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Dynamic ground support — design methodologies and uncertainties

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Abstract

The design of ground support needs to account for a number of uncertainties relating to loading conditions, rock mass variability, rock mass response and ground support performance. When designing ground support for dynamic conditions, the uncertainties are magnified due to significant gaps in our understanding of how the rock mass responds to dynamic loading as well as limitations in available design methodologies (conceptual uncertainty).

In reality, the fundamentals of dynamic ground support design have changed little over the last three decades and there are many assumptions and limitations. This paper will discuss some of these limitations, as well as highlight how uncertainty around significant parameters, such as peak particle velocity and design magnitude, impact on the design. Comparisons will be made on how dynamic ground support design is approached in Australia and South Africa.

A case study that demonstrates both our general lack of understanding and how variable the rock mass loading and response can be over a short distance will be presented. Suggestions will be made on how to address some of the shortcomings and uncertainties in the design of ground support for dynamic conditions.

Keywords: *ground support, dynamic, uncertainty, design*

1 Introduction

Ground support is critical in ensuring the stability of underground mining excavations thereby contributing to safety and uninterrupted production. The design of ground support in underground mining needs to follow a sound and auditable design process, and should consider a range of uncertainties both in the design and implementation processes. Dunn (2013) provides a detailed overview of the various uncertainties associated with ground support design in underground mining.

When designing ground support to cater for dynamic conditions, the uncertainties are magnified due to significant gaps in our understanding of how the rock mass responds to dynamic loading as well as limitations in available design methodologies. This paper will explore, in some detail, the uncertainties in the design of ground support for dynamic conditions from the perspective of a geotechnical engineering practioner.

2 Dynamic ground support design

The author was first introduced to the challenges of designing ground support for dynamic conditions in tunnels and tabular man-entry stopes in the deep level gold mines in South Africa during the mid-1990s and struggled with this complex issue for over a decade. Over the following decade, the author had intermittent involvement in ground support design for dynamic conditions. Recently, the author has had renewed involvement with the design of ground support for dynamic conditions. From this recent involvement, it was realised that whilst there had been a number of research projects investigating rockburst damage, development of various dynamic test facilities, significant improvements in numerical modelling as well as advancements in dynamically capable rocks bolts and surface support systems, there had been limited advancements in design methodologies available for ground support design (or parameter validation) for dynamic conditions.

2.1 Design methodologies

The design of ground support for dynamic conditions is based on the assessment of energy absorption based on the kinetic and potential energy method described in 'An Industry Guide to Methods of Ameliorating the Hazards of Rockfalls and Rockbursts' (Anon. 1988), which was based on earlier publications (Wagner 1984; Roberts & Brummer 1988). This method was described in more detail in the 'Canadian Rockburst Support Handbook' (Kaiser et al. 1996), which is considered the 'go to' reference on this topic. This is a widely used method, based on simple mechanics related to the ejection of a block of rock from the back or walls of an excavation.

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 most commonly applied component, in the author's experience, is for the assessment of seismic ejection; the energy absorption requirement (E_a in units of kJ/m²) of ground support under dynamic loading is calculated as follows:

$$E_a = (1/2\ mv^2) + q \times m \times g \times d \tag{1}$$

where:

m = Mass of potentially ejected rock.

v = Ejection velocity.

g = Acceleration due to gravity.

q = Direction factor.

d = Stopping distance.

This method has a number of shortcomings and these have been highlighted and discussed by Mikula (2012), and Potvin and Wesseloo (2013), amongst others. The main shortcomings listed by Mikula (2012) are as follows:

- 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.

Uncertainty, with respect to size and thickness of failures, can be reduced if there are sufficient high quality survey data from previous rockbursts. By using detailed observations and instrumentation, it is also possible to calibrate numerical models to provide a more reliable estimate of the possible failure thickness.

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.

Alternatives to this method are complex numerical modelling (Lilly et al. 2013), but most mines do not have sufficient information to confidently apply this approach. Empirical methods can also be applied; these include rockburst simulation using blasting (Heal & Potvin 2007), excavation vulnerability potential (EVP) methods using mXrap (Harris & Wesseloo 2016) and empirical design charts (Mikula 2012). At this stage, rockburst simulation using blasting has a number of logistical difficulties and weaknesses and is not a practical design tool. Aspects of the EVP method are applied at some mine sites, specifically the probabilistic determination of peak particle velocity (PPV). The use of empirically derived design charts, as described by Mikula (2012), cannot be widely applied as the database at many mines is too limited to be considered reliable, however, efforts to expand and improve databases should be continued.

2.2 Dynamic ground support in Australia and South Africa

2.2.1 Australia

In broad terms, the following approach is applied when using the kinetic and potential energy method for ground support design under dynamic loading and seismic ejection conditions:

- A design event magnitude is estimated based on statistical hazard analysis.
- A critical distance between the design event (source) and the excavations is assumed, or back analysed.

- Using either generic scaling law or a site specific scaling relationship for PPV, the PPV is estimated using the design magnitude and critical distance.
- A site amplification factor is applied (typically in the range one to three) to calculate the ejection velocity.
- The ejection thickness is generally estimated based on observations of previous incidents or from observed failures in the excavation walls.
- A Factor of Safety between 1.5 and 2.0 is applied to account for input parameter uncertainty.

Whilst there is normally a reasonable basis for estimating the design magnitude, the assessment of the distance from the source and the site amplification factor is challenging.

2.2.2 South Africa

In South Africa, the approach to the design of dynamic ground design follows a similar approach with a few differences or simplifications.

- Generally, an ejection velocity of 3 m/s is assumed, although in some cases a lower value may be justified. Measurements at several mine sites confirmed that this was a reasonable ejection PPV value for design purposes (Milev & Spottiswoode 2005).
- The 95% cumulative thickness of ejections from previous rockburst incidents; given the high frequency of occurrence of rockbursts, data is readily available.
- A Factor of Safety between 1.5 and 2.0 is applied to account for input parameter uncertainty.

The simplification of the methodology in South Africa takes away some decisions on the design event magnitude, critical distance and the amplification or site factor. This approach reduces the engineers' ability to optimise ground support when smaller magnitude design events are expected or when seismicity is specifically associated with geological structures that are large distances away from excavations.

As it does not account for the 5% of the worst conditions, it is unlikely that the 95% cumulative thickness would be acceptable in Australia under the 'as low as reasonably practicable' principles that are generally accepted.

2.3 Uncertainties in dynamic ground support design

The term 'uncertainty' is loosely applied in geotechnical engineering and is used to describe natural variability as well as a lack of data, knowledge and understanding. Baecher and Christain (2003) distinguish between uncertainty related to natural variations in time and space (randomness) and uncertainty related to lack of understanding or knowledge. These are referred to as aleatory and epistemic uncertainty respectively by Kiuregihain and Ditevsen (2009, in Hadjigeorgiou & Harrison 2011). Brown (2007) concluded that there are two general types of uncertainty:

- Parameter uncertainty — what we know we do not know (i.e. aleatory uncertainty).
- Conceptual uncertainty — what we do not know we do not know (i.e. epistemic uncertainty).

In the design of ground support for dynamic conditions there are all the usual parameter uncertainties (aleatory) relating to variability in the intact rock strength and the rock mass quality, as well as variability with respect to geological structures (orientation, continuity, shear strength etc.) and unknown structures. These uncertainties arise from: natural variability in the geological environment, lack of data, errors in collecting data, errors in testing, errors in analysis and interpretation, etc.

There have been a number of studies (Durrheim et al. 1997; Heal et al. 2006) that highlight and identify factors that contribute to rockbursts; but there are still uncertainties related to the rock mass response to the extraction sequence and how the excavation geometry and dimensions contribute to rockbursts.

There are also uncertainties related to how different support elements (bolts and surface support) interact with each other and how they interact individually and as a system with the rock mass.

There are also uncertainties associated with future seismic event locations, expected maximum magnitude, PPV variation, and site amplification factor. In addition to the known uncertainties, there are likely to be several unknown uncertainties (epistemic) and this is demonstrated by the following example.

Sometime ago, the author was involved in a rockburst investigation on a deep level South African gold mine. A local magnitude 2.2 seismic event occurred on a geological structure resulting in significant rockbursting, approximately 120 m away from the source location. Damage was associated with two tunnels, a return airway (RAW) and the main haulage. The tunnels were sited approximately 2,250 m below surface and about 100 m below the stoping horizon; this was sufficiently far away from the stoping front for the tunnels not to be directly influenced by stress changes associated with stoping. The two tunnels were parallel to each other and were spaced 18 m apart with dimensions of 3.5 by 3.0 m.

The rock mass was typical for Witwatersrand quartzite with a uniaxial compressive strength in the range of 180 to 220 MPa. Bedding planes and joints were present. Typical of this environment, there was a well-defined fracture zone of ~2 m thickness around the tunnels. The virgin principal stress (pre-development) is vertical and in the region of 60 MPa; stresses around the excavation would be significantly higher resulting in the well-defined fractured or failed zone.

The RAW was supported with primary support, which consisted of 1.5 m long mechanically anchored rockbolts on a 1.5 by 1.5 m pattern; no surface support was installed. Damage was scattered seismic induced rockfalls from in between the bolts; the RAW was still serviceable and accessible.

Damage to the main haulage consisted of major bursting (rock mass bulking) and total closure over distance of approximately 88 m. The haulage was supported with the same primary support that had been upgraded with a 50 mm thickness fibre reinforced shotcrete (FRS).

This incident highlighted several issues: firstly, the tunnel with less ground support suffered less damage, secondly, there was a huge difference in the observed damage for what should have been similar loading conditions. The obvious question was why? The different response was partially explained by the presence of a dyke that day-lighted along a portion of the northern wall of the main haulage. It could also be argued that the installed support was inadequate for the loading conditions experienced but this does not satisfactorily explain the different rock mass responses.

Thirdly, the severity and extent of damage observed in the main haulage could not be related to any PPV calculated using a scaling relationship. Possibly this was a seismically induced strainburst on a rather large-scale or there was a secondary event triggered by the first event. No evidence of a secondary event could be found, although possibly this was because of the seismic network configuration and limitations.

This incident raised many questions that could not be answered at the time and highlighted the limitations of design methodologies available at the time as well as how much is unknown about rockbursts. The distribution of damaged and undamaged areas was particularly perplexing and has been observed by the author in several other cases.

This has been noted by Hagan et al. (2001) that the severity of rockburst damage often varies greatly over small distances. Other researchers (Spottiswoode et al. 1997; Milev et al. 1999) found that ground motions measured at points about 1 m apart on a stope hanging wall showed variations of up to a factor of five in kinetic energy and this could possibly explain differences in damage.

3 Impact of uncertainty on dynamic ground support design

Whilst there have been some advancement in the development empirical methods for dynamic ground support design (Mikula 2012); these are very site specific and reliant on having sufficient data points to develop a site specific relationship or chart. Advanced numerical modelling is an alternative but most mine sites do not have the capability to do this. Villaescusa et al. (2014) have qualitatively defined the rock mass demand for highly stressed rocks and have defined displacement and energy absorption criteria for each category. This has been combined with the Western Australian School of Mines reinforcement dynamic capacity database (Player 2012) to create a chart that can be used to assist with the design of ground support for dynamic loading conditions.

The reality is that many mines that experience rockbursts are dependent on the kinetic and potential energy method (Wagner 1984; Kaiser et al. 1996) for dynamic ground support design under ejection conditions. For strainbursting and seismically triggered shakedown mechanisms, the methodologies outlined in Kaiser et al. (1996) are generally used.

3.1 Estimating energy absorption (E_a) demand

For strainbursting, the method is reliant on assessing the dynamic depth of failure (d_f) based on numerical assessment of the expected stress conditions and the uniaxial compressive strength of the rock. There are uncertainties and variability associated with both stress conditions and rock mass strength.

When assessing the potential for shakedown, the method is reliant on assessing the PPV that an excavation will be subjected to; this is dependent on the seismic event magnitude and its distance from the excavation.

When designing for the ejection mechanism, the major uncertainties are the ejection velocity, which is a function of the incoming PPV and the site amplification factor. The incoming PPV is a function of the seismic event magnitude and its distance from the excavation. The site amplification factor is used to capture many of the aspects we do not understand about rockbursts.

Although several mechanisms have been proposed for PPV amplification in the fractured zone around an excavation, it is still poorly understood. The degree of amplification appears to be partly dependent on the frequency of the incident seismic wave, the thickness of the broken zone around the excavation and the reflection of the wave from the excavation (McGarr et al. 1981; Kaiser et al. 1996; Potvin et al. 2010).

In Western Australia's mines, the fracture zone is likely to be 2 m or less and this is typical of other Australian mines. Heal (2007) suggests that the site effect in Western Australian mines is more likely to be two or less. A fracture zone of 2 to 3 m is also typical in many South African deep level mines. Kaiser et al. (1996) present the view that those ejection velocities greater than the PPV are 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.

Mikula and Lee (2007) state that joints are energy sinks and that they slide, grind and absorb incoming dynamic energy; the addition of ground support increases the ability of a jointed rock mass to absorb energy and this could reduce the likelihood of ejection. This further complicates the estimation of ejection PPV.

The incoming PPV is typically based on a far field relationship or scaling law that relates the seismic event magnitude to an estimated PPV at a distance from the source; in many cases a generic scaling law is used or a site specific ground motion prediction equation (GMPE) is developed. In the authors' opinion, a site based GMPE is preferable as it is based on site specific measurements. These equations are based on a statistical fit to PPV measurements at points in a number of boreholes. Whilst based on far field assumptions, improvements have been made to better estimate the PPV closer to the source.

As the GMPE is a statistical fit, variations can be expected and this is reflected in the standard deviations for the GMPE and the various coefficients. Typically, the GMPE is applied in a deterministic manner and is defined for a specific level of confidence; this implies that the PPV could be higher or lower than the confidence level value. Higher PPV values are problematic and this uncertainty should be accounted for in the design process.

The impact of uncertainty or variability for design event magnitude, critical distance, and amplification factor and ejection thickness is shown in Table 1. For these examples, the following inputs have been used:

- A typical mine site GMPE has been used with the mean PPV and a PPV plus 20% (representing the standard deviation (SD)) applied.

- Amplification factors of two and three.
- Ejection thicknesses of 1 and 2 m.
- Gravitational acceleration (g) of 9.81 m/s².
- A direction factor of one was applied.

Table 1 Summary of required E_a for a range of scenarios with FS shown in brackets

Design magnitude (M_L)	**2.3**		**2.6**	
Distance from source (m)	10	50	10	50
PPV_{mean} (m/s)	0.5	0.2	0.8	0.4
$PPV_{+20\%}$ (m/s)	0.6	0.22	0.96	0.48
(1) Ejection PPV_{mean} (Amplification factor 2)	1	0.4	1.6	0.8
(2) Ejection $PPV_{+20\%}$ (Amplification factor 2)	1.2	0.44	1.92	0.96
(3) Ejection PPV_{mean} (Amplification factor 3)	1.5	0.6	2.4	1.2
(4) Ejection $PPV_{+20\%}$ (Amplification factor 3)	1.8	0.66	2.88	1.44
Ejection thickness = 1 m; FS for a 20 kJ/m² capacity support system shown in brackets				
E_a Required for Back (kJ/m²) — Scenario (1)	6.6 (3.0)	5.5 (3.6)	8.8 (2.3)	6.2 (3.2)
E_a Required for Back (kJ/m²) — Scenario (2)	7.2 (2.8)	5.6 (3.6)	10.3 (1.9)	6.5 (3.1)
E_a Required for Back (kJ/m²) — Scenario (3)	8.3 (2.4)	5.8 (3.5)	13.1 (1.5)	7.2 (2.8)
E_a Required for Back (kJ/m²) — Scenario (4)	9.7 (2.1)	6.0 (3.3)	16.5 (1.2)	8.1 (2.5)
Ejection thickness = 2 m; FS for a 20 kJ/m² capacity support system shown in brackets				
E_a Required for Back (kJ/m²) — Scenario (1)	13.3 (1.5)	11.0 (1.8)	17.5 (1.1)	12.3 (1.6)
E_a Required for Back (kJ/m²) — Scenario (2)	14.5 (1.4)	11.2 (1.8)	20.5 (1.0)	13.1 (1.5)
E_a Required for Back (kJ/m²) — Scenario (3)	16.7 (1.2)	11.6 (1.7)	26.1 (0.8)	14.5 (1.4)
E_a Required for Back (kJ/m²) — Scenario (4)	19.3 (1.0)	12.0 (1.7)	33.0 (0.6)	16.2 (1.2)

It can be seen that varying these factors can have a significant impact on the required energy absorption. A ground support system with an energy absorption capacity of 20 kJ/m² has been assumed and FS have been calculated for each scenario. This demonstrates how variations in ejection thickness and ejection velocity have a significant impact on FS.

3.2 Estimating ground support E_a capacity

Whilst we do not completely understand how the support system interacts with the rock mass; geotechnical engineers have to make a number of pragmatic decisions when designing a ground support scheme. Typically, energy absorption inputs for different support types are based on values reported in the literature or on some form of laboratory testing (e.g. Varden et al. 2008; Player et al. 2009; Villaescusa et al. 2013). There are a number of dynamic (drop testing) systems (Hadjigeorgiou & Potvin 2011) that are used to provide these inputs. In addition, there are conventional pull tests for bolts that can be used to describe their load-deformation characteristics. For FRS, tests such as the European Federation of National Associations Representing for Concrete (EFNARC) beam and the round determinate panel can be used to assess the energy absorption capacity of FRS, however, because of completely different boundary conditions it is difficult to relate these tests to an in situ FRS lining performance.

Some dynamic drop testing systems are capable of limited testing of ground support systems (e.g. bolts, mesh and shotcrete) but none are capable of testing a complete system that includes surface support connections and overlaps. The loading system is generally simplified (axial loading) and does not reflect the complexities experienced in a rockburst. Generally, this sort of testing can be considered as index testing and provides useful insight into some aspects of how support systems behave and is good for comparison purposes. However, the results are applicable to the specific testing machine setup and loading conditions. Currently, there is no accepted way of converting these index values into design values; also the number of tests are generally limited making it difficult to compile reliable statistics.

Limited underground simulations using blasting have been undertaken to assess how ground support systems behave (Hagan et al. 2001; Haile & Le Bron 2001; Heal & Potvin 2007). Again these simulations are useful and provide some insight into how support systems behave under the test loading conditions; typically much higher frequency waves and introduced gasses are experienced making true comparison to seismic loading questionable. These simulations are difficult to set up and only a small number have been undertaken and no accepted method is available to convert the test results into design values.

Conventional pull testing and data on steel characteristics can be used to assess the likely energy absorption for different types of bolts. However, the majority of this testing is under axial loading conditions and does not adequately consider asymmetrical loading and shear loading.

Whilst there are established methods of assessing the energy absorption capacity of FRS, there are no accepted methods of converting these values into design values. Papworth (2002) related energy absorption to rock mass classes defined by the Q-system (Barton et al. 1974), however, this does not specifically consider dynamic loading. More recently, Joughin et al. (2012) developed design charts relating applied energy absorption at different thicknesses to the EFNARC beam and the round determinate panel testing.

Once you have determined the energy absorption for different support elements using a variety of sources, these need to be combined to determine the system energy absorption capacity. Currently, this is done by summing the energy absorption for individual units and normalising it over the wall area (Scott et al. 2008; Fuller 2010; Drover & Villaescusa 2016). This is a simple and pragmatic approach but is not necessarily correct as it does not take into account the complex interactions between the different elements and it does not consider the weak links such as mesh overlaps. However, no alternative methods are available and this is a reasonable approach, provided consideration is given to factors not explicitly included or understood.

4 Catering for uncertainty in dynamic ground support design

Whilst there is an appreciation that there are many uncertainties associated with the design of ground support for dynamic conditions in terms of both methodology and inputs; geotechnical engineers need to provide practical ground support designs that capture both variability in the input parameters as well as some of the unknowns.

This typically involves the following:

- Using conservative inputs to assess the required energy absorption (demand).
- Using conservative inputs to assess the energy absorption provided by a support system (capacity).
- Applying high Factors of Safety (typically FS ≥ 2).

When assessing the required energy absorption for the ejection conditions, the potential ejection thickness and ejection velocity have the most significant impact; a brief discussion follows.

4.1 Ejection thickness

Ejection thickness is typically based on previous experience, observations of the failure depth from drilling or borehole observations, numerical modelling or a combination of these. The potential ejection thickness is used directly in the energy absorption equation but is also used to assess the required rockbolt length. Fuller (2010) outlined the need for longer ground support elements to tie-back the potential failure or ejection zone to a stable anchorage zone. This approach has been applied in several South African deep level gold mines for many years.

The depth of ejection will vary as a function of stress conditions, rock mass strength, excavation geometry, excavation dimensions and presence of structurally controlled wedges or slabs. A conservative worst case ejection thickness can be assigned to cater for all conditions i.e. one value for standard development drives, stope brows, intersections; alternatively ejection thicknesses can be derived for specific excavations and areas.

In order to reduce the uncertainty regarding ejection thickness, it is important to maintain a detailed database of all rockburst damage especially observed ejection thicknesses and the conditions (rock mass, structures, geometry, stress) at the time. The extent of potential failure zones should also be assessed by observations from damage mapping and boreholes, instrumentation and numerical modelling. Ideally, all observations should be used to calibrate numerical models.

4.2 Ejection velocity

As discussed earlier, the ejection velocity is made up of a number of factors; to reduce the uncertainty a number of approaches can be used. Ideally, a site specific scaling law or GMPE should be developed to estimate the incoming PPV; it is also important to understand what the variability is for the scaling law and what confidence levels should be applied.

To apply the GMPE, it is necessary to define the design seismic event or events, this requires an understanding of what magnitude events cause damage on a particular mine site, the seismic character for different areas of the mine and seismic hazard analysis.

It is possible to define a design seismic event and apply the GMPE in a deterministic manner and come up with a PPV at a distance of interest from the source and this approach is commonly applied. A more suitable method is to develop probabilistic contours or iso-spheres of PPV that can be related directly with the risk assessment method used on a mine; this can be done in with mXrap apps (Wesseloo & Harris 2015) or using Vantage (Institute of Mine Seismology 2016). This approach is based on statistical hazard analysis and has the weakness that it is backward looking.

An improved approach is to develop a calibrated numerical model and to then model or simulate future seismicity using the extraction sequence going forward (Malovichko & Basson 2014). The simulated seismicity can then be used for seismic hazard analyses and for the probabilistic assessment of the ground motion hazard (Malovichko 2016). This approach avoids the issues associated with having to pick a design event and a distance from the source; this method allows a threshold PPV to be expressed as the probability of exceedance within a time period of interest. Typical likelihood classifications used in mining industry risk assessment matrices can be converted into the probabilities of occurrence for different time periods of interest assuming a stationary Poisson process. This approach allows elements of risk-based design to be considered in the design process.

The amplification factor needs to assess through observation and back analysis of rockburst damage trying to calculate the ejection velocity. Several authors (Ortlepp 1993; Drover & Villaescusa 2016) have reported high ejection velocities, although this is not always the case. The type of seismicity also needs to be considered, the amplification on the skin of an excavation is likely to vary dependent on the frequency of the seismic waves. The site amplification factor is probably the most significant uncertainty in the design of ground support for dynamic conditions.

4.3 Accounting for uncertainty in dynamic ground support design

Whilst there are a number of ways to assess individual input parameters; the design engineer still needs to make decisions about how the parameter is chosen and could apply one of the following:

- Choosing the mean or median.
- Using confidence levels (e.g. 90, 95 or 99%).
- Using the mean minus one or half a SD.
- Using percentiles e.g. P25 (75% of the data exceeds this value).
- Using a worst case value (can result in overly conservative and uneconomic designs).
- Using a cumulative curves and cumulative value e.g. 95% cumulative value (implies only a 5% likelihood of exceedance).
- Using lower bound, expected and upper bound estimates.

For dynamically capable ground support design, a conservative approach is typically adopted. Irrespective of which method is applied to select design input parameters, there is always an element of engineering judgement required and a level of acceptable risk should be considered in this process.

Typically, a deterministic approach is applied in dynamic ground support design; by using sensitivity analysis it is possible to gain an understanding of how the demand and capacity will vary and how this influences the FS.

Elements of probabilistic design can be incorporated in the numerical modelling of excavations, as well as in the seismic hazard analysis and by estimation of PPV. This can be taken further by the simple application of point estimate method (PEM) to determine the expected value and SD for FS. An explanation of the PEM is not included, as this is well covered in Harr (1996). Using this approach requires a number of simplifying assumptions to be made. An example is shown in Table 2; where the SD for both demand and capacity has been assumed to be 20%. The examples have been calculated for two ground support systems with 20 and 30 kJ/m² energy absorption capacities. The demand is based on Scenario 3 (Table 1) for a 2 m ejection thickness (i.e. M_L = 2.3; PPV_{mean} at 10 m from source; site amplification factor of 3).

Table 2 Example of FS variation using the PEM

	Mean	SD	+	-	Mean FS	Expected FS	SD FS
Demand (kJ/m²)	16.7	3.3	20.0	13.4	1.20	1.25	0.36
Capacity (20 kJ/m²)	20.0	4.0	24.0	16.0			
Demand (kJ/m²)	16.7	3.3	20.0	13.4	1.80	1.87	0.53
Capacity (25 kJ/m²)	30.0	6.0	36.0	24.0			

This simple example demonstrates how FS varies and provides valuable information on how much the FS can vary; this information also allows for the probability of failure to be calculated. This approach provides information on the design reliability as well as accounting for uncertainty in design inputs. This example was simplified down to two variables, however, as most design calculations are typically done in spreadsheets, it is relatively easy to account for a number of key variables.

It could be argued that undertaking sensitivity or probabilistic analysis is of limited value when the design methodology is flawed. The author is of the view that there are no viable alternative design methods currently available; and there is unlikely to be a significant breakthrough in the short to medium term. Geotechnical engineers have to take a pragmatic approach to the design of ground support for dynamic conditions and this should include improved accounting for variability and uncertainty in key inputs.

5 Reducing uncertainty in dynamic ground support design

To some extent, uncertainties in design ground support for dynamic or rockburst conditions can be reduced by following a rigorous design process and using methods that take into account variability in the input parameters. This includes sensitivity analysis and the use of probabilistic methods. Diligent observation and collection of data from rockburst incidents all assist in reducing uncertainty in the inputs.

Whilst there are many uncertainties in the design of ground support for dynamic or rockburst conditions, the most significant are our lack of knowledge or understanding of: rockburst damage mechanisms including the complex interactions of the ground support systems and rock mass; and PPV at the excavation skin and a reliable means of estimating ejection PPV. A brief discussion of these follows.

5.1 Improving our understanding of rockburst damage

Understanding the character of mining induced seismicity on a particular mine site or area of a mine is an important component of understanding rockbursts and this is sometimes neglected by geotechnical engineers. There is scope for more collaboration between geotechnical engineers and seismologists.

Kaiser and Cai (2013a, 2013b) have very clearly outlined the need for more detailed forensic analysis of rockburst events and a clearer understanding and categorisation of the types of rockbursts and contribution factors. This increased focus on forensic analysis will undoubtedly close the gap in our understanding and reduce uncertainty.

It is also important to collect data from areas where damage was expected but did not occur; understanding this is just as important as understanding actual rockburst mechanisms. This aspect is often neglected with only minimum amount of focus and attention.

The author believes that there also needs to be more focus on understanding how ground support systems behave under real dynamic loading and rockburst conditions, as well as the interaction with the rock mass. This requires in situ monitoring programmes, which are challenging to implement but needs to be persevered with. Only by improving our understanding of this aspect, can we develop realistic relationships that allow laboratory index testing to be related to design values that reflect the real in situ performance. This will also assist in developing calibrated numerical models.

5.2 Improved understanding of PPV at the excavation skin

With the widespread implementation of good quality seismic monitoring networks on mines, there has been a significant improvement in the quantity and quality of seismic data available. This has allowed for improved PPV and distance scaling relationship or GMPE. However, this is only part of the solution; and very little work has been done on quantifying PPV at the skin of an excavation. It is known from published case studies (Ortlepp 1993; Drover & Villaescusa 2016) that there are cases where the ejection velocities are higher than the predicted PPV and this has led to the widespread use of the site amplification factor. This site effect will vary with frequency of the vibration and is unlikely to be a single number. In many cases it is based on engineering judgement or less frequently on back analysis.

Technology improvements have resulted in the widespread availability and significant reductions in the cost of both accelerometers and geophones. Accelerometers are widely used in many smart phones, the challenge is to find a way to tap into this ever improving technology and embark on cost-effective and widespread monitoring programmes to actually measure peak ground accelerations that can then be converted to PPV at the excavation skin, allowing engineers to calculate the site amplification factor (measured PPV versus predicted PPV). This would need to be done for a range of geotechnical conditions.

Results would be highly variable but, if you have enough measurements, you can get a distribution and make an informed choice. There are a number of challenges to doing this (Mikula, pers. comm., 24 March 2016):

- Instrumentation (accelerometers) has to be accurate and properly calibrated and managed so that data is believable.

- The accelerometers need to be standalone and with a lower power requirement.
- Remote download to the mine data system (fibre optic, etc.).
- Accelerometers need recalibration if vibrated beyond their design range.
- The site effect will vary with the frequency of the vibration, so it will be a package rather than a single number.

Alternatively, a geophone can be installed close to the surface of an excavation (e.g. ~0.5 m); this can be paired with a second geophone installed within a borehole 10 m into the rock mass. This would allow for the site amplification factor to be assessed (Malovichko, pers. comm., 4 November 2016).

The installation of accelerometers or geophones on or close to the surface of an excavation is challenging. With the correct focus, the issues can be addressed and it would be possible to move forward with monitoring programmes that will allow for a more reliable assessment of PPV at the excavation skin for different geotechnical conditions.

Ideally, this type of monitoring programme should be linked to monitoring programmes designed to understand ground support interaction with the rock mass under dynamic loading.

6 Conclusion

There are significant uncertainties in the design of ground support from dynamic and rockburst conditions. 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. This is demonstrated by observation of how variable rockburst damage can be spatially.

By applying a rigorous design process and appropriate methodologies, some these uncertainties can be catered for in the design calculations. This allows for the calculation of more reliable Factor of Safety as well as improved understanding of how it varies, which is an important input into risk assessments. Any design process needs to be supported by quality observations and data from rockbursts.

The use of numerical modelling, statistical seismic hazard assessments and probabilistic assessment of PPV in time and space are, in the authors' opinion, better than the more commonly used deterministic approach; using this approach it is easier to incorporate elements of risk based design and related directly to the risk assessment process and matrices commonly used in the mining industry.

The limitations of current design methods are well known, however, until alternatives are developed we need to take a pragmatic approach and apply them in a sensible manner and attempt to reduce uncertainty in the key inputs.

Improved understanding of rockburst mechanism will be developed through better characterisation of the seismicity and detailed forensic analysis of rockburst events. Forensic analysis should also be expanded to include areas where damage was expected but did not occur.

There is 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. This will assist in deriving design values from these index tests as well as the calibration of numerical models.

Currently, the assessment of ejection PPV is based on using scaling relationships and a site amplification factor based on back analysis of a limited number of cases or engineering judgement. There is a need to undertake widespread measurements of PPV at the excavation skin to allow for this area of uncertainty to be narrowed. Technological improvements in instrumentation and communications need to be harnessed to enable to better understand PPV on the excavation skin. This should be considered as an integral part of forensic investigations as well as to improve understanding of ground support systems. This is a research opportunity that needs to be taken up by the mining industry.

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