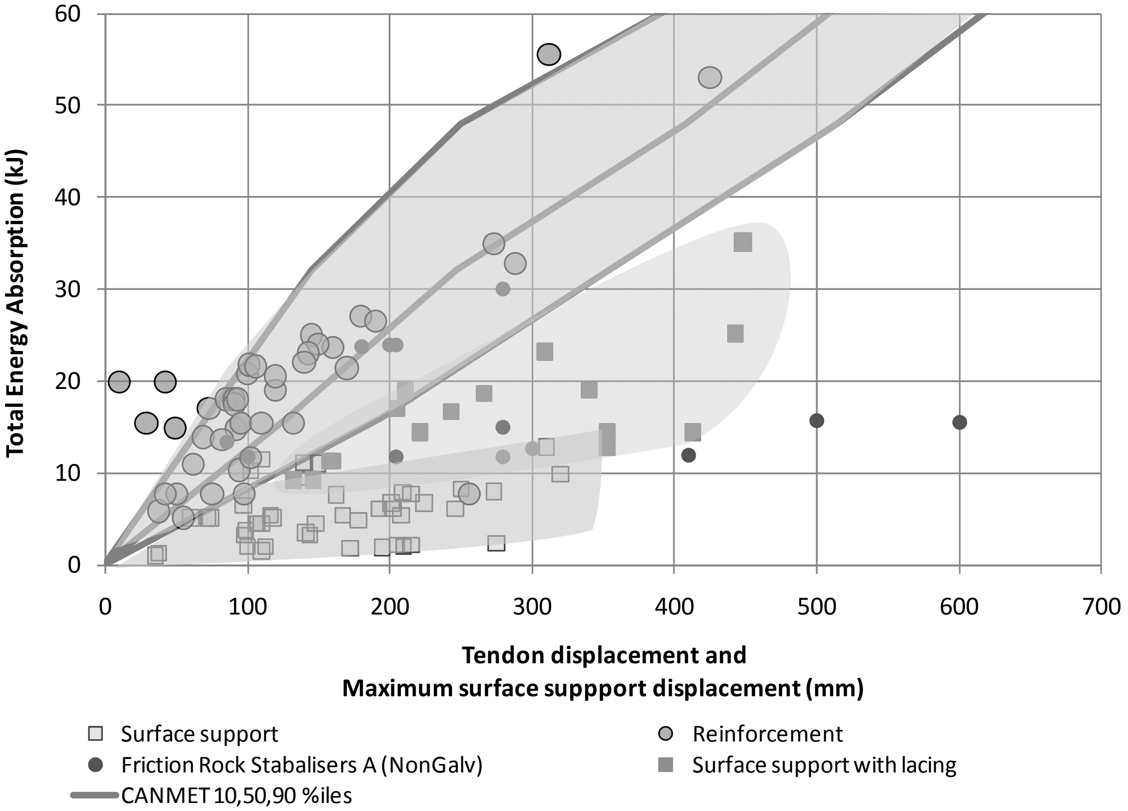
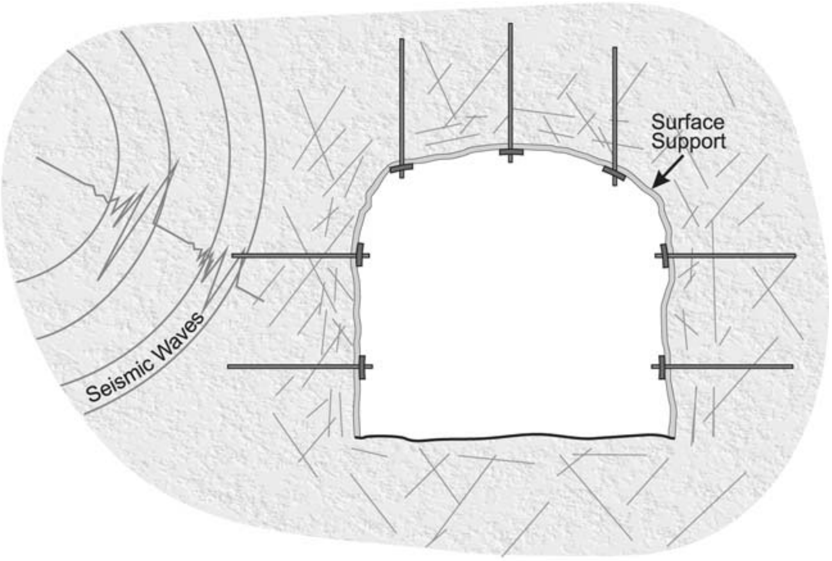
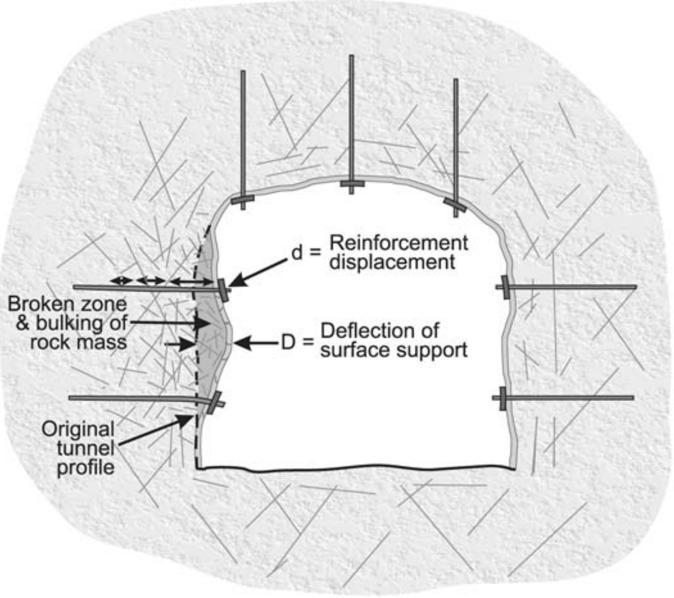


Figure 7 Total energy absorption and displacement of reinforcement and surface support dynamically loaded using drop weight tests

It is important to clarify that although all data is displayed on the same graph, the displacement of the reinforcement is different to the displacement of the surface support (Figure 8). The displacement of the surface support is the deflection 'D' often measured at the central point of the deformed surface (in between the reinforcement) and can be described as the maximum bulging of the surface. The reinforcement displacement 'd' could be a combination of steel stretching or other bolt elongation mechanisms, bond slipping or even bolt ploughing through the grout, in the case of cone bolts. This is illustrated in Figure 8. These two different forms of displacement are connected to one another only in the sense that as the surface support bulges, it pulls on the bolts through the connection and adds to the displacement in the reinforcement. Since the surface support typically only absorbs small amounts of energy before it fails (say less than 10 kJ for most surface support, according to Figure 6) this will result in having only a fraction of the capacity of the reinforcement being solicited. In this scenario, the total energy absorbed by the support system is the energy capacity of the surface support, plus whatever fraction of energy was absorbed by the bolts while the surface support was still functional. At the total failure of the surface support, the rock mass between the rockbolts unravels around the bolts, often leaving naked tendons.



(a)



(b)

Figure 8 Schematic of the deflection 'D' of the surface support compared to the deflection 'D' of the reinforcement; (a) before rockburst damage; (b) after rockburst damage

The practical implication of this is that, with the exception of mines that use high capacity surface support such as rope lacing, mesh straps or high tensile chain link mesh, a conservative approximation would be to assume that the energy capacity of the support system is in fact the capacity of the surface support (the weakest link). According to Figure 6, this is less than 10 kJ per square meter. This assumes that the fraction of energy transfer to the bolts is small and could be neglected in the design calculation, given the low accuracy of the design approach. It also highlights the futility of using high capacity dynamic reinforcement with low capacity surface support.

With high capacity surface support, load transfer will occur and the dynamic loading will be shared between the reinforcement and the surface support. This energy will be dissipated through the respective displacements of the reinforcement and surface support. The upper limit of the support system capacity would be achieved only if the behavior of the reinforcement was perfectly matched to that of the surface support. In this idealised situation, since the energy would be dissipated through the elongation of both the reinforcement and surface support, the energy absorption capacity of the support system would be greater than the capacity of the weakest component (the surface support according to Figure 7). The lower limit of the support system capacity would be equal to the capacity of the surface support alone, assuming that it is the weakest link and that minimal load transfer to the reinforcement has occurred.

The above discussion is based on an idealised dynamic tensile loading of the support system. If the dynamic loading has significant shearing components, the load transfer and failure mechanism could be quite different and invalidate some of the assertions made above.

Given the difficulties outlined in this paper, multiple assumptions, sources of inaccuracies and the interpretation required to achieve an FOS based dynamic support design, it is strongly argued that such approach will require comprehensive calibration before it can be used with confidence. Investigating the dynamic capacity of ground support by simulating rockbursts using blasting technique can provide a cross-reference to some of the observations made using the drop test results.

3.4 Dynamic capacity of ground support estimated from simulated rockbursts

Simulating rockbursts using blasting represents another level of difficulty when compared to drop testing. The tests are generally performed underground in operating mines and they are destructive tests. Therefore, the logistics of setting up and carrying out the tests is complicated and the cost is high. Nevertheless, the advantage is that the ground support is installed and tested in situ and tested as a system rather than individual support elements. Issues such as the interaction with the rock mass and installation procedures are also well simulated and weaknesses in the overall system are highlighted.

The shockwaves caused by blasting are different to those generated by large seismic events. Typically, the frequencies are higher and wave lengths shorter compared to actual seismic events. Also, blasting will create gases which are not present during seismic events. Despite these differences, shattered rock mass moving at high velocity can be reproduced by blasting and this is believed to be similar to the typical dynamic loading mechanism of rockbursts.

As with drop tests, a number of researchers have attempted simulated rockburst tests, but many with only limited success. In some cases, the velocity generated was not sufficient to create the intended damage to ground support, and in other cases the effect of gasses distorted the results. Hadjigeorgiou and Potvin (2008) summarised the specifications of seven of these simulated rockburst trials (Table 2). From the descriptions presented in Tannant et al. (1993, 1994); Hagan et al. (2001); Hildyard and Milev (2001); Reddy and Spottiswoode (2001); Espley et al. (2002); Archibald et al. (2003); Heal (2005); Andrieux et al. (2005); Heal and Potvin (2007), very few of these tests have given quantitative results usable for an FOS design approach of ground support submitted to dynamic loading. The UWA series of tests by Heal (2010) are the only published simulated rockbursts tests results interpreted in terms of energy absorbed by the support system and damage. These are summarised in Figure 9.

Table 2 Comparison of the dynamic load simulation methods used for each trial (after Hadjigeorgiou and Potvin, 2008)

Test Denomination	Dynamic Load Simulation	Stand-off Dist. (m)	Max. Vel. Achieved (m/s)	Appraisal of Gas Effect	Support Tested	Comments
GRC CANMET Lab	Pilot round and slash	> 6	1.0–1.2	Negligible	Rockbolts only	Velocity may be too low to test bolts capacity
GRC Bousquet#2	Angled blasthole from face	0–3.7	High and variable	High	Integrated systems (shotcrete, fibrecrete and rockbolts)	Possibly poor simulation of rockburst due to gas effect
CSIR Kopanang	Parallel blastholes, large charge (261 kg) emulsion, chocked-blasted far from face	> 6	3.3	Negligible	Unsupported and rockbolts only	Relatively good simulation of rockburst Velocity may be too low for dynamic support testing
Inco	Parallel blastholes, small charge close to face	<0.5	0.5–3	Negligible	Integrated systems (shotcrete, TSL, mesh and rockbolts)	Relatively good simulation of rockburst Velocity may be too low for dynamic support testing
Queen's	Crater blasting	Approx. 1.2		High	Integrated systems (shotcrete, TSL, mesh, bolts)	Possibly poor simulation of rockburst
UWA	Parallel blastholes, medium charge (10–60 kg) emulsion, blasted far from face	2.5–5	Up–3.5	Negligible	Integrated system (fibrecrete, TSL, mesh, bolts)	Relatively good rockburst simulation. High velocity with no gas effect was achieved
Falconbridge	Angled blasthole from face (26 kg)	2.5–3.75	0.15–3	Negligible further from the collar of the blasthole	Integrated support systems (mesh and mesh-straps, fibrecrete, TSL, bolts)	Angled blastholes are difficult to control. Velocities are lower than required to damage dynamic resistant support

Between 2004 and 2008, Heal has performed simulated rockbursts tests at six different sites. He has calculated energy absorption results from eleven different support systems, most of which are commonly used in Australian mines.

Heal has also compared the test results with back calculations of energy absorbed from case studies, using the FOS approach described in Section 2.1. The results of the simulated rockbursts are shown as red bars in Figure 9 and the results from cases studies are shown as the top bar in each category (Heal, 2010). The correlation between the simulated rockburst results and the back analysis of case studies is excellent. It is also noted that the energy absorption values in Figure 9 vary from 1.5 to 9 kJ/m^2. These numbers compare very well with the relevant surface support results (FRS, weld and chain link mesh and mesh/FRS) from the drop tests shown in Figure 6. This gives credibility to the assumption that support systems often fail on the weakest link and that, for most commonly used ground support systems, a relatively small amount of energy is being transferred to the reinforcement during dynamic loading. Hence, as a conservative design approach this suggests that the capacity of the support systems can be approximated by the capacity of the surface support assessed using drop testing.

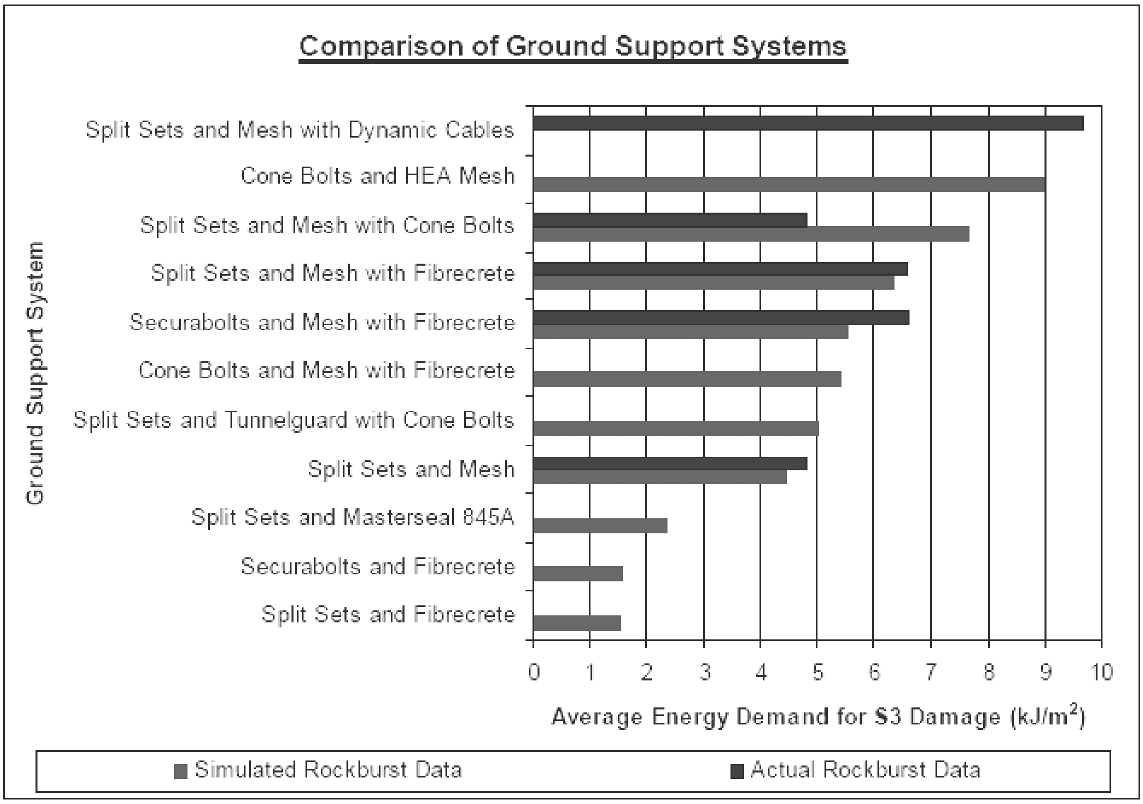


Figure 9 Comparison of energy demand required to create rockburst damage to support systems based on simulated rockburst and from back calculation of case studies (after Heal, 2010)

One notable inconsistency between the drop tests (Figure 6) and the simulated rockburst results (Figure 9) is the performance of FRS. From the drop test, FRS consistently achieved between 5 and 10 kJ whilst from the blasting test they failed at around 2 kJ. It could be that FRS under-performed during the blasting tests because of the effect of gas, although Heal (2010) has argued that this is not likely given the steps taken to minimise this effect (for example through the use of high shock and low heave explosives, adequate standoff distance between the charge and the test wall and a number of observation holes drilled on the test wall to provide a conduit for blast gasses).

Alternatively, it could be that FRS over-performed in the drop test, perhaps because it is not adhered to a deforming rock mass or due to artefacts from some of the testing procedures.

4 Summary and conclusion

Mine seismicity and rockburst risk is an increasing problem in the global mining industry due to the gradual deepening of underground mines as near surface mineral resources are depleted. Ground support is the most common line of defence for mitigating the consequences of rockburst. Despite intensive research during the last two decades, the current state-of-the-art for designing ground support systems submitted to dynamic loading remains deficient. In this paper, an approach relying on factor of safety (FOS) where the energy demand is compared to the capacity of the support system has been examined. Using this design method, the energy demand can be estimated only by assuming that an event of a certain size will occur at a certain distance from the area being designed. Then the expected velocity of ground motion brought about by the seismic wave generated from this hypothetical event must be scaled down to account for the attenuation caused by its travel through the rock mass. The energy demand on ground support can then be calculated by estimating through energy calculations incorporating the mass that will be set in motion when the stress wave reaches the excavation boundary and the square of the scaled velocity. The calculation of the energy demand requires several assumptions and the reliability of the calculation will be highly dependent on their validity.

A number of research initiatives involving laboratory drop tests and simulated rockbursts were undertaken during the last two decades on the premise that the calculation of the capacity of ground support systems submitted to dynamic loading can be assisted using the results from such tests. However, no clear guidelines have emerged from this research. Observations from rockburst damage have shown that the weakest link of support systems submitted to dynamic loading is often the surface support or the connection between the surface support and the reinforcement. Considering that a system is only as strong as its weakest link, a conservative assumption would be to use the energy absorption capacity of the surface support as the capacity of the overall support system. This assumes that the amount of energy absorbed by the reinforcement is negligible and is seen as a conservative assumption. Figure 6 provides a compilation of published energy absorption results from drop testing different surface support. Most surface support systems, with the exception of cable lacing, have an energy absorption capacity of less than 10 kJ. This is in accordance with the simulated rockburst tests and case history back-calculations on full support systems published in Heal (2010).

Given the number of assumptions and the comprehensive interpretation required to use the dynamic testing results, it is evident that applying the FOS approach for designing ground support systems under dynamic loading will require calibration against local rockburst damage data. Expanding Heal's (2010) database of rockburst damage is seen as critical to further advance the design of ground support system submitted to dynamic loading.

Acknowledgements

The ACG sincerely thanks the following organisations who provided funding for this research through the Mine Seismicity and Rockburst Risk Management project at the Australian Centre for Geomechanics:

- Agnico-Eagle Mines Ltd
- AngloGold Ashanti Australia
- Barrick Gold of Australia
- BCD Resources (Operations) NL (previously Allstate Exploration Beaconsfield Gold NL)
- BHP Billiton Nickel West
- Codelco Chile (El Teniente)
- Gold Fields Australia (St Ives and Agnew Gold)
- Harmony Mt Magnet Gold
- Kalgoorlie Consolidated Gold Mines
- Kirkland Lake Gold
- Lightning Nickel (Independence Group NL)
- Luossavaara-Kiirunavaara Aktiebolag (LKAB)
- Minerals and Energy Research Institute of Western Australia (MERIWA)

- MMG Minmetals Group (Golden Grove) (previously Oxiana Limited and Oz Minerals)
- Newcrest Cadia Valley Operations (Ridgeway)
- Newmont Asia Pacific
- Norilsk Nickel (formerly LionOre Australia Ltd)
- Perilya Limited
- Reliance Nickel P/L (Consolidated Minerals Group)
- Xstrata Copper (Kidd Mine)
- Xstrata Zinc (Brunswick Mining and Smelting)
- Xstrata Nickel (Cosmos Nickel Project) (previously Sir Samuel Mines).

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