



A critical appraisal of the deformation-based support design approach

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Abstract

Empirical approaches, numerical modelling, and analytical methods are employed in ground support design for rockburst conditions, but only analytical approaches attempt to quantify the safety margins of a design. The Canadian Rockburst Handbook approach is the most widely known analytical approach. Stacey (2016) identified a state of ‘design indeterminacy’, arguing that neither demand nor capacity can be determined with sufficient accuracy for conventional design processes. Since then, several important advancements were made with the development of the deformation-based support design approach. An independent appraisal of the DBSD approach is lacking. This paper provides an independent appraisal of the deformation-based support design method, summarising the approach, identifying implicit and explicit assumptions, highlighting uncertainties, and raising questions requiring resolution. The resolution of the identified issues is necessary to demonstrate that the deformation-based support design methodology – when applied as a design tool – satisfies the standards expected of a robust engineering approach.

Keywords

Deformation-based support design, DBSD, dynamic ground support design

Introduction

Approaches to ground support design in general, and more specifically for dynamic conditions, are quite varied in methodology and sophistication. Although numerical modelling can be used to model specific instances of dynamic ground displacement and the interaction with ground support elements (e.g., Lilley et al., 2013), Stacey (2016) concluded that it is not practical for rock support design under dynamic loading conditions.

Empirical methods, on the other hand, provide guidance in selecting appropriate support for different conditions. Many approaches exist with several being site-specific (Graham et al., 2023; Mikula, Gebremedhin, 2017; Mikula, 2013; Counter, 2017 in Potvin, Hadjigeorgiou 2020). Being based on historical rockburst damage data, these approaches seldom include newer products or systems and do not provide any way to quantify the safety margin.

Analytical methods aim to quantify the demand on, and the capacity of, the support system and with that quantify the safety margin associated with a support system under the chosen design conditions. The most well-known analytical support design approach was developed as part of the Canadian Rockburst Research Programme performed in the 1990s (Mining Research Directorate, 1996) and is often referred to as the Canadian Rockburst Handbook (CRH) method. Often informally discussed, but seldom officially acknowledged, is the fact that analytical methods are sometimes used with carefully selected input parameters for the purpose of satisfying the requirement for a design justification, while the selection of support is done with empirical methods or with a process of evolution – upgrading components or systems when current systems start to underperform. Kaiser and Cai (2013) critically evaluated the design assumptions underpinning several support design approaches and concluded that ‘it is time to rethink’.

In 2016, Stacey concluded that design of rock support to contain rockburst damage cannot be carried out using a conventional design process as a state of ‘design indeterminacy’ exists, since neither the demand on the support system, nor the capacity of the support system, can be sufficiently accurately determined.

A critical appraisal of the deformation-based support design approach

Since Stacey (2016) came to that conclusion, some important contributions have been made to analytical support design in the form of the deformation-based support design (DBSD) approach collectively contained in the DBSD literature, which is discussed further on in this paper.

Since its early development, the DBSD has increasingly been implemented at mine sites with examples reported in literature (Lowther et al., 2022; Primadiansyah et al., 2025). It is important to recognise the improvements made with the DBSD approach as well as to understand its assumptions and shortcomings. An independent evaluation and appraisal of the DBSD approach is, however, lacking. Rigby et al. (2026) points out that the design approach needs to be transparent and interpretable. This paper provides an appraisal to contribute to this end.

The Canadian Rockburst Handbook approach

The Canadian Rockburst Handbook (CRH) developed a comprehensive and systematic analytical approach that distinguished between three different loading mechanisms with different design assumptions and acceptance criteria for each of these. These three loading mechanisms are (Mining Research Directorate, 1996):

- strainburst
- strainburst triggered by remote event
- shakedown.

Self-initiating rockbursts and dynamic loading from remote events share a similar framework, whilst the approach to shakedown loading differs considerably from them.

The methodology for strainburst and triggered strainburst mechanisms can be summarised as follows:

- Assess the depth of dynamic failure and the mass to be mobilised.
- Assess the velocity of movement of failing rock mass.
- Assess the kinetic energy of the mobilised rock mass (demand) and compare it with the energy absorption capacity available within the support system.

The CRH equated the velocity of movement of the rock mass to an ejection velocity, which was obtained from the peak ground velocity (PGV) and an uncertain amplification factor. The link between PGV and ejection velocity appears tenuous (Kaiser, Cai 2013). The unknown amplification factor contributed to the design indeterminacy that Stacey (2016) refers to.

Kaiser and Moss (2022) point out that the CRH approach assumes the full installed capacity of the support to be available for arresting the rockburst loading and points out that this is not the case, as some of the support capacity is consumed through quasistatic rock mass deformation.

These two major shortcomings of the CRH are addressed in the DBSD approach.

Deformation-based support design

Summary

The deformation-based support design (DBSD) is collectively contained in several publications. These are Kaiser and Moss (2022), Kaiser and Malovichko (2022), and Rigby et al. (2026), all of which present and discuss the approach in design, and Moss and Kaiser (2022), which presents and discusses the approach in the form of preventative support maintenance. Malovichko (2023) and Primadiansyah et al. (2025) discuss the implementation of the

approach and the selection of input parameters. The approach to assessing the support system capacity used in the DBSD literature was first presented by Cai and Kaiser (2018).

The DBSD approach addresses the three loading mechanisms mentioned in the previous section, making important adaptations to the first two mechanisms and maintain the original approach from the CRH for the shakedown mechanism.

The DBSD and CRH approaches share the same methodology as listed in the previous section. In the DBSD, however, the velocity of movement of the rock mass is linked to the bulking velocity rather than an ejection velocity, which is a conceptually more defensible approach.

Another important conceptual change in the DBSD approach is its focus on the residual, rather than installed, capacity. The DBSD approach also provides a conceptual framework that, together with its graphical representation, facilitates discussion on the functioning of support systems under dynamic loading.

From the DBSD literature, I found the approach conceptually easy to understand but difficult and somewhat esoteric when attempting its implementation. The following sections present the DBSD as I understand it from the literature. This may provide readers with a useful introduction to the DBSD and will allow the authors of the DBSD approach to correct any misconceptions I might have, and which others might share. With these sections of the paper, I aim to contribute to making the method more transparent and interpretable.

Several assumptions are made in the DBSD approach, not all of which are explicitly stated. The qualification of the assumptions and the quantification of uncertainties related to them are not always clear. In this paper, the implicit and explicit assumptions made in the DBSD are highlighted to facilitate further discussion and analysis.

General framework

The performance of support components and support systems are often expressed as force versus displacement, as shown in Figure 1a. The energy consumed by the support system is obtained through the integration of the force–displacement curve, i.e., the area under

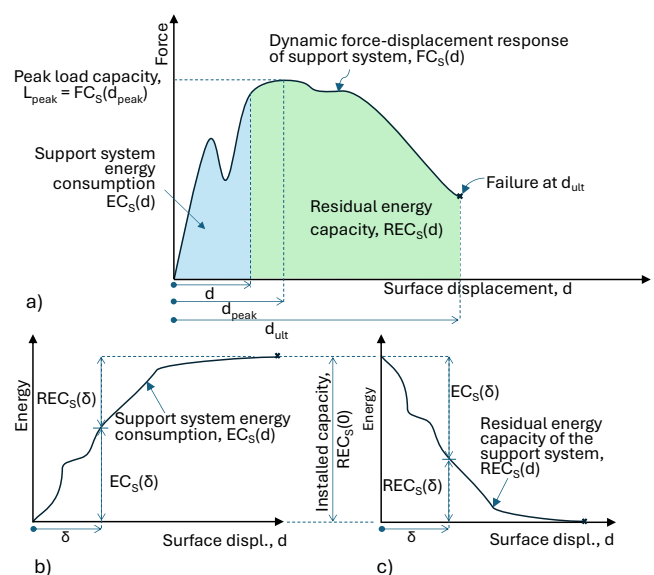


Figure 1—Conceptual illustration of consumed energy and residual energy capacity of the support system

A critical appraisal of the deformation-based support design approach

the curve, and is generally displayed as shown in Figure 1b.

Over time, excavations will deform under quasistatic stress changes and dynamic loading, and some of the capacity of the support system will be consumed. For this reason, the DBSD focuses on the residual support system energy capacity (REC_s) rather than the total installed capacity ($REC_s(0) = EC_s(d_{ult})$), as presented in Figure 1b. At any surface displacement value, d , the remaining capacity of the support system is given by the $REC_s(d)$ function.

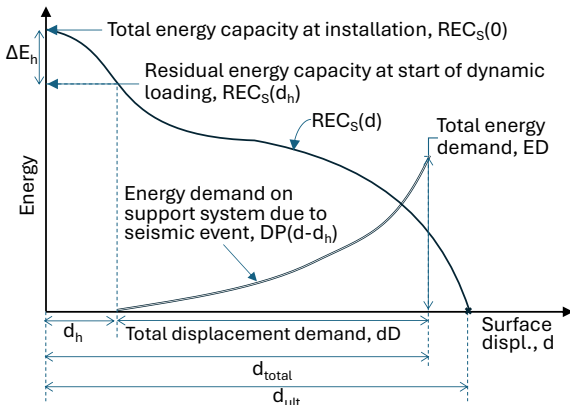


Figure 2—Deformation-based support design representation of energy demand on, and energy capacity of, the support system as a function of surface displacement

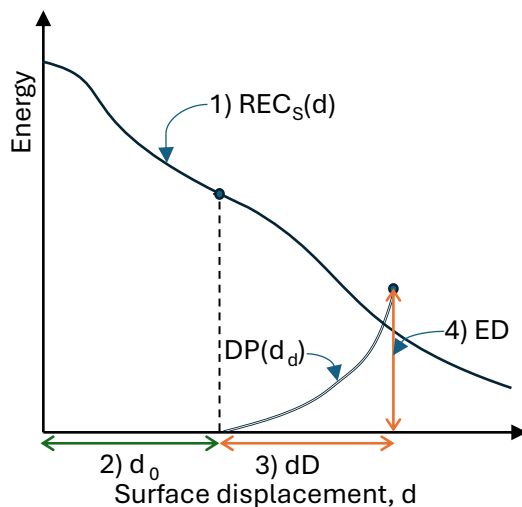


Figure 3—Components of the deformation-based support design framework that need to be quantified for use in design and preventative support maintenance

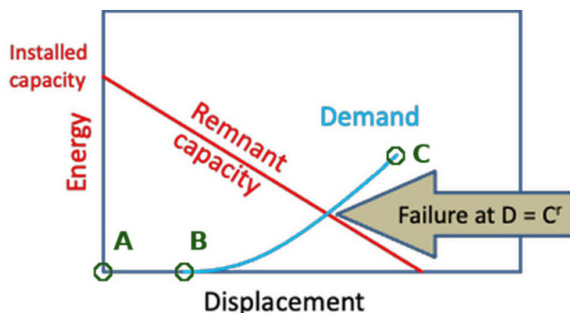


Figure 4—Definition of failure in current formulations of the deformation-based support design (Malovichko, 2023)

In the DBSD literature, the preferred way of graphically representing the $REC_s(d)$ is shown in Figure 1c, which is the inverse representation of Figure 1b. Figure 2 provides the graphical representation of the DBSD framework that is generally used in the DBSD approach. In addition to the REC_s , Figure 2 also shows what DBSD refers to as the 'demand path', represented as a double line. The demand path represents the kinetic energy demand that is placed on the support system due to dynamic displacement of the rock mass (Kaiser, Moss, 2022; Malovichko, 2023). The DBSD highlights that since some deformation will occur before the system is loaded dynamically, the energy demand function should not start at the origin but at the total historic displacement, d_h . Due to d_h , the residual energy capacity of the support system is less than the total available capacity at installation, as illustrated in Figure 2, with ΔE_h of the capacity being consumed through d_h .

An important feature of the DBSD approach is the fact that with both the energy capacity and the energy demand expressed as functions of displacement, one can evaluate stability in terms of the displacement imposed on the support system.

Within the DBSD framework the historic mode of displacement (quasistatic or dynamic) is not important in the assessment of REC_s (Moss, Kaiser, 2022). Since the total displacement imposed on the support system can be measured, the residual capacity of the support system can, at any time, be assessed and evaluated against expected future dynamic demand. In this way, the DBSD approach provides a framework for both design and preventative support maintenance (Moss, Kaiser, 2022).

The four components that need to be quantified to use the DBSD methodology for support design and preventative support maintenance are listed in the following and are shown in Figure 3:

- The residual energy capacity of the support system as a function of displacement, $REC_s(d)$.
- The historical displacement, d_h , before the design dynamic loading is imposed.
- The total dynamic displacement demand, dD .
- The total kinetic energy demand, ED .

Components one and two quantify the residual energy capacity of the support system available to arrest a design dynamic event. Components three and four quantify the dynamic energy demand. Within the current DBSD framework, failure is defined as the point of intersection between residual capacity ($REC_s(d)$) and the demand path, $(DP(d))$ or extension thereof, as illustrated in Figure 4.

Estimation of support system capacity

Cai and Kaiser (2018) proposed the estimation of the design capacity of a support system as the superposition of the average support pressure of individual components with displacement. They point out that during a rockburst, the energy is absorbed by the entire system, which includes the energy absorbed due to deformation of the bolts at the plates (direct loading), EC_{bd} , the internal loading of the support, EC_{bi} , the areal support, EC_{AS} , and the energy consumed through the breaking and deformation of the rock mass, EC_{rock} , i.e.,:

$$EC_s = \sum EC_{bd} + \sum EC_{bi} + \sum EC_{AS} + EC_{rock} \quad [1]$$

where EC_s is the energy absorption capacity of the support system.

The summation indicates that the capacity is the result of different types of surface support and reinforcement elements.

Cai and Kaiser (2018) argue that under strainbursting

A critical appraisal of the deformation-based support design approach

conditions only a small part of the energy released from the ground surrounding the burst volume is dissipated by the failing rock and that EC_{rock} may be assumed to be zero. They also point out that under tangential straining conditions one would not expect this to be the case. Assuming $EC_{rock}=0$ is, however, a conservative assumption in all cases.

By assuming a constant direct/indirect loading split, Equation 1 is simplified to:

$$EC_S = (1 + \kappa) \sum EC_{bd} + \sum EC_{AS} \quad [2]$$

where,

EC_{bd} = energy absorption through direct loading (plate loading)

EC_S = energy absorption of the support system

κ = work split ratio between direct and indirect loading = $\frac{EC_{bd}}{EC_{AS}}$

There seems to be no justification for assuming a constant load split value over time, or between different reinforcement element types. One would expect different values of κ for different rockburst magnitudes and depths. It is not clear what the impact of this assumption is, and currently, there appears to be no way to evaluate this assumption.

Load splitting values of $\kappa=1$ indicate conditions where only internal loading occurs, with the internal loading capacity being assumed to be twice that of the direct loading. A $\kappa=0$ indicates that only direct loading occurs through the plate connection. For debonded tendons, the two modes are the same and $\kappa=0$ should be used. Cai and Kaiser (2022) highlights the importance of considering the ratio of energy absorption between single-tube and split-tube tests when selecting ground support elements and provides typical ratios for different type of bolts. The single- and split-tube tests are, however, laboratory index tests and design values for κ cannot, with any confidence, be based on these laboratory values. There appears to be no other way of estimating the value.

The methodology for estimating the $REC_S(d)$ proposed by Cai and Kaiser (2018), and used within the DBSD approach (Kaiser, Moss, 2022; Moss, Kaiser, 2022; Primadiansyah et al., 2025), can be summarised as follows:

- Estimate the load–deformation capacity of each of the elements in the support system. Load for reinforcement element will be expressed as force (kN) and for areal support as force per unit area (kN/m²).
- Normalise each of the element contributions as a square unit contribution by multiplying the force from (step 1)

with the number of units of that type per square meter. Both areal support and reinforcement elements are then expressed as a support pressure (kN/m²).

- Assume a level of load splitting, $0 \leq \kappa \leq 1$ and adjust displacement values for load splitting by multiplying displacement values with $(1+\kappa)$.
- Offset the load–deformation curve for any element with deformation that may have occurred in the drive before that particular element was installed.
- Construct the system energy absorption capacity, $EC_S(d)$, of the support system as the superposition of the individual curves. The residual energy capacity of the support system is obtained as $REC_S(d) = EC_S(d_{ult}) - EC_S(d)$.

An example application of the evaluation of the support system capacity using this approach is presented in Figure 5, based on the support system specifications listed in Table 1. The values in Table 1 are obtained from the example presented by Kaiser and Moss (2022).

When superimposing the energy capacity, care needs to be taken to represent physically possible behaviour. Kaiser and Moss (2022) point out the energy consumption capacity of the surface support can only be mobilised as long as it is anchored by tendons. However, it should be noted that this capacity is not lost at the point of bolt failure but is never available and should not be included in the capacity prior to the bolt failure (Figure 6). Figure 5e shows a total energy absorption capacity of the areal support of 14 kJ/m² at a total displacement of 250 mm (Kaiser and Moss (2022) Figure 9). The surface support functions only as part of the system and cannot mobilise its residual capacity beyond the breaking point of the bolts at about 163 mm. The total available energy capacity from the areal support is thus limited to about 9 kJ/m².

When combining the energy capacity of the different elements of the support system, an assumption needs to be made about the relative deformation of the support elements. The relative displacement between reinforcement elements and the areal support is illustrated in Figure 7.

Figure 7a illustrates a deformation profile as a result of a rockburst, with the bolt head displacement denoted as d_b and the maximum displacement of the areal support as d_{AS} . One can write the d_{AS} as a multiplier of d_b , i.e.,:

$$d_{AS} = (1 + f) \cdot d_b \quad [3]$$

where f is a factor > 0 .

The value of f is related to the relative proportion of energy

Table 1

Specifications for support system as presented by Kaiser and Moss (2022)

Reinforcement			Areal support	
Name	Cable bolt	Debonded bolt	Name	Mesh reinforced shotcrete
Yield load (kN)	146	146	Yield load (kPa)	55
Spacing (m × m)	1.3 × 1.3	1.3 × 1.3	$d_{yield\#}$ (mm)	0
d_{ult}^* (mm)	110	40	d_{ult}^* (mm)	250
Pre-install displacement (mm)	25	50	Pre-install displacement (mm)	0
Load split, κ -value	0.25	0		

* d_{ult} = ultimate displacement; # d_{yield} = yield displacement

A critical appraisal of the deformation-based support design approach

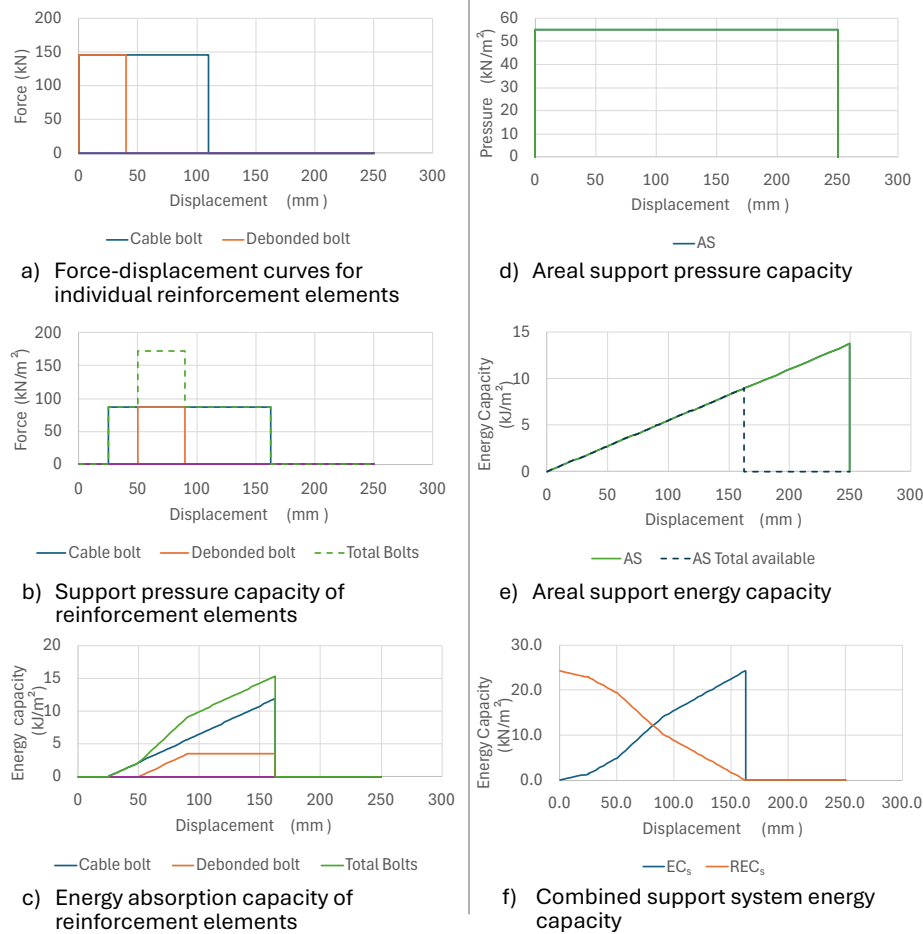


Figure 5—Assessment of the energy absorption capacity (ECs) and residual energy capacity of the support system (RECs) for a support system with components listed in Table 1

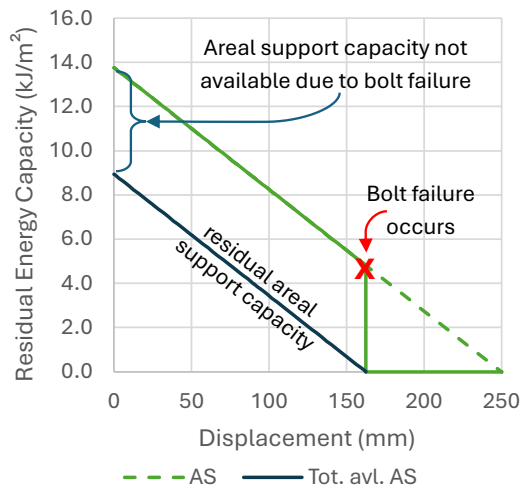


Figure 6—Residual capacity of the areal support (AS) in accounting for premature bolt failure

consumed by the bolts and the surface support. Cai and Kaiser (2018) discuss the split of energy consumption between the tendons and the surface support and state that the energy partition between reinforcement and surface support can be highly variable as it depends on the dynamic failure process and associated displacement pattern imposed on the different components. Based on the work by Bucher et al. (2013) and Ortlepp and Erasmus

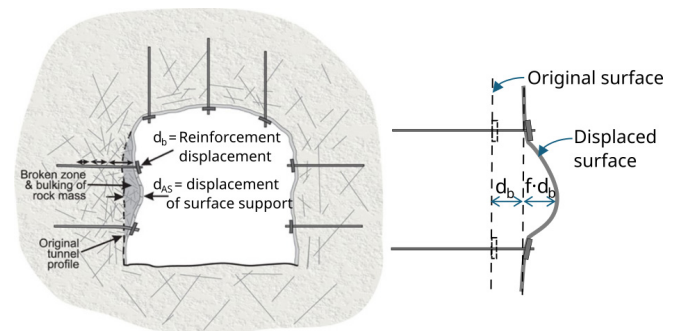


Figure 7—Illustration of deformation profile (Potvin et al., 2010)

(2002), they suggest practical ranges of the energy split to be between 25:75 and 75:25 and conclude that even with more case studies, it would likely be impossible to give more specific values.

In the DBSD literature, the energy split is not directly considered and is a result of the chosen value of f , with the assumption, generally made, that $f = 1$ ($D = 2d$). This assumption is convenient as it allows the plotting and superposition of the areal support and the reinforcement elements on the same displacement axis without the need for any adjustment. No justification, however, is given for this assumption and there currently appears to be no defensible way to choose one value over another.

A critical appraisal of the deformation-based support design approach

The implicit assumption also made is that different reinforcement elements of different types are all subjected to the same deformation during a rockburst event, acting in perfect unison similar to the uniform piston model of the assumed loading regime, as illustrated in Figure 10.

The support reaction forces acting spatially at different locations are converted to a uniform support pressure, effectively smearing the reinforcement element point loads uniformly over the supported wall, irrespective of the relative placement of support elements.

To evaluate the validity of such an approach, this paper introduces the concept of representative support pattern, similar to the concept of a representative elementary volume (REV), the volume above which a rock mass can reasonably be described as a continuum (Cundall et al., 2008; Esmaili et al., 2010; Hudson, Harrison 1997; Schultz, 1996). Different approaches to estimate REV lead to ranges of 10 to 30 times the mean block size (Cundall et al., 2008). Esmaili et al. (2010) performed an in-depth study for a massive sulphide rock mass at the Brunswick Mine and estimated a mechanical REV of about 10 m × 10 m × 20 m.

Similarly, the scale at which the support system may reasonably be represented as a uniform pressure will be several times greater than the smallest representative support pattern (SRSP). The SRSP can be described as the smallest area forming a pattern which, if repeated in a tessellation, will represent the full support pattern over a large area (Figure 8).

For the approach of describing the support capacity as a combined support pressure obtained from the different components to be valid, the loading mechanism needs to be uniform over an area several times larger than the SRSP.

Rockburst damage investigations, however, often indicate a non-uniform and complex deformation profile, as illustrated in Figure 9. Support elements often fail in different modes in the same rockburst area – naked tendons with plates attached often occur together with goose-necked bolts and others that failed in shear.

Cai and Kaiser (2018) point out that this approach described in this section to assess the support system capacity assumes that no weak links exist and that all connections survive the dynamic impact load. They also highlight the assumption that all the tendons and the surface support energy capacities are simultaneously mobilised. An installed support system, however, consists of several elements with different stiffness installed over a rough blast profile

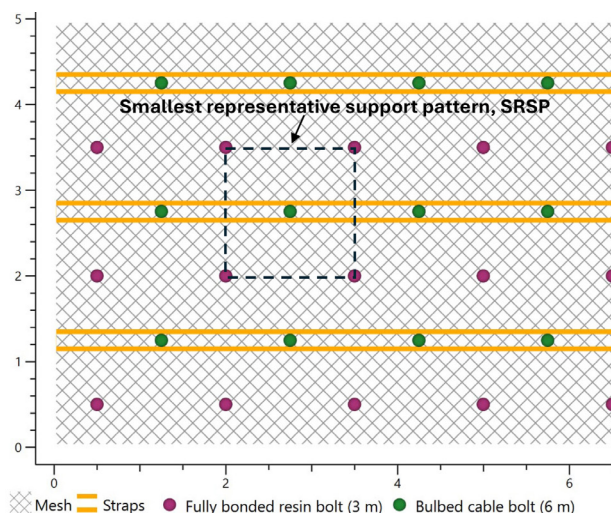


Figure 8—Support pattern used as an underground mine with the smallest representative support pattern shown

with variable installation qualities, subjected to varying loading by an anisotropic discontinuous rock mass. It is difficult to envisage these assumed conditions for an installed support system.

Matching the strength of the different units to mitigate against premature failure of any component is, of course, a prerequisite for a defensible design and will lead to a better performing system, as highlighted by the DBSD approach. The point, however, remains that the simple uniform piston loading model does not adequately represent the true loading regime and the simple superposition of energy absorption components within a uniform piston loading framework will likely overestimate the capacity of the system by ignoring both the spatio-temporal load and strength variation.

Estimation of the displacement–energy demand

Although the equations used for energy demand calculations in the CRH and DBSD are similar, there is an important conceptual difference. The CRH assumes a starting velocity equal to the ejection velocity. The rock mass decelerates due to the effect of the ground support, and the energy demand is assumed to be the total kinetic energy associated with the deceleration to zero velocity.

The demand path and total energy demand in the DBSD represent the kinetic energy of the moving rock mass during the rockburst process without any support constraint and the total energy demand. The kinetic energy that needs to be absorbed by the support system, ED, is the kinetic energy of an unrestrained rock mass at the end of the bursting process.

The assessment of the deformation–energy demand, that is, the demand path (DP) is no trivial exercise. Kaiser and Malovichko (2022) and Kaiser and Moss (2022) have proposed a method for assessing a demand path for design purposes. They propose an estimation of the total energy, ED, and total dynamic displacement demand, dD, for a given design rockburst assuming no ground support.

ED is dependent on the bulking velocity, which, in turn, is dependent on the depth of failure and the bulking factor (BF). Kaiser and Moss (2022) and Kaiser and Malovichko (2022) use the conceptual model presented in Figure 10 and propose the following



Figure 9—Support system damaged by a seismically triggered strainburst causing loading by rock mass bulking (Kaiser, Cai 2013)

A critical appraisal of the deformation-based support design approach

estimate of the dD, and bulking velocity, v_b :

$$dD = d_{sb} \cdot BF \quad [4]$$

where:

d_{sb} = the strainburst depth of failure
BF = the bulking factor.

$$v_b = \frac{(\text{failure depth})(BF)}{\text{time of strainburst}} = \frac{dD}{\Delta t_{sb}} = \frac{d_{sb} \cdot BF}{\Delta t_{sb}} \quad [5]$$

where:

dD = the dynamic displacement demand
 Δt_{sb} = the time of the strainburst bulking.

The conceptual model underlying the formulations in Equations 4 and 5 is illustrated in Figure 10.

The conceptual model (Figure 10) considers two rock volumes, the first being the volume of rock in the skin of the excavation and fractured before the rockburst occurs. This rock volume acts as a burden to the violently expand rock behind it. The second volume, behind the burden, is the failing rock – the source of the rockburst. The expanding rock mass is assumed to act as a piston pushing the burden at v_b .

The equations presented in the DBSD approach for the assessment of the ED implicitly assume a constant acceleration and an associated linear change between start and end velocities. Assuming a constant acceleration, the energy required to bring the burden to rest, DE_b , is:

$$DE_b = \frac{1}{2} \cdot m_b v_b^2 \quad [6]$$

where:

m_b = the mass of the burden
 v_b = the bulking velocity.

The bulking velocity at the deepest edge of the expanding mass is zero and equal to v_b at the edge closest to the surface in contact with the burden. Assuming a linear velocity profile and a constant acceleration, the total kinetic energy of the burden, DE_{sb} , is:

$$ED_{sb} = \frac{1}{4} \cdot m_{sb} v_b^2 \quad [7]$$

where m_{sb} is the mass of the strainbursting rock.

The total amount of kinetic energy demand is estimated as:

$$ED = ED_b + ED_{sb} = \frac{1}{2} \left(m_b + \frac{m_{sb}}{2} \right) v_b^2 \quad [8]$$

The total kinetic energy demand estimate for this strainburst is similar to that of a self-initiated strainburst with the additional energy transferred from the remote event.

$ED = [\text{Strainburst energy demand}] + [\text{energy transferred from remote event}]$

$$ED = \left[\frac{1}{2} \left(m_b + \frac{m_{sb}}{2} \right) v_b^2 \right] + \left[\frac{1}{2} (m_b + m_{sb}) (n \cdot PGV)^2 \right] \quad [9]$$

where:

n = an amplification factor
PGV = the peak particle velocity from the remote events acting on the bursting rock mass.

One would expect the bulking to vary from zero somewhere behind the back of the rockburst to a maximum value closer to the wall. BF in Equation 4 is therefore a representative or characteristic value representing the varying bulking within the rock mass.

Assuming a linear distribution from the depth of the rockburst to the surface, the minimum, maximum, and mean BFs will be 0, 2BF and BF, respectively. Equation 5 assumes the failure depth, d_{sb} , and the bulking rate to be constant over the bulking time Δt_{sb} . No data is available to either support or defeat this assumption.

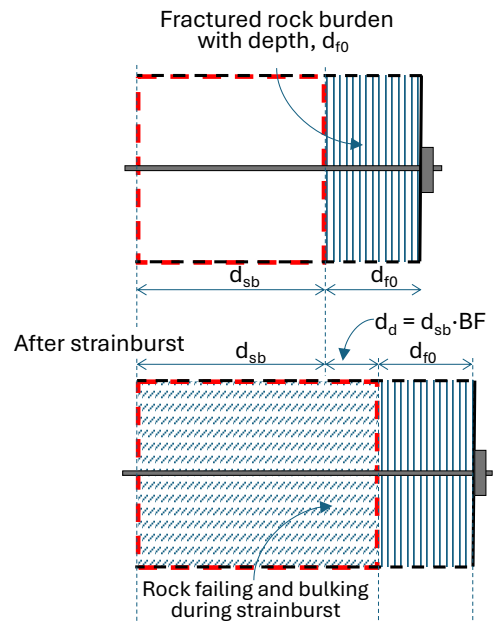
Parameters necessary to estimate the energy demand

Cai and Kaiser (2018) point out that the actual volume increase varies considerably with BFs up to 25% for unconfined highly fractured rock, and smaller values (5% – 10%) for rock that is confined and remains in place even after being fractured. As the BF is dependent on the support performance, an assumption on the support performance is required to estimate demand on the ground support (ED and dD). Due to the assumption made on the BF, the dD includes the presence of ground support – the associated energy consumption is, however, ignored (a point discussed in more detail further on in this paper).

The BF is an input parameter and presupposed, with a user required to choose a lower BF when a support system is expected to perform well. As lower BFs lead to lower displacement and energy demands, the expected good performance of the system becomes a self-fulfilling prophecy.

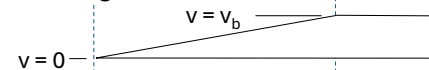
Conceptual Geometry

At initiation



Velocity profiles

Self-initiating rockburst



Remote triggered rockburst

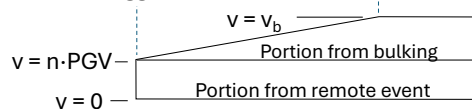


Figure 10—Conceptual model for estimation of displacement demand and bulking velocity (modified after Kaiser and Moss, 2022)

A critical appraisal of the deformation-based support design approach

The duration of the bulking process can be greater than the rupture time, $\Delta t_{sb} \geq t_r$. Malovichko (2023) states that under the assumption that the fracturing and bulking of rock during the strainburst is contained and that the bulking rock remains mechanically coupled with the surrounding rock mass, then the duration of seismic radiation and duration of bulking will be approximately the same. This may not be the case when severe rockburst damage occurs, but is reasonable as a design assumption where severe rockburst damage is to be avoided. In all cases, however, this assumption will be conservative.

With the lack of direct measurements, Kaiser and Malovichko (2022) and Malovichko (2023) present back-calculated estimates of both Δt_{sb} and d_{sb} , as shown in Figure 11. The values of Δt_{sb} are assumed to be equal to the duration of the source. The duration of the source is assumed to be twice the difference between the origin time calculated from the P- and S-wave first arrivals, and the centroid time evaluated from a source–time function inversion, constrained by the moment tensor (Malovichko, 2022).

The values of d_{sb} are calculated from the moment using a source model for crush type events in the skin of a tunnel, developed by Malovichko and Rigby (2022). For this back-calculation, they assumed the length of the rockburst source along the tunnel, L_3 , to be 15 times the d_{sb} and be at least 3.5 m, and that there was no influence of local geology (Malovichko, 2023).

Kaiser and Malovichko (2022) recommend the use of Δt_{sb} between 20 ms and 50 ms and d_{sb} between 0.5 m and 1 m for depth of failure. These boundaries are shown as a box in Figure 11. Since smaller Δt_{sb} and greater depth result in higher demand, $\Delta t_{sb} = 20$ ms and $d_{sb} = 1$ m may be optimistic.

With both the axes on the chart being logarithmic and the energy associated with a moving mass being proportional to the square of the bulking velocity, small changes in the proposed ranges have a large influence on the estimated energy demand. This is illustrated in Figure 12, which plots the cumulative distribution of the kinetic energy demand based on three different ranges. The blue and orange distributions assume a bulking factor of 5% and 10%, respectively, along with the ranges suggested by Kaiser and Malovichko (2022) (blue box in Figure 11). The green distribution assumes an upper limit for d_{sb} of 0.5 m deeper and assumes the range of $\Delta t_{sb} = 0.01$ to 0.02 ms (purple box in Figure 11). For the purpose of generating Figure 12, a uniform distribution was assumed for BF. For both Δt_{sb} and d_{sb} uniform distribution was assumed on logarithmic scale, i.e., data is assumed to be uniformly distributed through the blue or purple boxes.

Currently, a high degree of uncertainty exists on the estimation of design parameters for strainburst depth and duration.

Stability assessment with the deformation-based support design approach

With analytical design approaches, some design acceptance criteria (DAC) are defined, with the design accepted when the DAC has a sufficient margin of safety appropriate to the level of uncertainty and consequence associated with the design.

Common DACs are factor of safety (FS) and safety margin (SM). FS is more commonly used in engineering design calculations, but SM is more easily represented graphically. Similar to Kaiser and Moss (2022), this paper uses FS as the DAC and uses SM in graphical representation. These two measures are related as follows:

$$FS = \frac{\text{Capacity}}{\text{Demand}} = \frac{SM + \text{Demand}}{\text{Demand}} \quad [10]$$

$$SM = \text{Capacity} - \text{Demand} = \text{Demand} \cdot (FS - 1) \quad [11]$$

The capacity and demand factors in the DAC can be defined in different ways and with respect to different design parameters. Within the current DBSD (e.g., Kaiser, Malovichko, 2022; Kaiser, Moss, 2022; Malovichko, 2023; Primadiansyah et al., 2025), failure is defined as the point of intersection between residual capacity, $REC_S(d)$ and the demand path, $DP(d)$ or extension thereof, as illustrated in Figure 4.

Kaiser and Moss (2022) proposed the use of two residual FSs that need to be evaluated for the acceptance of a design. These two FS_R measures are defined in terms of deformation and energy.

$$FS_{Rd} = \frac{\text{Residual displacement capacity}}{\text{Displacement demand}} = \frac{RdC_S}{dD} \quad [12]$$

$$FS_{RE} = \frac{\text{Residual energy capacity}}{\text{Energy demand}} = \frac{REC_S}{ED} \quad [13]$$

Kaiser and Moss (2022) present the corresponding SMs in their Figure 14 reproduced here in Figure 13. The figure illustrates two SM definitions (green) quantifying the proximity of the REC_S to the

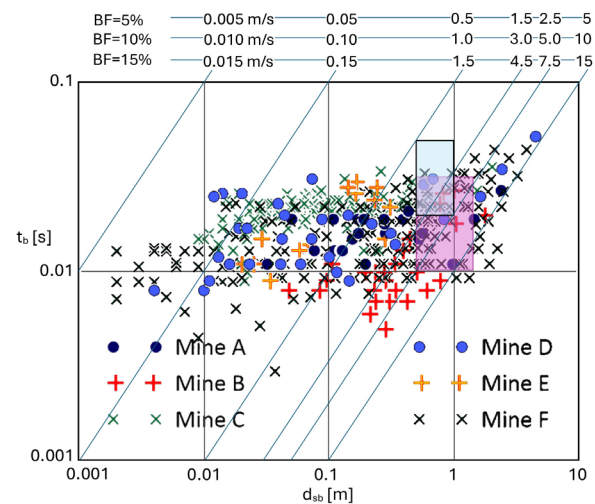


Figure 11—Estimated depth and duration of seismic events recorded in underground mines (modified after Malovichko, 2023)

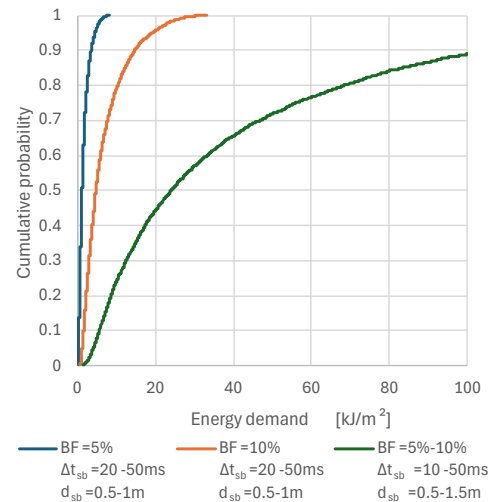


Figure 12—Cumulative probability distribution of kinetic energy demand estimates based on different parameter range assumptions

A critical appraisal of the deformation-based support design approach

ultimate displacement and energy demand (blue circle) resulting from the rockburst loading path (blue). They calculate the following FS_R :

$$FS_{RE} = \frac{SM_E + ED}{ED} = \frac{18 \text{ kJ/m}^2}{5 \text{ kJ/m}^2} = 3.6 \quad [14]$$

$$FS_{Rd} = \frac{SM_d + dD}{dD} = \frac{95 \text{ mm}}{50 \text{ mm}} = 1.9 \quad [15]$$

Kaiser and Moss (2022) point out that the loading path is inclined (light blue) and suggests that the most realistic FS_R is obtained with the SM defined along the loading path trajectory. With this definition, the two previously-defined FS_R values are conditional on the load path. The conditional FS_R s, for the example shown in Figure 13b, are calculated as follows:

$$FS_{RE} = \frac{SM_{Ec} + ED}{ED} = \frac{11.5 \text{ kJ/m}^2}{5 \text{ kJ/m}^2} = 2.3 \quad [16]$$

$$FS_{Rd} = \frac{SM_d + dD}{dD} = \frac{(20 + 50) \text{ mm}}{50 \text{ mm}} = 1.4 \quad [17]$$

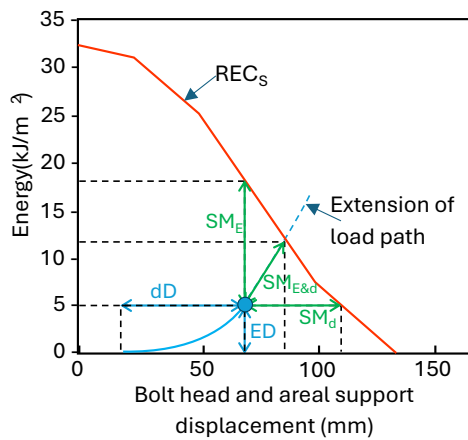
These load-path conditional FS_R s appear to be the preferred FS definition within in the DBSD methodology. In a more recent publication Rigby et al. (2026) focused on the displacement safety factor, FS_{Rd} as expressed in Equation 12. Rigby et al. (2026) argue for the use of this definition, based on the fact that the energy demand cannot be measured and the remnant support capacity is controlled by the imposed displacement. Since the energy and displacement are inextricably linked in both the demand and

residual capacity estimation, and the displacement residual capacity is defined in energy–displacement space, this argument is not convincing.

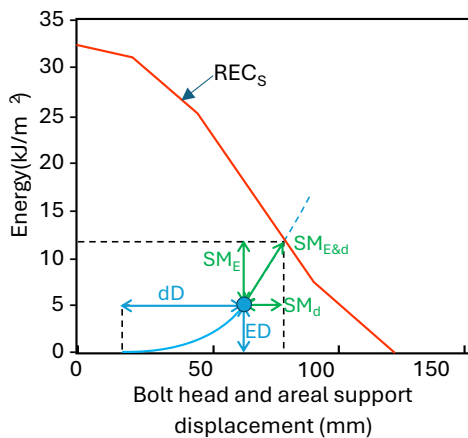
It appears that the reasoning behind designating the crossing point as failure is the fact that beyond this point, the calculated energy demand exceeds the residual capacity at the same displacement.

Ground support will, however, restrain the accelerating mass as soon as the bolts are mobilised and the acceleration of the rock mass will be reduced by the reaction force imparted by the support system and the energy absorbed already during the bursting period. This is illustrated in Figure 14, where the total support energy consumed during the bursting displacement is shown in orange as ΔREC_s . In this illustration, the ΔREC_s is greater than the total ED and is not accounted for in the DBSD approach.

Figure 14b illustrates the scenario where the displacement-energy demand falls above the REC_s curve. According to the definitions of SMs illustrated in Figure 13, SM_E , SM_d , and $SM_{E\&d}$ are all negative and zero with FS_{RE} and $FS_{Rd} < 1$. For the situation illustrated in Figure 14b, the energy consumption during the rockburst exceeds the demand ($\Delta REC_s > ED$). One would expect a support system with more available capacity than required, to perform satisfactorily. The DBSD implicitly recognises the importance of the ground support during the rockburst process in the form of a bulking factor chosen to represent the support system's efficiency in inhibiting the bulking. At the same time,

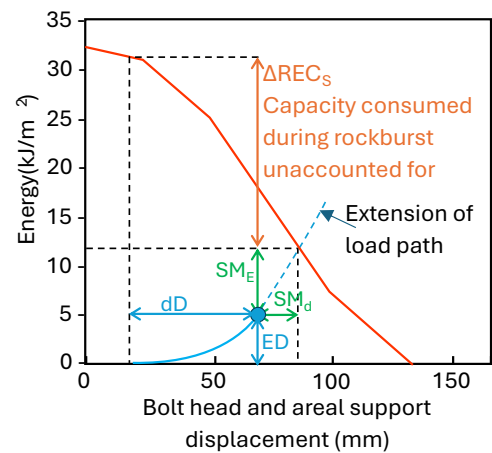


a)

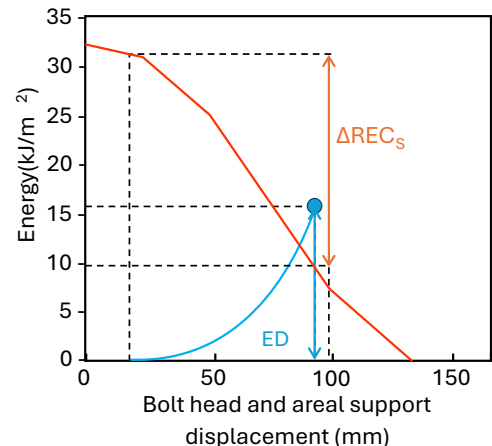


b)

Figure 13—Illustration of the safety margin definitions as proposed by Kaiser and Moss (2022)



a)



b)

Figure 14—Unaccounted for energy consumption

A critical appraisal of the deformation-based support design approach

the DBSD implicitly assumes that the support system experiences deformation, dD , and loses all the associated energy capacity ΔREC_s (Figure 14) without performing any work. This assumption seems strange and is not stated or justified in the DBSD literature.

As mentioned earlier, the demand path represents the increase in kinetic energy with displacement during a rockburst process, ignoring the effect of the ground support (except for assuming a BF appropriate to the effect of the ground support). The kinetic energy at the end of the bursting process is the ED that the support system is required to consume. In defining the FS, the DBSD approach does not seem to consider the deceleration action the ground support has on the moving mass.

The moving rock mass is decelerated by the ground support until it comes to rest (kinetic energy = 0) or failure occurs. Let's call this the energy consumption path, illustrated in Figure 15 by the purple line. The kinetic energy of the rock mass is the result of the demand path and consumption path and is conceptually illustrated in red.

In light of Figures 14 and 15, it is difficult to see the significance of the crossing point between the load path and the REC_s , and the meaning of the definition of FS in the DBSD approach is not clear.

REC_s as a state boundary

Rigby et al. (2026) mentions the design capacity is reached when the demand path intersects the residual capacity curve (FS = 1), but redefines this point from 'failure' to 'onset of damage'. With this redefinition, the calculated REC_s curve is assigned a damage level of zero and a family of curves is generated to designate state boundaries for higher damage levels.

For this, they employ the rockburst damage scale proposed by Kaiser et al. (1992) and Heal et al. (2006). A state of R0 damage is assigned to the calculated REC_s curve. State boundaries for R3 and R5 damage levels are defined as $REC_s(d + \Delta D)$ and $REC_s(d + 2\Delta D)$. With these state boundaries, it is possible to assess the SM for different levels of damage. These state boundaries are illustrated in Figure 16 for the support system presented in Figure 7 of Kaiser and Moss (2022).

This approach implies that after consuming all available support

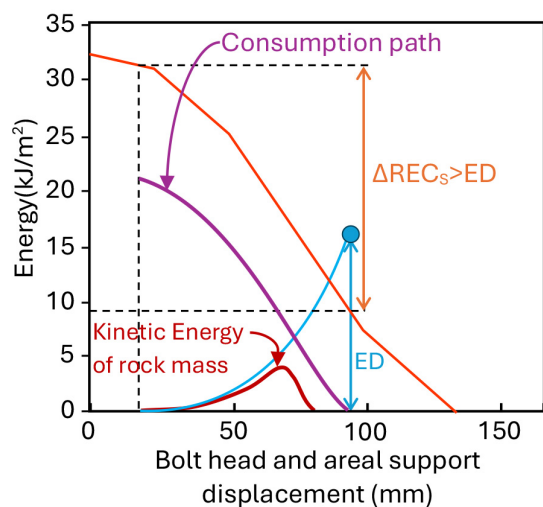


Figure 15—Conceptual illustration of load path and consumption paths and the kinetic energy of the rock mass resulting from their simultaneous interaction on the rock mass

capacity over 200 mm displacement, R0 conditions will prevail (point '1' in Figure 16). It is difficult to envisage a support system after 200 mm displacement at the bolts, and an extra 200 mm displacement between bolts (assuming $f = 1$) to show no sign of damage.

Figure 16 also shows a demand path and the ΔREC_s are first presented in Figure 14. Interpreting the ΔREC_s as a loss of support capacity during the rockburst (ignoring any work done by the support in the process), it is difficult to interpret the reduction of ΔREC_s with increase in damage. It seems to imply that for a smaller rockburst with a demand path ending at point *a* (R0 damage), more support capacity is lost during the rockburst process (ΔREC_{R0}) than for a larger event with R5 damage at point *c* (with ΔREC_{R5}).

Justification for the REC_s to a state boundary appears to be that an exceedance of the design capacity at one location on the tunnel circumference does not imply failure or collapse of the entire excavation. This statement is, of course, correct and the interpretation consistent with the argument presented earlier for complex and non-uniform loading but is, however, inconsistent with the assessment of the REC_s as discussed in an earlier Section of this paper.

The assessment of the REC_s assumes a mean support pressure resisting a uniform-piston like displacement. The formulation of the support system capacity in this way does not allow for distinction between the failure of a support element or multiple support elements and no distinction can be made between local and large-scale failure. The reality of non-uniform reaction forces and variable displacement throughout the support system cannot be accounted for.

It should be noted that the R0-R5 damage scale does not distinguish between damage extent and damage severity. Both the demand and capacity assessment components of the DBSD focus on the rockburst damage severity. The extent of damage is largely driven by the extent of rockburst demand. Accounting for damage extent with the simple addition of extra allowable displacement capacity lacks justification.

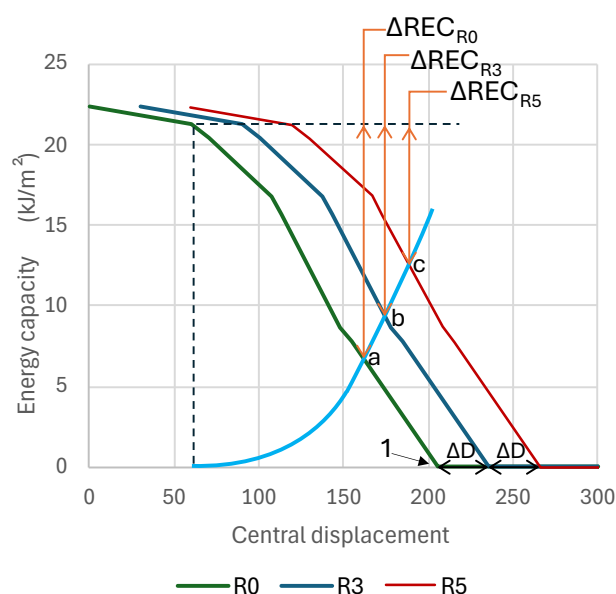


Figure 16—Residual support system capacity for R0, R3 and R5 rockburst damage levels

A critical appraisal of the deformation-based support design approach

Table 2 Key assumptions and factors where supporting evidence or justification remains limited or uncertain			
No	Assumption/component	Influence	Notes
Component 1 - Estimation of system capacity			
1	Constant load split over time.	Not clear	Does not seem reasonable.
2	Constant load split between different support elements.	Not clear	Does not seem reasonable.
3	Single load split value for different rockburst magnitudes and depths.	Not clear	Does not seem reasonable.
4	Load split values obtained from laboratory tests are representative for underground rockburst loading conditions.	Not clear	Currently no way to estimate the load split with confidence.
5	Relative displacement between support elements and surface support. f in Equation 3.	Unknown, depends on chosen value	$f = 1$ often implicitly assumed. No apparent reason to choose any particular value.
6	Uniform support loading mechanism according to 'piston model'.	Optimistic	Seems contrary to observation.
7	Uniform strength capacity mobilisation.	Optimistic	Seems contrary to observation.
Components 3 and 4 - Demand estimation			
8	Presupposition of bulking factor.	Unknown, depends on chosen value.	Leads to presupposition of outcomes.
9	Constant bulking depth over time.	Not clear	
10	Constant bulking depth over space.	Not clear	Seems contrary to observation.
11	Constant bulking rate/constant rock mass acceleration.	Not clear	implicit assumption.
12	Linear bulking profile/linear velocity profile.	Not clear	
13	Support system deformation during rockburst occur without any associated work performed.	Conservative	Implicit assumption inconsistent with 8.
Stability assessment			
14	Failure is defined as the intersection between residual capacity and the demand path.		True only if 13 is true. Internally inconsistent with 8.
REC_s interpreted as state boundaries			
15	REC _s = R0 damage.		Contradictory to assumptions made in assessing the REC _s . Lacks justification.
16	R3 and R5 state boundaries can be defined by offsetting REC _s with a specified displacement.		Conflates damage level and damage extent. Lacks justification.

Summary

The previous sections have provided a detailed assessment of the DBSD approach and identified several underlying assumptions. Table 2 summarises the key assumptions and factors that may influence the resulting outcomes, particularly where supporting evidence or justification remains limited or uncertain. The extent to which these assumptions affect the results, and whether their influence is conservative or optimistic, is not always evident.

Further investigation, validation, and/or supporting evidence is required to provide confidence in the DBSD methodology. In addition to these factors listed, uncertainty about reasonable design values for several of the parameters also exist, leading to a wide uncertainty in the outcome.

Conclusion

Analytical design approaches for rockburst-resistant ground

A critical appraisal of the deformation-based support design approach

support remain attractive due to their promise of explicitly quantifying demand, capacity, and safety margin. Few analytical ground support design approaches for rockbursting conditions have been developed with the CRH approach being the best known with the most important further developments being the DBSD approach. The DBSD approach introduces several important conceptual improvements to the CRH approach. In particular, the emphasis on bulking velocity, residual support capacity, and displacement-based assessment of energy demand and capacity.

Notwithstanding these advances, the appraisal presented in this paper demonstrates that the DBSD approach relies on a series of implicit and explicit assumptions that are difficult to justify and that remain largely unconstrained. The most important among these are the assumptions of uniform piston-like loading, simultaneous mobilisation of all support elements, constant load-splitting behaviour, and constant representative bulking factors. Together, these assumptions oversimplify the complex, non-uniform interaction between a heterogeneous bursting rock mass and support system consisting of discrete elements at different locations. The cumulative effect is not clear and may result in either unconservative or overly conservative estimates of support capacity.

The DBSD approach requires one to assume a constant (or characteristic) bulking factor with the calculated kinetic energy demand being directly proportional to the square of the chosen bulking factor. The DBSD approach assumes that the total bulking, bulking velocity, and energy demand are suppressed by the installed ground support. When evaluating the safety margin, all work done during the bursting process is ignored. In this way, the DBSD approach makes internally inconsistent assumptions. This internal inconsistency undermines the physical interpretation of the defined factors of safety and the significance of the intersection between the demand path and the residual capacity curve is unclear.

The reinterpretation of the residual capacity curve as a zero-damage state boundary, and its extension to higher damage states lacks justification. These extensions of the REC_s to state boundaries is also inconsistent with the assumptions and process for capacity estimation, which does not allow for distinction between local and large-scale failure. The role of the extent of the demand on the extent of damage is, however, ignored.

The DBSD approach constitutes an important contribution to the ongoing discussion on dynamic ground support design and provides a useful framework for further discussion. However, in its current form, it does not overcome the problem of design indeterminacy associated with rockburst support design. Significant uncertainties in both model structure and parameter selection remain, and the quantification of safety margins continues to be subject to substantial ambiguity.

The resolution of the identified issues is necessary to demonstrate that the DBSD methodology – when applied as a design tool – satisfies the standards expected of a robust engineering approach.

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