Deep Mining 2024 – P Andrieux & D Cumming-Potvin (eds)
© 2024 Australian Centre for Geomechanics, Perth, ISBN 978-0-6450938-9-6
doi:10.36487/ACG_repo/2465_0.02

Inconvenient truths about ground support in deep and high-stress mines

John Hadjigeorgiou [a,*]

[a] *University of Toronto, Canada*

Abstract

Ground support is an integral part of geomechanical risk management in deep and high-stress mines. Maintaining the integrity of underground excavations under extreme ground conditions has been the driving force for significant innovations in ground support technology. In addition, access to powerful analytical and numerical tools and monitoring technology have illustrated opportunities for significant improvement in the design process. This paper employs field observations, performance data from controlled laboratory experiments, and forensic investigations to challenge common assumptions in the design and implementation of ground support systems in deep and high stress mines.

Keywords: *ground support, material properties, rockbolt configuration, quasi-static and impact testing, field observations, forensic investigations*

1 Introduction

The management of geomechanical risk in deep and high-stress mines is a complex process involving multiple stakeholders. In a seismically active mine, this usually involves a four-stage process: data collection, defining the seismic response to mining, the implementation of control or mitigating measures, and a seismic risk assessment (Potvin et al. 2018). In this context, information on the capacity and deformation characteristics of ground support would fall under the initial data collection stage, while the design and performance of ground support is part of the control measures to mitigate risk.

Ground support is only one of several possible control measures along with mine design, preconditioning and exposure controls. In a risk management framework, the use of ground support is the last line of defence. The selection, design, and implementation of ground support systems for deep and high-stress mines is the focus of this paper. The use of the term 'inconvenient truths' has been deliberately chosen to provoke discussion and possibly challenge common assumptions and perceptions on the use of ground support in deep and high-stress mines.

2 Loading and failure mechanisms

It is convenient to differentiate between 'normal', 'high stress' and 'large deformation' ground conditions. In deep and high-stress mines, it is common to focus on the use of ground support to mitigate damage and failure associated with seismic events under complex loading for a range of ground conditions. The reality is that all three conditions can be present at a particular site and conditions can change over time as a mine matures. The LaRonde mine is an example of a site that had to manage both extreme squeezing (Mercier-Langevin & Hadjigeorgiou 2011) and high levels of seismicity (Turcotte 2014).

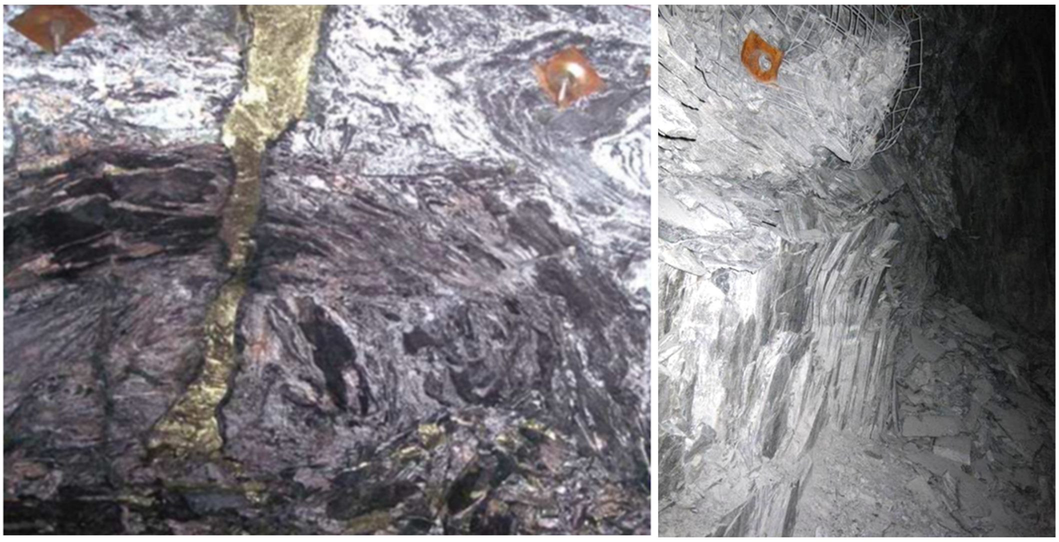
Conceptual charts provide some guidance on the potential failure mechanisms as a function of stress and rock mass quality, e.g. Hoek at al. (1995). Over time, these charts were modified by defining rock mass quality using any one of the rock mass classification systems such as Q (Barton et al. 1974), rock mass rating

---

[*] Corresponding author. Email address: john.hadjigeorgiou@utoronto.ca

(Bieniawski 1989) or geological strength index (Marinos et al. 2005), and the ratio between maximum far-field stress and the unconfined compressive strength (σ_1/σ_c) (Martin et al. 1999). Although useful in identifying conditions susceptible to rockbursts, they do not account for either localised stress or rock mass heterogeneity and their impact on excavation behaviour mode over time. The complex interaction between mining activities, stress changes and rock mass behaviour in complex rock mass conditions can only be captured by a comprehensive instrumentation program as described by Jones et al. (2019).

The applicability of most rock mass classification systems is limited by the assumption that a rock mass has a sufficient number of 'randomly' oriented fractures to be treated as a homogeneous isotropic mass. This is frequently not the case, as illustrated in Figure 1. Another limitation is that the same classification rating can reflect diverse ground conditions and different potential failure mechanisms. Finally, conversions between the different classification ratings, although convenient, are based on what are often flawed and non-representative conversions (Hadjigeorgiou 2012). Consequently, it is difficult to defend ground support recommendations based on rock mass classification systems developed for 'normal' ground conditions (Potvin & Hadjigeorgiou 2016).



(a) (b)

Figure 1 In situ examples. (a) Rock mass heterogeneity; (b) Rock mass anisotropy

A major challenge is to match the rock mass behaviour and failure mechanisms to select ground support that is both effective and cost efficient. In deep and high-stress mines, progressive, or brittle failure, is associated with a stiff loading mechanism, while sudden and violent failure is typical of soft loading conditions (Hudson et al. 1972; Kaiser et al. 1996). Potvin & Hadjigeorgiou (2020) suggested that there are three fundamental ground support options that can be used for the failure mechanisms observed at a mine site: stiff reinforcement for low stress conditions, soft and ductile reinforcement for high stress and stiff loading, and stiff and ductile reinforcement for soft loading under high-stress conditions. This underscores the need to characterise the behaviour of reinforcement and surface support elements, and ground support systems both in the laboratory and in situ.

3 The demand/capacity problem

In an underground mine, a seismic event may occur because of a movement or the creation of a new fracture within a rock mass. Ortlepp & Stacey (1994) classified seismic event sources in underground mines. It is convenient to differentiate between events in which the source of the seismicity and the location of the damage are coincident (strainbursts) and events in which the source of the seismicity and the location of the rockburst damage may be separated by substantial distances, often described as rupture type or fault slip rockbursts

(Ortlepp & Stacey 1994; Kaiser et al. 1996). The inconvenient truth is that current ground support practice is inadequate to reliably mitigate damage at a location near the source of a large fault slip event.

It is desirable to define stability problems as a function of demand and capacity as this facilitates the determination of a Factor of Safety. This is often interpreted as an indication of a rigorous design procedure that meets corporate and legislative requirements. The same process used for static conditions has been extended to dynamic conditions (Kaiser et al. 1996). In both cases, the Factor of Safety is defined as a function of equilibrium between load (demand) and capacity of any of these parameters:

- force
- displacement
- energy.

Consequently, it is routinely claimed in ground control management plans that the design of ground support for seismic conditions has been established using the above criteria. However, the reality is that the use of these approaches is consistently proven inadequate both as design and back analyses tools. This is illustrated by case studies where localised failure of the ground support can be observed following a seismic event, while adjacent areas remain intact (Figure 2). The dynamic load and capacity assumptions would have been identical for a far-field event, even though this event resulted in localised total failure and in no sign of loading on the ground support in adjacent areas. There can be several reasons for these discrepancies, ranging from quality assurance (QA)/quality control (QC), poor understanding of the seismic loads, inadequate load distribution between surface and reinforcement, and yielding versus non-yielding ground support. The inconvenient truth is that the priority should not be on calculating a Factor of Safety where, due to inherent uncertainties, there is limited confidence, but towards establishing safer operations through the use of ground support.

(a) (b)

Figure 2 Examples of localised rockburst damage. (a) Open stope mine; (b) Block caving mine (Stacey & Rojas 2013)

Stacey (2012) attributed the discrepancy in ground support performance to the fact that the determination of both the demand and the capacity under rockbursting conditions is problematic. This was described as a ‘design indeterminacy’ condition. The design indeterminacy problem for rockbursts has been recognised by several authors where the focus has been on predicting the demand. Potvin & Wesseloo (2013) recognised that peak ground motion does not adequately capture the complexity of the problem. The radiation pattern and the complex interaction between the seismic waves, geology, and mining excavations must be accounted for if the seismic event is further away from an excavation. The contribution of local site effect and the phenomenon of triggering a local strainburst or buckling type events in a stressed brittle rock is difficult to quantify. Kaiser & Cai (2013) also commented that the 'often assumed direct relationship between ground motion and yielding support demand is overly simplistic and, in many situations, wrong'.

It is extremely difficult to determine the capacity of a ground support system as it is a combination of individual reinforcement and surface support elements that are expected to have good connectivity to allow load transfer and distribution between the different components. A ground support element is likely to be subjected to a combination of tensile, shear, bending and torsional load. Unless all these loads are reliably quantified, any Factor of Safety analysis will involve widely varying degrees of ground support data uncertainty.

This paper focuses on highlighting the knowledge gap that exists and promoting a more thorough understanding of the challenges in evaluating the ground support capacity under seismic loading. It does not address issues related to establishing a reliable estimate of demand.

4 Ground support

The use of ground support is integral in maintaining the structural integrity of excavations in rock for their projected working life. Reinforcement is the process where rockbolts and cablebolts are applied internally to the rock mass, while surface support is a technique in which elements such as shotcrete, steel mesh, and straps are applied to externally to excavation surfaces (Hadjigeorgiou & Potvin 2011). A successful ground support system employs both reinforcement and surface support elements that work as a system to maintain the stability of an excavation under the anticipated load and ground conditions.

A discussion on rock reinforcement would be amiss if it did not acknowledge the following realities. As commercial patents expired for some of popular rockbolts such as Split Sets (Scott 1980) and Swellex (Wijk & Skogberg 1982), these are now available by multiple suppliers under the grouping of friction rock stabilisers and expandable rockbolts, respectively. Although conceptually similar, variations in steel quality and geometric configuration can influence the performance of these rockbolts. It is also quite possible that some of the historical performance data, e.g. Stillborg (1993) and Stjern (1995), may not reflect current steel and configuration characteristics of these 'similar' rockbolts.

Similarly, when a consensus was reached that 'yielding' rockbolts are better suited to mitigate the effects of mine seismicity, this created a proliferation of new products in recent years. Following the introduction of the D-bolt some 15 years ago (Li 2010a), there are now several additional paddled energy-absorbing rockbolts available from multiple suppliers, including the Versa Bolt, PAR1- resin, E-bolt, etc. Although conceptually similar, the rockbolts may have variations in steel grade and geometric configuration.

There are several guidelines for ground support design in deep and high-stress mines. These include site-specific approaches, e.g. Mikula (2012), Mikula & Gebremedhin (2017), and Morissette & Hadjigeorgiou (2019). Villaescusa et al. (2016) provided recommendations on selecting ground support elements as a function of demand and capacity derived from laboratory impact tests. Kaiser & Cai (2013) and Kaiser & Moss (2022) provided a template for calculating a Factor of Safety. All of the above approaches are subject to sources of error and uncertainty. Hadjigeorgiou & Harrison (2012) differentiated between sources of error associated with data collection and material testing methods, and aleatoric and epistemic uncertainty.

This paper focuses on reducing sources of error and epistemic uncertainty associated with ground support data and design. This section reviews the details of rock ground support elements including material properties, QA/QC, and performance under controlled conditions.

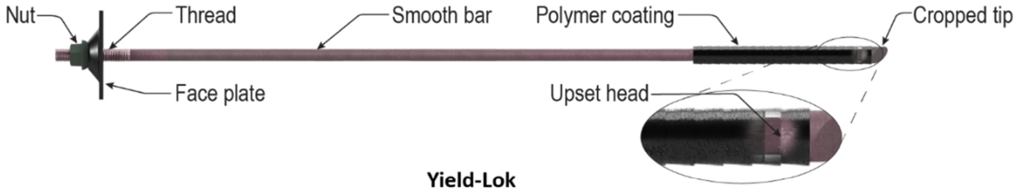
4.1 Conventional versus energy-absorbing rockbolts

The connotation 'normal conditions' can be used to describe excavations in shallow or moderate depth in relatively competent rock masses in relatively low stress conditions. Under normal conditions, ground support provides confinement and limits the loosening of the rock mass (i.e. gravity driven failure). There are multiple analytical, empirical and numerical models that can be used to select, design and implement appropriate ground control for these conditions. Traditional deterministic and probabilistic Factor of Safety analyses are both appropriate and reliable tools for static conditions.

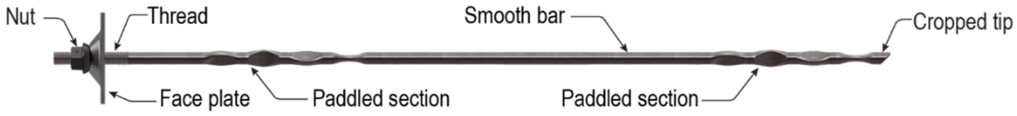
The term conventional ground support has been retroactively used to describe reinforcement that did not display yielding behaviour or high energy absorption. In seismically active ground conditions, the rock mass tends to display significant deformation. Consequently, energy-absorbing ground support can better match the anticipated rock mass failure mechanism.

In response to the challenges of mitigating rockburst damage, a multitude of energy-absorbing systems, including a combination of reinforcement and surface support elements, have been introduced in the last 20 years. A non-exhaustive representation of energy-absorbing rockbolts is presented in Figure 3.

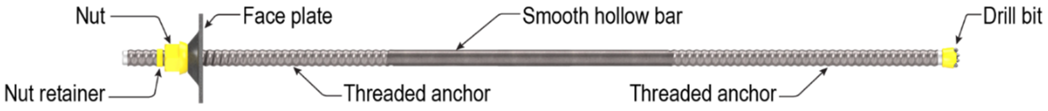
Modified Cone Bolt



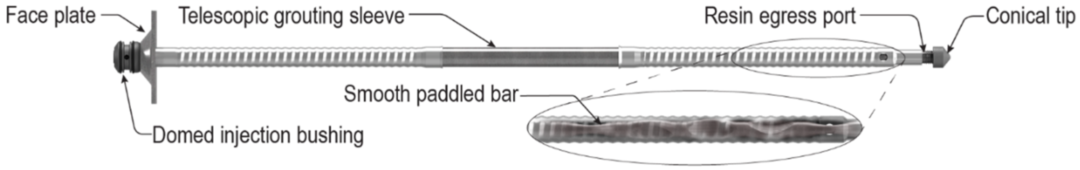
Yield-Lok



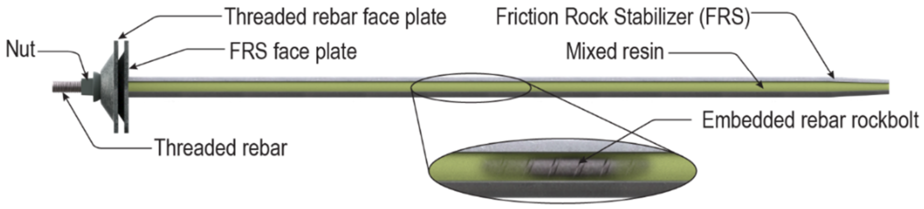
Paddled Energy-absorbing Rockbolt



Energy-absorbing Self Drilling Anchor



Pumpable Paddled Energy-absorbing Rockbolt



Hybrid Rockbolt

Yielding Mechanical Hybrid Rockbolt

Figure 3 Types of energy-absorbing rockbolts

Early attempts to increase the yielding capability of reinforcement elements included applying a plastic sleeve that was used over the central portion of a chemically anchored rebar to decouple it from the chemical bonding agent and allow the bar to stretch over the debonded length (Potvin & Hadjigeorgiou 2020). As far back as 2000, energy-absorbing bolts were not widely used even though their potential was demonstrated in simulated dynamic/impact loads under blasting conditions (Ortlepp 1969). Stacey (2016) notes that the dynamic rockbolt by Ortlepp was never implemented commercially. The *Canadian Rockburst Handbook* (Kaiser et al. 1996) only referred to the cone bolt (Jager 1992) as an example of a yielding rockbolt. The modified cone bolt (MCB) was probably the first designed energy-absorbing rockbolt to be used as part of a mine's ground support standard. The MCB design was based on the original South African cone bolt but employed resin as opposed to cement grout, making it adaptable to bolting practices in Canadian mines (Simser et al. 2007).

Although there is no universally acceptable classification system for rockbolts, it is sometimes useful to describe them as a function of the reinforcement mechanism and the installation method. A number of these rockbolt types utilise debonding agents, while others employ debonded bars with anchors that are designed to slip or plough through the chemical bonding agent. While earlier hybrid bolts used a bonding agent (Mercier-Langevin & Turcotte 2007), recent mechanical hybrid bolts do not use bonding agents (Darlington et al. 2018). Recently, self-drilling anchors that display high energy-absorbing capacity are also receiving attention (Knox & Hadjigeorgiou 2023).

The various configurations of the cone bolt absorb energy through the plastic deformation of the anchor medium. Paddled energy-absorbing rockbolts (Li 2010a), yielding mechanical hybrid rockbolts (Darlington et al. 2018), the hybrid bolt (Mercier-Langevin & Turcotte 2007), and yielding self-drilling anchors (Knox & Hadjigeorgiou 2023a) are grouped together as they all absorb energy through plastic deformation of the bar. Finally, Yield-Lok (Wu et al. 2010), Garford (Varden et al. 2008) and the He rockbolt (He et al. 2004) absorb energy through extrusion (radial plastic deformation). The behaviour of pumpable energy-absorbing rockbolts is defined mostly by primarily plastic deformation of the bar, although there is some 'ploughing' (anchor medium plastic deformation).

Although energy-absorbing rockbolts may display similar trends in performance under certain seismic loading conditions, differences in material properties, manufacturing process, configuration and other details may result in significant variations in performance. The lack of information on the performance of rockbolts in shear, discussed in Section 4.5, is a concern as the ground motion involves both a compressive and a shear wave. Finally, the ability to successfully install the rockbolt in challenging ground conditions can have a dramatic impact on the product capacity and performance and may override other considerations.

4.2 Material properties

In theory, ground support elements can be produced using different materials. However, the large majority of rockbolts are manufactured using low carbon steels containing alloying elements. The chemical composition of steel controls its strength, hardenability, formability, weldability, ductility, and susceptibility to corrosion (Hadjigeorgiou et al. 2020, 2023). Any one of these characteristics may be critical depending on the final application. Table 1 summarises advantages and limitations of selected elements in the chemical composition of carbon steel used for manufacturing rockbolts and accessories.

In practice, multiple combinations of alloying elements can be used to meet the performance requirements of steel. In this context, it is necessary to undertake trade-offs in the elements used to favour a particular mechanical property, for example, higher capacity or elongation. The selection of a particular steel composition is sometimes based on availability or as part of a conscious decision to optimise costs.

In addition to the chemical composition, the processing (including melting, cooling, and heat treatment) can change the grain of the metal and influence its tensile strength, hardness, and brittleness. Processing modifies the behaviour of a metal as it is crystalline and forms grain microstructures as it cools. Although steel is available as both hot rolled and cold rolled, rock reinforcement elements are manufactured from hot rolled steel. The process consists of heating steel slabs to an extremely high temperature, above their recrystallisation point, to soften the steel. The softened steel is then passed between powerful rollers to thin and shape the steel into its desired thickness. Cold rolling is the process of taking hot rolled steel and allowing it to cool to room temperature before passing it through rollers under significant pressure to achieve tighter tolerances and a smoother finish. Hot rolled steel is outsourced from different suppliers and is available as sheets/plates/flats and as wire/bars/sections (Figure 4). The steel is subsequently processed to manufacture rock reinforcement elements such as rockbolts, cablebolts and accessories such as nuts and plates.

Table 1 Advantages and limitations of specific elements in the chemical composition of low carbon steel used for manufacturing rockbolts (Hadjigeorgiou et al. 2020)

Element	Advantages	Limitations
Carbon (C)	Defines the strength and hardness of rockbolts	Can result in lower ductility, toughness, and machinability
Sulphur (S)	Increases machinability	Decreases weldability, impact toughness, and ductility
Manganese (Mn)	Improves wear resistance and increase strength without reducing forgeability	
Phosphorus (P)	Results in higher strength and hardness and better machinability	Results in higher brittleness
Silicon (Si)	Increases tensile and yield strength, hardness, and forgeability	
Nickel (Ni)	Increases strength and hardness without sacrificing ductility and toughness	
Chromium (Cr)	Contributes to increased strength, hardness, toughness, resistance to wear and abrasion, and reduces susceptibility to corrosion	If combined with carbon, then Cr is not available for corrosion resistance
Molybdenum (Mo)	Beneficial to the corrosion resistance of steel and furthermore increases the hardenability, toughness, and tensile strength of steel	
Vanadium (V)	Increases strength, hardness, wear resistance, and resistance to shock impact	Need a fine precipitate distribution for strengthening to be optimised


(a) (b)

Figure 4 Steel available as (a) hot rolled plate and (b) bars

The ground support industry is global, with manufacturing plants and distribution networks worldwide. This means that steel can be procured in one country, ground support elements manufactured elsewhere and then distributed worldwide. Beyond the logistic challenges of delivering ground support to remote places with sometimes only seasonal access, it is important to establish the necessary steel requirements. All steel used in ground support complies with some national and steel standard, e.g. ASTM International (ASTM; formerly American Society for Testing and Materials); European Standard (EN); National Standard of the People's Republic of China (GB); South African National Standard (SANS); Canadian Standards Association (CSA). Table 2 provides examples of national standards used in the manufacturing of rockbolts and accessories. In addition, different countries can adopt any existing standard for its purposes and several ground support suppliers may add internal requirements to the referred standard. The list is not exhaustive and is continuously evolving. Although it is implied that latest version of the pertinent standard is used, this may not always be the case. Arguably, the subtleties of the implications to ground support performance may be difficult to appreciate.

Table 2 Examples of steel grades used for manufacturing rockbolts and accessories

Standard	Designation	Profile	Application
ASTM A1011	HSLAS Grade50, HSLAS Grade 60	Hot rolled plate	Friction rock stabilisers
EN 10149	S420MC	Hot rolled plate	Friction rock stabilisers
GB 912	Q345B	Hot rolled plate	Friction rock stabilisers
EN 10149	S355MC, S420MC	Hot rolled plate	Expandable rockbolts
SANS 920	High Yield	Deformed bar	Conventional chemical anchored rockbolts
ASTM A615	Grade 60, Grade 75	Deformed bar	Conventional chemical anchored rockbolts
ASTM A706	Grade 60	Deformed bar	Conventional chemical anchored rockbolts
ASTM A416	Grade 270	7 strand cable	Cablebolts
ASTM A29	5140	Seamless tube	Self-drilling anchors
ASTM A29	5140	Billet	Self- drilling anchors
EN 10025	S450J02	Hot rolled round bar	Paddled energy-absorbing rockbolts
EN 10267	19MnVS6	Hot rolled round bar	Paddled energy-absorbing rockbolts
ASTM A1018	HSLAS Grade 50, HSLAS Grade 65	Hot rolled plate	Washer/plates
ASTM A572	HSLAS Grade 65	Hot rolled plate	Washer/plates
EN 10025	S355JR, S275	Hot rolled plate	Washer/plates

Note: ASTM International (formerly American Society for Testing and Materials); EN European Standard; GB National Standard of the People's Republic of China; SAN South African Standard.

The next step in the process is to manufacture the ground support elements. Each manufacturer adheres to its own specifications but also to some national standard chemical, mechanical, and dimensional requirements, e.g. ASTM F432 for rock reinforcement. Table 3 captures the chemical conformity requirements for steel but there are additional requirements depending on the reinforcement type, e.g. ASTM A615 for rockbolts and ASTM A416 for cablebolts that prescribe the tensile, yield strength, and elongation requirements.

It is commonly assumed that there is some means of a direct conversion between standards. However, the various steel standards are not equivalent as most of them do not provide identical ranges for the various elements. Furthermore, the tolerance level for any given element may overlap. For example, if a steel specifies less than 0.10% sulphur content while another allows up to 0.06%, are they equivalent? It is possible that small variations in steel properties may not be of significance in certain cases but may be important in specific applications.

Table 3 Chemical requirements for rockbolts and accessories (ASTM F432)

Product	Carbon, max, %		Sulphur, max, %		Phosphorus, max, %	
	Heat	Product	Heat	Product	Heat	Product
Bolts, threaded bars[A]	0.75	0.79	0.13	[B]	0.050	0.058
Hardened spherical flat, or beveled washers	0.80	0.84	0.050	0.058	0.050	0.058
Spherical or beveled washers	0.80	0.84	0.050	0.058	0.050	0.058
Baring and header plates	1.00	1.04	0.050	0.058	0.050	0.058
Steel threaded tapered plugs	0.60	0.64	0.13	[B]	0.050	0.058
Steel expansion shells	0.30	0.33	0.050	0.058	0.050	0.058

[A] Bars furnished in accordance with the chemical composition section of Specification A615/A615M may be substituted for these requirements.
[B] Check analysis for sulphur if a resulphurised steel is not technically appropriate.

A practical solution adopted by most manufacturers is to evaluate comparable steels as a function of their mechanical properties. This is the process of understanding the influence of the chemical composition based on the ground conditions, loads, corrosive environments, deformation requirements.

It is reiterated that adhesion to any standard rests with the manufacturer. This is not necessarily a bad thing in that it provides for greater flexibility. The manufacturing process can have influence on the mechanical properties of the finished product. These factors, however, reinforce the need for strict QA/QC procedures and traceability of the final product delivered at mine sites for all steps of the process.

4.3 Rockbolt configuration

It is not surprising, and is commendable, that suppliers aim to continue to improve the performance of ground support equipment. This often involves changes to rockbolt configuration. The significance of these changes is open to interpretation, especially in the case of energy-absorbing rockbolts available from multiple suppliers. The case is often made that there are intrinsic differences between products, hence there is no infringement of patent, but at the same time, the rockbolts are interchangeable. Arguably the trends may be similar, but details can be important under loading conditions. For example, in paddled energy-absorbing rockbolts, the location of the paddles is critical as they influence the stretch. There is also a recent trend for manufacturers to optimise and ensure compatibility between installation equipment and ground support.

4.4 QA/QC of manufactured rockbolts and accessories

The discussion in the previous section illustrates the need for a comprehensive QA/QC program for manufactured rockbolts. In practice, most suppliers have their own standards that are often developed based on their experience and corporate culture. In the absence of an independent audit, it is difficult to establish the level of applied diligence. From a mining company perspective, a useful indication would be verification that a ground support manufacturer is ISO 9001 certified. This implies that they have put effective QC processes in place, trained staff, and documented evidence of adherence to the process.

There are a number of inconvenient truths associated with the QA/QC of ground support. The current trend towards centralised procuring departments, with sometimes limited communication with ground support engineers, is not optimal. It is not always evident that a mine will replace all ground support elements that failed the defined QA/QC standards. There will always be an argument to overcome if it requires a stop in production, e.g. rehabilitation of a ramp.

4.4.1 *Non-destructive and destructive testing*

In addition, it is necessary to review the details of a QA/QC program that typically includes both non-destructive and destructive testing. Non-destructive tests aim to establish whether the manufactured rockbolts comply with the configuration guidelines (e.g. dimensions, thickness, etc.) (Figures 5 and 6). Beyond manual testing, certain manufacturers are beginning to employ automated scanning systems to test for geometric compliance.

Figure 5 Examples of non-destructive geometric tests for rockbolts to verify compliance

(a) (b)

Figure 6 Examples of non-destructive geometric tests for nuts. (a) Acceptable; (b) Rejected

As part of the QA/QC process, a number of destructive tests are undertaken at the manufacturing plants. These typically follow a selected standard, e.g. ASTM Designation F432, ISO 6892, e.g. Figure 7. The results of these tests are typically supplied on delivery of requisitioned ground support elements at mine sites. Unfortunately, these valuable data are often not reviewed by the ground control teams.

(a) (b)

Figure 7 Destructive quality assurance/quality control testing. (a) Rockbolt elongation behaviour and ultimate capacity of rockbolt; (b) Plate ultimate deformation and capacity

The frequency and tolerance for both non-destructive and destructive testing differs between manufacturers. Typically, testing protocols are developed following internal cost benefit analyses and can vary depending on the reinforcement and accessory type. A comprehensive compliance program includes the number of tests per production line, steel heat, etc. It is not uncommon that stringent guidelines are enforced at the beginning of the roll out process, but the frequency of testing may vary subsequently. A QA/QC should clearly outline all requirements, the rationale, and follow up actions if the desired compliance thresholds are not met. This information should be taken into consideration by mines when comparing ground support elements from multiple suppliers. The selection of ground support elements should be based on multiple factors that go beyond unit cost.

4.4.2 Susceptibility to corrosion

In addition to the mechanical properties of the steel, in certain cases, its susceptibility to corrosion may become critical (Hadjigeorgiou 2020, 2023). Table 4 lists the chemical composition compliance requirements for Grade 60 Class 2 steel that is often used in friction rock stabilisers. A cursory look shows what elements should be present and the assigned tolerances. The reality is that in a global ground support industry and markets, any one of the standards in Table 2 may be used.

Table 4 Compliance requirements for chemical composition Grade 60 Class 2 steel, A1011

Element	**C**	**S**	**Mn**	**P**	**Si**	**Cu**	**Ni**
Requirement	0.15 Max	0.04 Max	1.5 Max	0.04 Max	–	0.2 Max	0.2 Max
Element	**Cr**	**V**	**Mo**	**Al**	**Co**	**Ti**	**Pb**
Requirement	0.15 Max	0.005	0.06 Max	–	–	0.005 Min	–

Although issues of mechanical performance are addressed as part of a rigorous procurement process, the susceptibility to corrosion has not received the same level of attention. This, however, becomes a priority when the degradation of ground support in aggressive corrosion environments contributes to falls of ground. Hadjigeorgiou et al. (2023) report the results of a comprehensive investigation of three 'equivalent' friction rock stabilisers (FRS) where the intent was to use them interchangeably at one specific mine site where susceptibility to corrosion was perceived as an issue.

The chemical composition of each rockbolt outsourced from the three manufacturing plants is presented in Table 5. The carbon and sulphur analysis followed ASTM E1019 while for the remaining elements, it was determined by inductively coupled plasma atomic emission spectroscopy (ICP-AES) after ASTM E1479. In addition, accelerated corrosion techniques (open circuit potential, linear polarization resistance, and potentiodynamic anodic polarisation [AP]), were used to establish the performance of the rockbolt options when exposed to an aggressive corrosion environment (Table 6). The Rockwell B hardness was used to compare the mechanical steel properties of the material.

Table 5 Chemical composition of steel used for manufacturing friction stabilisers from the same supplier

Element	**C**	**S**	**Mn**	**P**	**Si**	**Cu**	**Ni**
FRS 1	0.187	0.060	0.800	0.012	0.010	0.040	0.020
FRS 2	0.064	0.002	0.585	0.013	0.011	0.010	0.002
FRS 3	0.185	0.010	0.370	0.017	0.010	0.010	0.010
Element	**Cr**	**V**	**Mo**	**Al**	**Co**	**Ti**	**Pb**
FRS 1	0.050	<0.010	<0.010	0.040	<0.010	<0.010	<0.010
FRS 2	0.022	<0.010	<0.003	0.038	<0.010	0.084	<0.010
FRS 3	0.030	<0.010	<0.010	0.010	<0.010	0.030	<0.010

Table 6 Results from accelerated corrosion and Rockwell B hardness tests (Hadjigeorgiou et al. 2021)

Rockbolt	R_p (Ω cm^2)	$I_{corr, Rp}$ (mA cm^{-2})	$r_{, Rp}$ (mm yr^{-1})	I_{corr} (mA cm^{-2})	r (mm yr^{-1})	Rockwell B Hardness
FRS 1	37.9 ± 3.7	0.745 ± 0.048	8.66 ± 0.56	0.321 ± 0.017	3.72 ± 0.20	79.3 ± 0.7
FRS 2	51.5 ± 4.2	0.533 ± 0.035	6.20 ± 0.40	0.276 ± 0.039	3.20 ± 0.45	97.4 ± 0.6
FRS 3	47.8 ± 8.0	0.581 ± 0.100	6.76 ± 1.16	0.271 ± 0.034	3.15 ± 0.39	91.2 ± 0.3

Note: Polarisation resistance ($_{Rp}$); estimated corrosion rate ($I_{corr, Rp}$); polarisation resistance corrosion rate; corrosion rate (r); corrosion current density (I_{corr})

FRS 1 was the most susceptible to corrosion and had the lowest Rockwell B hardness test value compared to the other rockbolts. The significant variation in performance between FRS 1 and the other 'similar' rockbolts was due to differences in their chemical composition (see Table 5). It was evident that 'similar' rockbolts could not be used interchangeably given the inferior performance of rockbolt 1. The decision was made as a result of a transparent interaction between manufacturers and the ground control team. It should be emphasised that the performance of ground support in corrosive environments is a very complex process and multiple factors come into play (Dorion & Hadjigeorgiou 2014; Hadjigeorgiou et al. 2019, 2020).

4.4.3 Traceability

It is important to be able to trace the origin of any batch of ground support elements delivered at a mine site. This becomes apparent when one considers the multiple sources of supplies, variations in steel quality, and differences in QA/QC mechanical and geometrical requirements. The need for a traceability process at the mine site is highlighted during rockburst investigations where it is sometimes a struggle to establish both the source of ground support and reliable timelines of installation, monitoring, etc.

4.5 Behaviour of rockbolts under different loading conditions

It is somewhat surprising that our understanding of the behaviour of rockbolts has been shaped from a very limited number of quasi-static laboratory pull tests in a concrete block reported by Stillborg (1993). These results have been collated in a single graph by Hoek at al. (1995) and routinely reproduced with the occasional addition of other types of rockbolts, e.g. Li et al. (2014). Stjern (1995) provided some of the earlier results of the performance of rockbolts in both tension and shear. Li et al. (2014) reproduced the results of Stjern (1995).

Although impact testing has been around for some time (Hadjigeorgiou & Potvin 2011), it is only after the industry demand for 'certification of new elements' that there has been a greater demand for impact or drop testing. There are currently six operating testing rigs worldwide and a mobile testing rig that can be used in situ (Knox 2023).

The proliferation of multiple quasi-static and impact testing rigs underscores the need for consistent reporting and interpretation of the results. Figure 8 defines the metrics for an axial quasi-static test while Figure 9 is based on earlier work by Li et al. (2021) for drop tests.

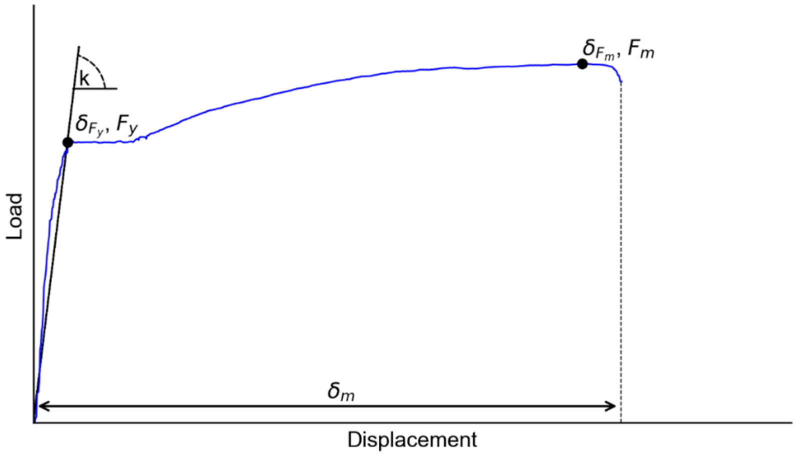


Figure 8 Load–displacement curve from quasi-static pull test: displacement at yield load (δ_{Fy}); yield load (F_y); displacement at ultimate load (δ_{Fm}); ultimate load (F_m); ultimate displacement (δ_m); Secant stiffness (k)

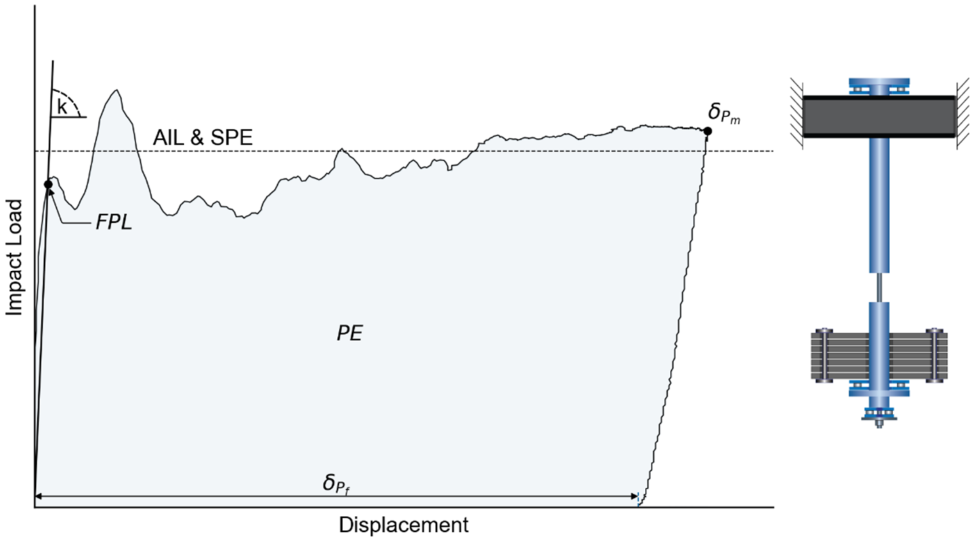


Figure 9 Impact load–displacement curve: first peak load (FPL); average impact load (AIL); specific energy absorption (SPE); maximum plate displacement (δ_{Pm}); final plate displacement (δ_{Pf}); plastic energy absorption (PE) (modified from Li et al. 2021)

4.5.1 Quasi-static testing on rockbolts

There are several types of quasi-static tests that are used to determine the behaviour of rockbolts under axial, shear, double shear and combined shear and axial loading. A convenient way to classify the tests is a function of the confining medium, e.g. steel pipes or concrete blocks. Another consideration is the ability to test full size rockbolts. Although it is possible to gain some insights from small-scale tests, they invariably introduce a significant degree of bias. The test configuration and testing methodology can significantly influence the results. Consequently, comparison of results should be made with caution.

Until recently, there was a significant knowledge gap regarding the performance of energy-absorbing rockbolts under quasi-static conditions. Doucet & Voyzelle (2012) report pull tests conducted in metal pipes (Figure 10). Chen & Li (2015) report the results of both tensile and shear using the SINTEF block system (Figure 11a) while Knox & Hadjigeorgiou (2023a, 2023b) employed the Epiroc rig (Figure 11b). The choice of tests in steel pipes or concrete blocks is significant and should be taken into consideration when interpreting the results.

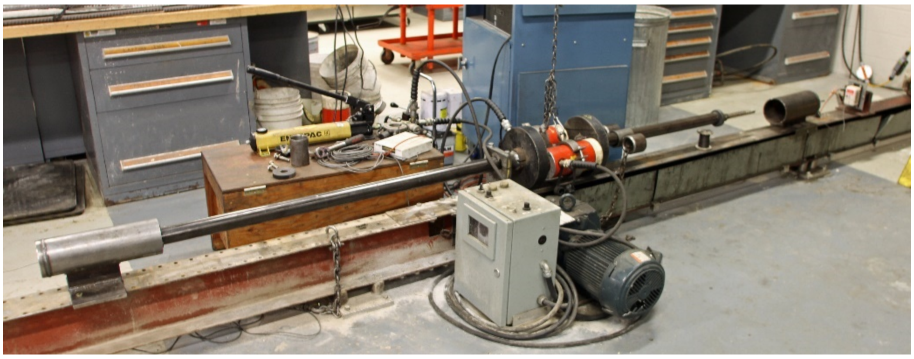
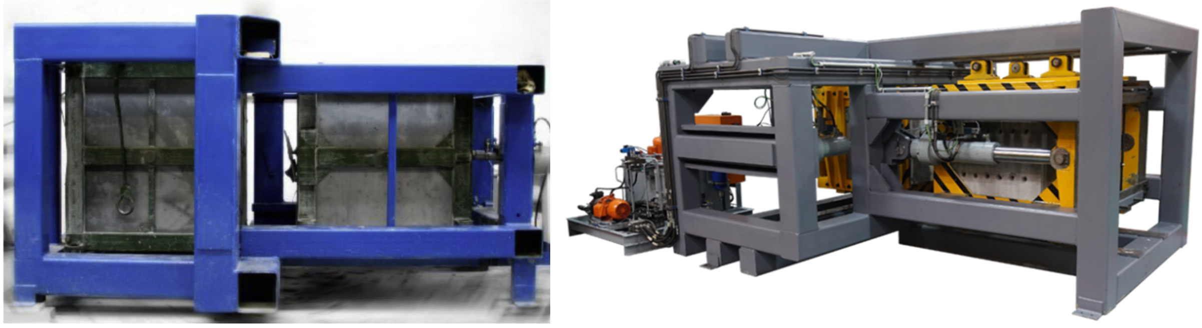


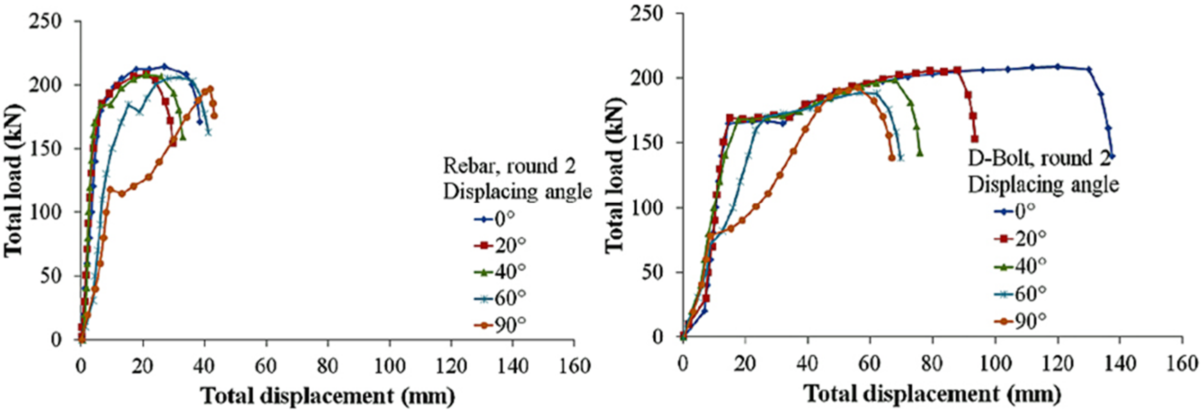
Figure 10 Quasi-static axial tests in steel pipes at CanmetMINING



(a) (b)

Figure 11 Combination shear and tensile rockbolt testing rig. (a) SINTEF; (b) Epiroc rig

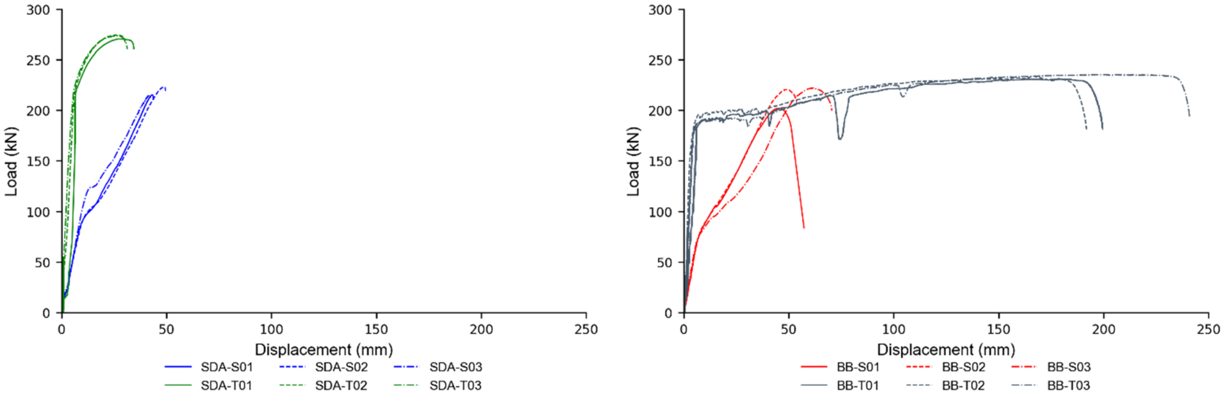
A possible explanation for the scarcity of data on the shear capacity of energy-absorbing rockbolts is that when first introduced, the emphasis was to ‘certify’ specific products under axial impact testing. Consequently, the limited laboratory tests are tensile pull tests with no information on their behaviour in shear. This is problematic given that rockbolts subjected to seismic loads appear to fail both under tension and shear loadings. To the knowledge of the author, there are no laboratory results on the MCB under shear, and the first published shear tests on paddled energy-absorbing rockbolts were conducted by Chen & Li (2015) on the D-bolt (Figure 12) and were only in 2015. This comprehensive study illustrated both the higher energy absorption capacity of paddled energy-absorbing rockbolts as well as their improved performance in shear. In addition, it illustrated the performance of combined shear and loading mechanism on rockbolts that is more representative of loading conditions observed in the field. This is an area that should be explored further for all rockbolt types.



(a) (b)

Figure 12 Shear and tensile load–displacement for (a) D-bolts and (b) rebar bolts (Chen & Li 2015)

Recent work aims to address this knowledge gap with respect to energy-absorbing rockbolts that can be used for a range of ground conditions. For example, self-drilling anchors (SDA) offer a practical alternative to overcome hole closures and blown-out holes as the rockbolt is not removed from the borehole and is post-grouted. In rockburst prone ground conditions, however, there may also be a need for energy-absorbing SDA. Figure 13 compares the performance of conventional and energy-absorbing SDA under tensile and shear loads (Knox & Hadjigeorgiou 2023a). In both cases there was a reduction in shear as compared to tensile capacity for both bolts. Of interest is that the laboratory tests revealed that the shear resistance of hollow core SDA is greater than previously assumed (Watt et al. 2018).



(a)

(b)

Figure 13 **Shear and tensile load–displacement response curves. (a) Conventional self-drilling anchors (SDA) samples; (b) Energy-absorbing SDA samples (Knox & Hadjigeorgiou 2023a)**

Mechanical hybrid bolts that do not use resin have obvious operational benefits. However, the focus in the past has been on axial quasi and impact tests as part of the drive to 'certify' new rockbolts for use in seismic conditions. Recent tests by Knox & Hadjigeorgiou (2023b) provided the first indication of the performance in shear of mechanical hybrid bolts (Figure 14). It is also important to note the relative higher shear resistance of mechanical hybrid bolts compared to their tensile capacity.

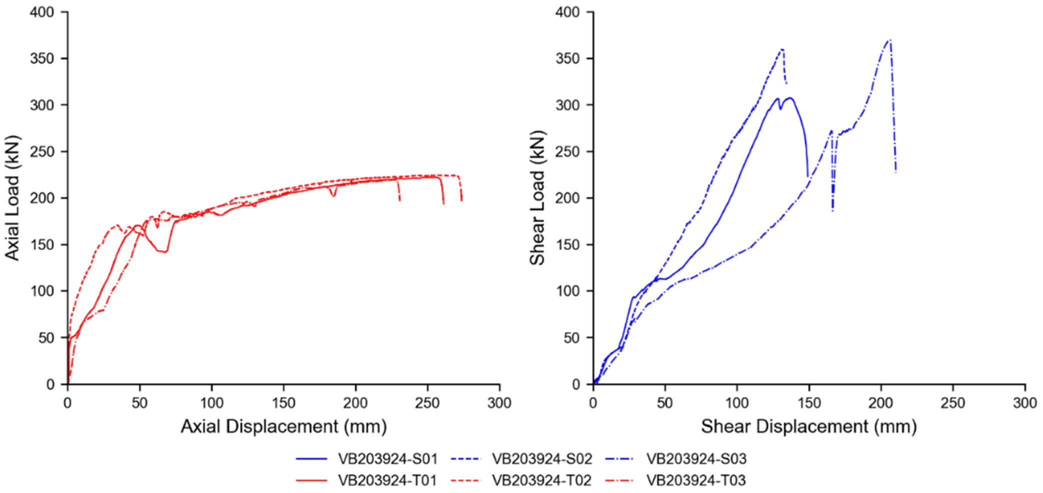


Figure 14 **Load–displacement response of the mechanical hybrid rockbolt under axial and shear loading cases (Knox & Hadjigeorgiou 2023b)**

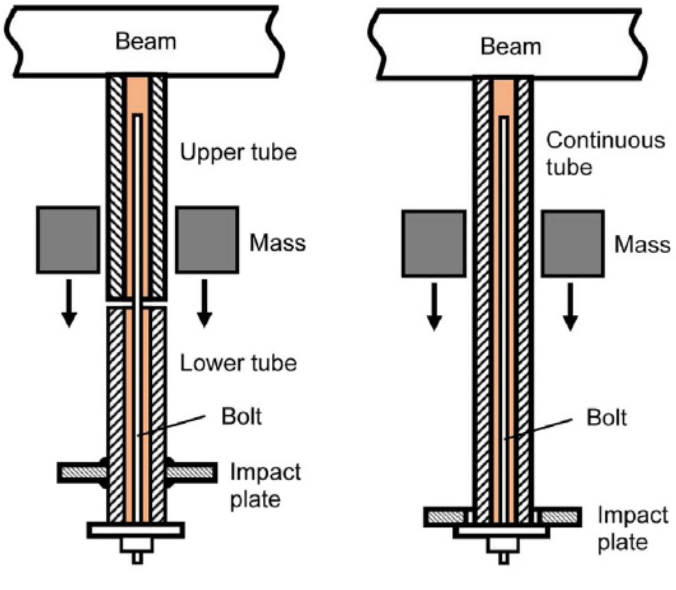
The described investigations demonstrate the superior energy absorption capacity, under controlled quasi-static conditions in the laboratory compared to conventional rockbolts. The need for an improved understanding of their behaviour in shear is critical given that ground motion involves a compressive wave and shear wave as well as the presence and orientation of rock joints. The practice of assuming a tensile/shear ratio for rockbolts in more sophisticated numerical modelling analyses is clearly a concern. This ratio is clearly a function of the rockbolt characteristics and host material.

4.5.2 Impact testing on rockbolts

It should be recognised that in the *Canadian Rockburst Handbook* (Kaiser et al. 1996) the provided energy-absorbing capacity values were derived under quasi-static conditions as these were the only available data at the time. However, the correlation between energy capacity from quasi-static and impact testing has yet to be satisfactorily established.

The introduction of energy-absorbing rockbolts generated a need for laboratory testing conditions (Hadjigeorgiou & Potvin 2011). It is desirable to have reliable data to understand and quantify the performance of ground support under impact loads. This was the motivation of some of the early work by Ortlepp & Stacey (1998) in South Africa. Since the latest benchmarking study of testing rigs by Hadjigeorgiou & Potvin (2011), several new rigs have been commissioned and there is a wealth of data for new rockbolts. Most testing rigs currently in operation use the 'mass freefall impact testing' with the Western Australian School of Mines (WASM) rig (Player et al. 2008) using the 'momentum transfer' method. In fact, both methods employ the potential energy by raising a known mass to a known height (Li 2018; Potvin & Hadjigeorgiou 2020; Knox 2023).

In Figure 15a a split tube configuration is used to simulate the loading condition of a rockbolt when a rock is ejected by an impact thrust. The continuous tube (Figure 15b) simulates the situation when the impact load is directly applied to the plate (Li et al. 2021). It is a common requirement of mining companies that prior to the use of any energy-absorbing rockbolts on site, tests results are provided using both split and continuous tube testing configurations. Recent work by Li et al. (2024) aims to reduce the uncertainty in impact testing in the laboratory by providing guidelines for consistent testing and reporting procedures.



(a) (b)

Figure 15 Impact test arrangements. (a) Indirect split tube; (b) Direct continuous tube (Li et al. 2021)

Several authors, including Stacey & Ortlepp (2007), Potvin et al. (2010) and Potvin & Hadjigeorgiou (2020), have compiled the results from multiple rigs while Villaescusa et al. (2015) reported the results from the WASM rig. Figure 16 illustrates that conventional (non-yielding) reinforcement elements consistently displayed low energy absorption (between 0 and 20 kJ) and low displacement (between 0 and 100 mm) compared to energy-absorbing rockbolts. Of interest is that the data scatter of individual tests for 'similar bolts' is significant. This underscores the need for addressing the specifics of each testing rig and procedures that evolved with time and the details of 'similar bolts'.

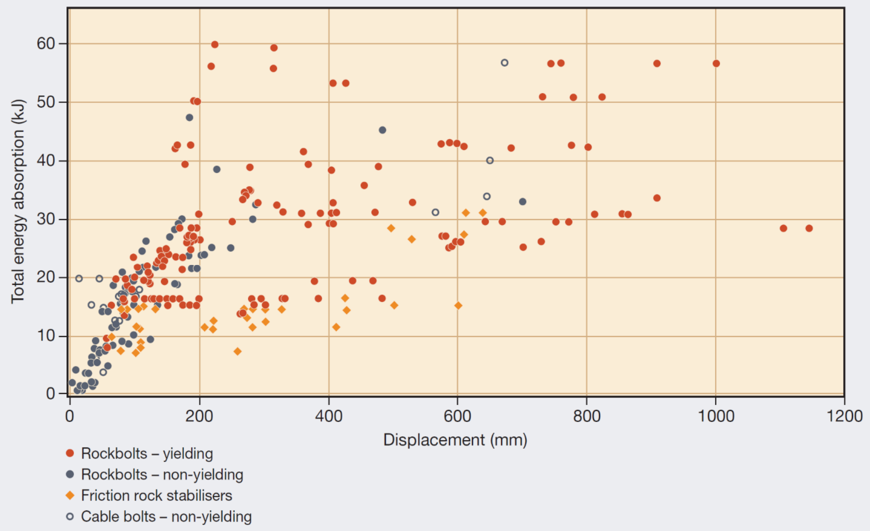


Figure 16 **Compilation drop tests from different rigs on yielding reinforcement (red), non-yielding (grey) and friction rock stabilisers elements (orange) (Potvin & Hadjigeorgiou 2020)**

Li et al. (2021) provided the only quantitative comparison between different rigs (Figure 17). A series of impact tests of identical thread bar rockbolts was carried out using the direct impact method (i.e. the mass freefall method) on the rigs in four laboratories in different countries. The intent of the tests was to test the consistency between the rigs rather than the performance of the rockbolts. To avoid bias associated with installation quality, the rockbolts were not encapsulated in holes but directly suspended at their upper ends. Although most rigs demonstrated a high level of repeatability, there was noticeable equipment-dependent bias when test results obtained from different laboratories were compared. It is anticipated that there is greater variation between energy-absorbing rockbolt results obtained at different rigs.

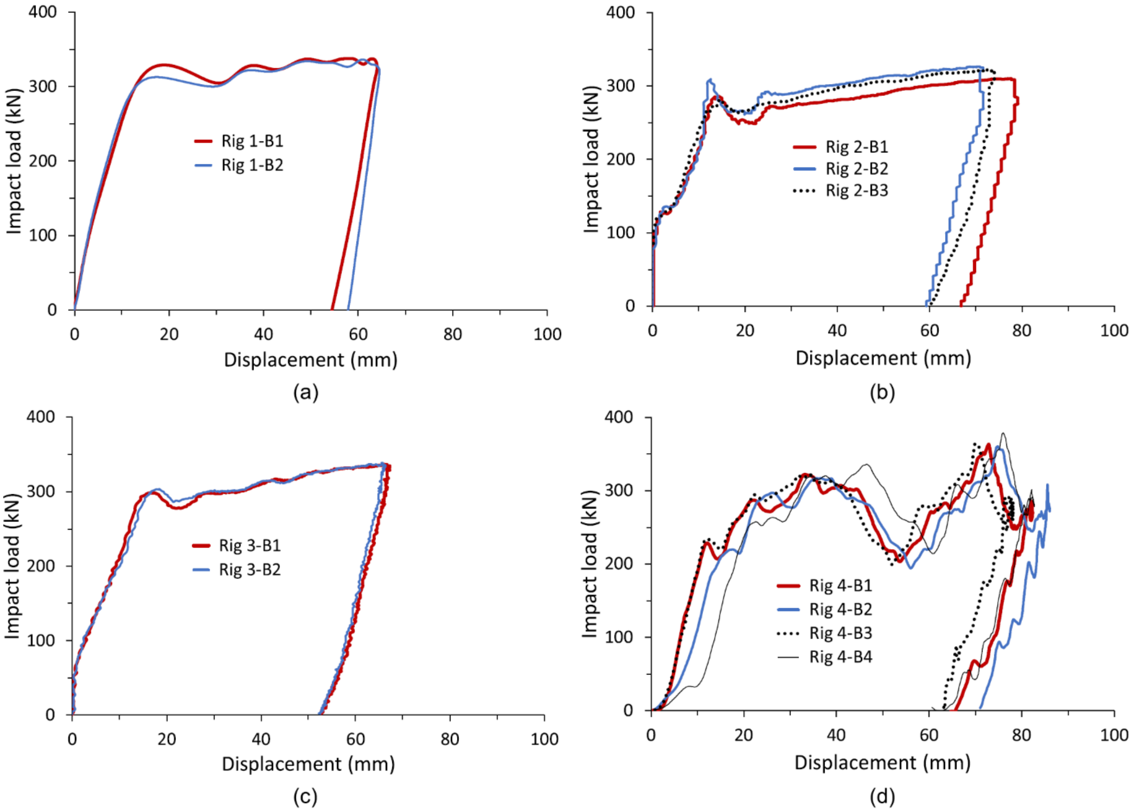


Figure 17 **The impact load versus displacement for the bolt samples tested on (a) Rig 1; (b) Rig 2; (c) Rig 3; (d) Rig 4 (Li et al. 2021)**

A comprehensive discussion on instrumentation and data acquisition requirements for impact testing rigs has been provided by Knox (2023) including strategic location of high frequency response piezo-electric load cells to capture impulse during loading. In addition, line scan and high-speed cameras capture the displacement while also discussing the choice of filters to treat the results.

The performance of energy-absorbing rockbolts is typically determined using direct impact continuous tube and indirect impact testing configuration with the split centrally located, Figure 16. Although none of the testing systems can reproduce the rockburst mechanism, they provide a comparative basis on performance under axial impact loading on a particular testing rig. It is an inconvenient truth that the energy absorption obtained from axial impact tests may not be representative of a rockbolt's dynamic capacity.

Knox & Hadjigeorgiou (2022) explored the influence of the location of the split along the length of the tube for paddled energy-absorbing rockbolts (Figure 18) and the results are summarised in Table 7. The location of a rupture point in the paddle set relative to the split in the host tube is shown in Figure 19.

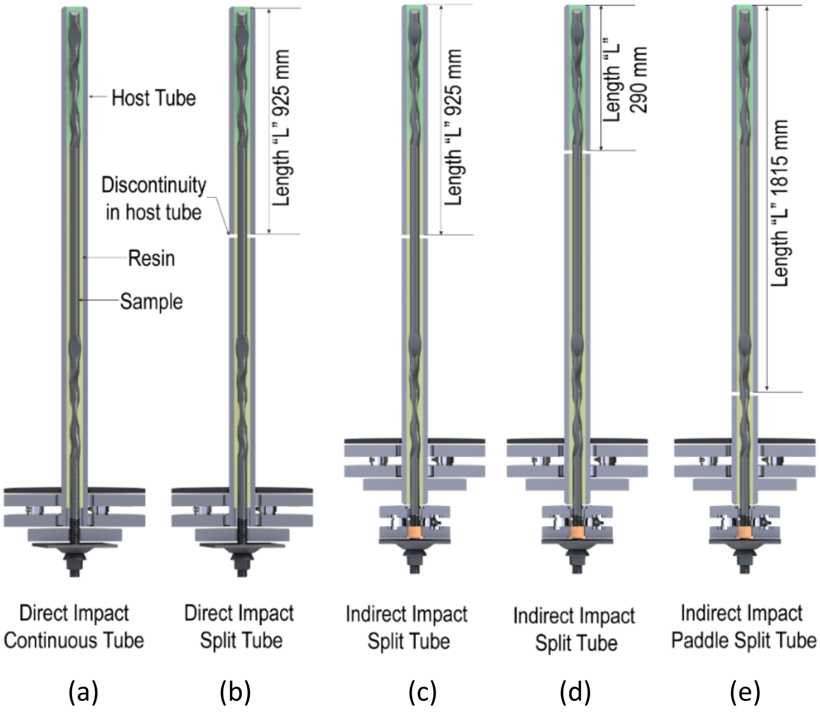


Figure 18 Different testing configuration for paddled energy-absorbing rockbolts (Knox & Hadjigeorgiou 2022)

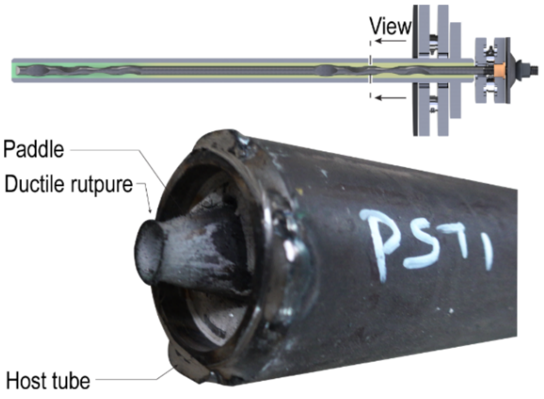


Figure 19 Rupture of the bar on the distal side of the split during an indirect impact paddle split tube test (Knox & Hadjigeorgiou 2022)

Table 7 **Influence of split location on total energy dissipated per sample (E_{total}) (Knox & Hadjigeorgiou 2022)**

Sample	Split location	Avg. E_{total} (kJ)
Direct impact continuous tube	No split	12
Direct impact split tube	At the centre of the distal stem L = 925 mm	52
Indirect impact split tube	At the centre of the distal stem L = 925 mm	56
Indirect impact split tube	At the distal stem L = 300 mm	49
Indirect impact paddle split tube	Between P2 & P3 of the proximal paddle set L = 1845 mm	6

This investigation demonstrated that the location of the split along the length of the rockbolt can have a significant influence on the results of paddled energy-absorbing rockbolts that has not previously been recognised. As shown in Table 7, the total energy dissipated per sample for paddled energy-absorbing rockbolts can vary from 6 to 56 KJ depending on the test configuration and location of the split. This underscores the challenge of selecting reliable input data for analysis and design purposes.

4.6 Behaviour of surface support and ground support systems under different loading conditions

4.6.1 Quasi-static testing on mesh

It is well recognised that mesh is often the weakest link in a ground support system in both static and dynamic conditions (Simser 2007; Hadjigeorgiou & Stacey 2018; Morkel et al. 2023). Although the results at different testing facilities can arguably illustrate differences in performance between mesh, the quantitative results are strongly influenced by the testing configuration such as boundary conditions (Figure 20), loading mechanism (pull or push), and size and shape of loading device.

(a) (b) (c)

Figure 20 **(a) Mesh tied to the testing rig frame; (b) Mesh shackled to the frame (Morton et al. 2007); (c) Mesh constrained by bolts and plates (New Concept Mining)**

This was demonstrated by Baek et al. (2020) using well calibrated 3D discrete element numerical models to determine the impact of testing rig configurations, including loading plate dimensions and orientation, and mesh dimensions, e.g. Figure 21. This has significant practical implications on how to interpret results obtained from different testing rigs and highlights the challenge of using laboratory results as input to analyses.

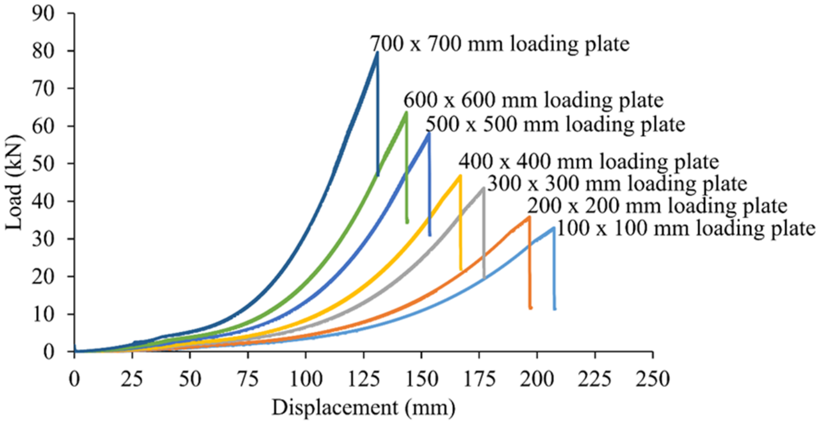


Figure 21 Axial load and displacement for a mesh size of 1.3 × 1.3 m for different loading plate dimensions (Baek et al. 2020)

It is recognised that the current quasi-static testing of mesh does not capture field conditions and makes comparison between testing facilities impractical (Hadjigeorgiou & Stacey 2018l; Morkel et al. 2023).

4.6.2 Impact testing on ground support systems

The complex mechanisms and interactions of a rock mass with the different elements used in ground support systems cannot be accurately replicated in a laboratory environment. Consequently, the early interest in the use of in situ dynamic testing by submitting ground support systems to strong ground motion generated by one or several carefully designed blasts. A review of field studies recognised the challenges in designing representative experiments given that rock breaking mechanisms in a blast are associated with gas expansion whilst seismic events exclusively generate stress waves (Hadjigeorgiou & Potvin 2007). Heal (2010) undertook a series of blasting experiments and noted inconsistencies between the obtained results and published drop test results on surface support systems. There have been limited in situ dynamic testing blasting studies in recent years, probably due to the challenges in designing, implementing, and interpreting the results.

Although existing testing rigs cannot reproduce the complexity of seismic loads on ground support, large-scale impact tests can investigate the retainment capacity of surface support and the interaction between reinforcement and surface support. Stacey & Ortlepp (1999, 2007) provided some of the earlier data on the performance of different surface support configurations under impact loads.

While there is an increasing wealth of individual reinforcement and surface support elements, data on ground support systems are limited. The Walenstadt testing rig (Roth et al. 2014) is arguably the only source of published ground support system data from drop tests in recent years. Valuable insights include investigating the compatibility between different reinforcement and surface support elements (Roth et al. 2014). Subsequently, the testing rig has been used to compare the performance of site-specific ground support systems under impact, e.g. Brändle & Luis Fonseca (2019) and Brändle et al. (2022). The test results also emphasise the influence of load distribution between reinforcement and surface support elements on system performance.

4.7 In situ axial pull tests

It is standard practice in ground control management plans to describe QA/QC requirements for ground support. In situ pull testing is only one element of a comprehensive testing program. A distinction needs to be made on the intent for in situ pull tests that can be used to establish the behaviour of new reinforcement elements, verify compliance of bolt performance with respect to manufacturer specifications or part of a long-term QA and QC strategy. Establishing clear objectives is necessary to design a fit-for-purpose testing program. It is an inconvenient truth that several mines implement the same frequency of tests for all rockbolt types. This is clearly not optimal as certain rockbolt types, e.g. FRS, are more susceptible to QA/QC issues and a higher testing frequency is necessary.

Hadjigeorgiou & Tomasone (2018) compiled and analysed pull tests results from hard rock mines in Ontario, Canada, to construct characteristic load–displacement plots (Figure 22). Similarly, they produced distributions for ultimate capacity that can be useful in the design of ground support standards for static loading conditions. The first step is the selection of an appropriate, or acceptable, percentile of performance for the displacement response and capacity. This value will be a function of the stage of the project (feasibility, design, operation, etc.) and the quality and quantity of all pertinent geomechanical data.

Although charts such as the one presented in Figure 22 are useful, it should be acknowledged that the data were collected from multiple mines in different geomechanical domains. It was also observed that destructive pull tests of 'similar' rockbolts typically display great variation in the obtained load–displacement curves in different geomechanical domains (Hadjigeorgiou & Tomasone 2018).

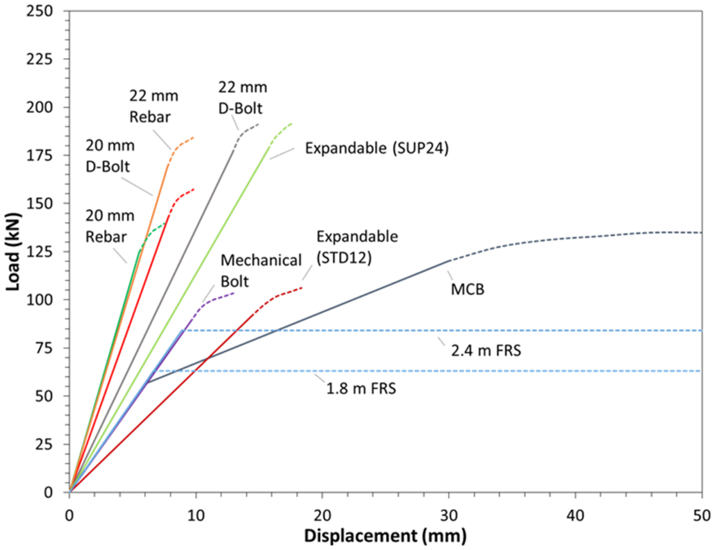


Figure 22 Load–displacement plots of rockbolts from in situ pull tests (Hadjigeorgiou & Tomasone 2018)

Other factors would come into play for more sophisticated numerical analyses where variations in rockbolt stiffness as a function of geomechanical domain is significant (Tomasone et al. 2020). Despite the challenges of destructive in situ pull testing, they are necessary to better understand the behaviour of energy-absorbing rockbolts studies in different ground conditions. This is a prerequisite if the long-term objective is to implement realistic rockbolt behaviour in explicit numerical models.

5 In situ ground support performance

It is a significant challenge to fully capture the ground support performance under seismic incidents. This is necessary, however, to reduce the epistemic uncertainty associated with ground support design. The objective is to accurately understand the ground support behaviour and develop improved strategies and new technologies. These are not easy tasks and can not be achieved alone by any one method discussed in this paper. It is necessary to reconcile all steps of the ground support process from manufacturing, design, performance under controlled conditions, installation, and performance during seismic loading.

5.1 Qualitative observations

Our understanding of the performance of ground support in deep and high-stress mines has evolved based on well-articulated field observations. Ortlepp and his colleagues provided early visual evidence of the advantages of yielding support introducing concepts such as 'naked tendon', 'protruding rockbolts' (Figure 23). Counter (2014) provided some of the earlier examples of improved performance of dynamic ground support under high seismic load (MN3.8) when the mine upgraded its existing ground support following a large seismic event. The rehabilitated area was hit by a second MN3.8 event but damage was significantly reduced compared to the first large event.

Visual observations of ground support performance by several authors including Li (2010b), Simser (2018, 2019), and Morkel et al. (2023) improved our understanding while Simser (2007) documented the role of the weakest link in a ground support system which is often the mesh (Figures 24 and 25). Drover & Villaescusa (2016) provided examples of installation issues associated with resin mixing that adversely affected the performance of grouted rockbolts during rockbursts. It was suggested this could be mitigated using a spiral mixing device or mechanised pumpable systems.

Qualitative observations are most useful when they can be reconciled with a good understanding of the rockbolt behaviour gained from controlled laboratory experiments. This was demonstrated in inconsistent behaviour of modified cone bolts at different mine sites where their effectiveness was limited when exposed to rockburst after significant static deformation had already taken place (Simser et al. 2007). The laboratory experiments confirmed that static deformation almost invariably causes some pinching of the bar that largely prevents any subsequent cone ploughing effect. This explains why modified cone bolts arguably perform best under rockbursting conditions when little deformation prior to the event occurs. Similarly, the work of Knox & Hadjigeorgiou (2022) can provide valuable insights on the in situ performance of paddled energy-absorbing rockbolts.

Figure 23 Examples of 'naked tendons' photographs taken by WD Ortlepp (Stacey 2016)

Figure 24 Examples of 'weakest link' in a ground support system (Simser 2007)


(a) (b)

Figure 25 Examples of mesh failures. (a) Tearing at the bolt–mesh interface including shotcrete and rockbolt failure; (b) Mesh overlap failure (Morkel et al. 2023)

Our understanding of the performance of shotcrete as part of a ground support system in seismically active mines has evolved. An inherent advantage of shotcrete is that it provides a reaction to excavation boundary deformation, preserving the confinement of the rock mass and its self-supporting attributes. Morissette et al. (2014) demonstrated that beyond a certain threshold of loading, the effectiveness of stand-alone shotcrete is diminished. This is due to its relatively high stiffness and brittle behaviour that results in the development of cracks in shotcrete under high static and dynamic loads. Drover & Villaescusa (2015) relied on field observations and a review of static and dynamic test results at WASM and concluded that increased performance can be attained by using shotcrete in conjunction with steel mesh, installed either externally or fully encapsulated within the shotcrete (Figure 26).

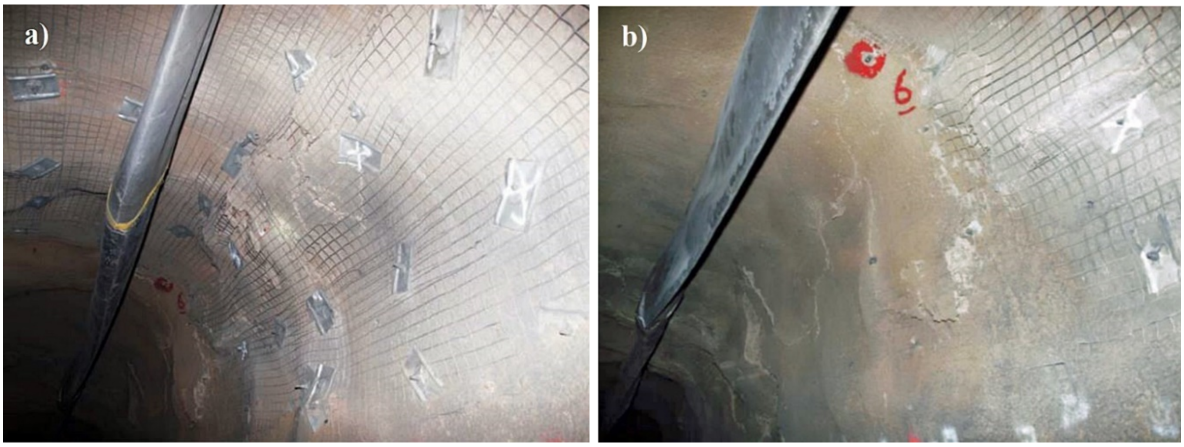


Figure 26 (a) Fibre-reinforced shotcrete; (b) Mesh-reinforced shotcrete (Drover & Villaescusa 2015)

5.2 Interrogating rockburst databases

Given current limitations of engineering analysis for rockburst conditions, there are advantages of looking at the performance of ground support systems over time. General guidelines have been developed by Heal (2010) based on case studies from multiple sites. Examples of site-specific guidelines include the empirical charting (Mikula & Gebramedhin 2017) and passive monitoring (Morissette & Hadjigeorgiou 2017, 2019) methods. Both methodologies are transferable to other mine sites provided adequate quality data are reported and the database is continuously updated to include ground support strategies that also evolve with time. Heal (2010) provided a breakdown of what component of the ground system failed in his rockburst database. Morissette et al. (2017) interrogated their database and identified common weaknesses in ground support systems under seismic load, during design, installation, and implementation (Figure 27). It is interesting to note that even though the rockburst database only included case studies from before 2014, the general lessons are still applicable.

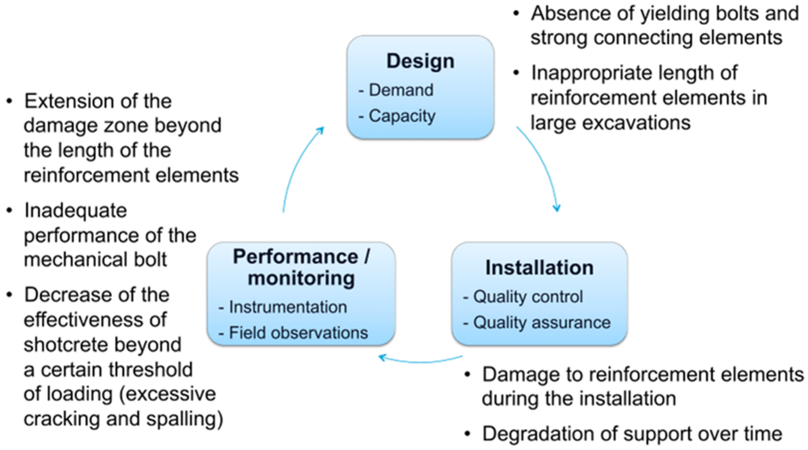


Figure 27 Typical causes of ground support failure under dynamic loads and the associated phases of the ground support cycle (Morrisette et al 2017)

It is tempting to combine rockburst databases from multiple sources. An inconvenient truth is that the necessary data are not always collected consistently at every mine (missing information) or even with the same diligence (lack of expertise or adequate resources) over time. There is invariably a high degree of uncertainty within a database that only increases when combining databases.

5.3 Rockburst investigations

In certain jurisdictions, it is a legislative and often a corporate requirement to investigate major rockburst events. The scope of these investigations can vary significantly and includes both process and technical factors. From a risk mitigation perspective, it is the performance of ground support and exclusion protocols that are the most important control measures.

This section does not discuss the requirements for a multidisciplinary rockburst investigation but highlights certain elements specific to ground support. These include identifying how the ground support failed. A non-exhaustive list should include the following:

- Rock reinforcement elements. This should include details on which element failed in case of multiple elements installed.
- Surface support elements (nuts on rockbolts, barrel and wedge on cablebolts, plates, mesh/screen and straps).
- Inadequate length of reinforcement for the resulting failure. A comprehensive review of rockbursts in the Sudbury basin, Canada, by Morissette et al. (2014) indicated the installation of cablebolts tended to enhance the overall performance of the support system in large excavations.
- Connectivity between the ground support elements. None of the elements will perform well unless there is effective load transfer.

In this context, irrespective of the energy-absorbing characteristics of any element, the ground support system will not reach its full potential unless all elements are well connected with effective distribution between the various elements. This is discussed in the following sub section.

5.3.1 Connectivity of ground support elements

It is a significant challenge to extrapolate the performance of ground systems based on ground support data from a controlled testing environment for individual elements. Unless the connecting elements between them perform equally well, the system will not be effective. Traditionally, the primary ground support functions have been identified as reinforce, retain, and hold (Kaiser et al. 1996) but this has been updated to explicitly identify connectivity as a major function in rockburst ground conditions (Figure 28.)

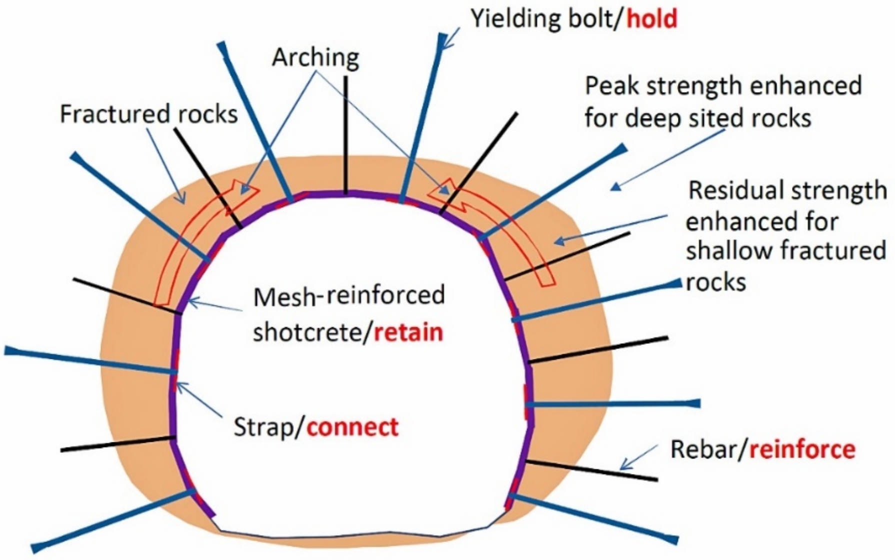


Figure 28 Four functions required to provide a reliable support system for rockburst prone ground: retain, reinforce, hold, and connect (Kaiser & Cai 2013)

Morissette et al. (2017) noted that in large excavations, the installation of cablebolts tended to enhance the overall performance of the support system, resulting in mitigating the severity of damage following rockbursts. These are only effective if they are well installed (Figures 29 and 30). Connecting elements include nuts on bolts, the barrel and wedge systems for cables, the face plates, and straps.

Surface fixtures consisting of a face plate and tensioned barrel/wedge assembly installed to each individual cable strand are an essential requirement for dynamic loading conditions as they provide load transfer from the rock mass and surface support to the cable reinforcement (Drover & Villaescusa 2016). Although it may sometimes be considered inconvenient, plating all cablebolts is critical in relatively deep zones of stress-fractured ground where the ground support is subject to seismic loads.

(a) (b)

Figure 29 (a) Non-plated cablebolts; (b) Cablebolts de-bonded at the collar resulting in the loss of connection between the plate and rock face, causing ineffective reinforcement

(a) (b)

Figure 30 (a) Failure of mesh around the plate (left bolts) and failure of the bolt head at the plate (right bolt), illustrating surface support/connection failure; (b) Poorly installed mesh strap

5.3.2 Compatibility of ground support elements

A ground support system is only effective if it matches the characteristics of the rock mass deformation (Figure 31). It is recognised that to be effective in a deep and high-stress mine, a ground support system should have similar displacement compatibility while providing higher energy dissipation capacity than demand (Li 2010a; Kaiser & Malovichko 2022). In an effective ground support system, both internal and external elements should be strong and deformable.

It is also important to interpret the compatibility of ground support elements from both field and laboratory tests. Roth et al. (2014) reported that the tests at Walenstadt, Switzerland, demonstrated that high-tensile mesh works together with the dynamic bolts and that the two systems were compatible. Simser (2018) reported cases of poor performance of ground support under dynamic loading due to deformation incompatibility of soft mesh with relatively stiff rockbolts. This case is of particular interest in that, although energy-absorbing rockbolts were used, they were still stiffer than the mesh.

Figure 31 Ground support systems (domed plates, welded mesh, and mesh straps) containing a rockburst (Simser 2018)

Ideally, a plate should begin to deform in the yielding zone of the bolt and ultimately fail after the reinforcement element fails (Figure 32). A consequence of poor compatibility between plate and rockbolt under seismic conditions was reported in the field and in the laboratory by Charette & Bennet (2017) where sudden release of energy resulted in a reinforcement failure creating a projectile nut (thread) or a fall of ground (Figure 33). The same phenomenon attributed to poor match between rockbolts and plates was reported in laboratory impact tests by Villaescusa et al. (2015).

Figure 32 Paddled energy-absorbing rockbolt with collapsed dome plate over top of deformed wire mesh strap plate (Simser 2019)

(a) (b)

Figure 33 (a) Rockbolt head as a projectile; (b) Plate displaying limited loading (Charette & Bennet 2017)

From a mine operator's perspective, there is an understandable desire to use the minimum type of ground support elements that are easy to install with the current installation fleet and are significantly cost-effective. Ideally, this would translate to an all-purpose ground support system. A pragmatic approach may result in guidelines of making suitable trade-offs without compromising safety. This, however, is extremely difficult to achieve in deep and high stress mines.

6 Ground support failure investigations

It is industry practice to conduct comprehensive investigations of all significant falls of ground in underground mines with several mining companies requiring a root cause analysis addressing the role of people, processes, and tools and equipment.

A fracture analysis can complement other forensic investigations and contribute to an improved understanding of the behaviour of ground support in rockbursts. Macro photography will provide the first interpretation of the fracture surface (Figure 34) while a chemical analysis and energy dispersive X-ray spectrometry at the fracture surface will ensure compliance with the nominal material properties. This is only possible if there is a reliable tracking system from manufacturing to installation, and operation.

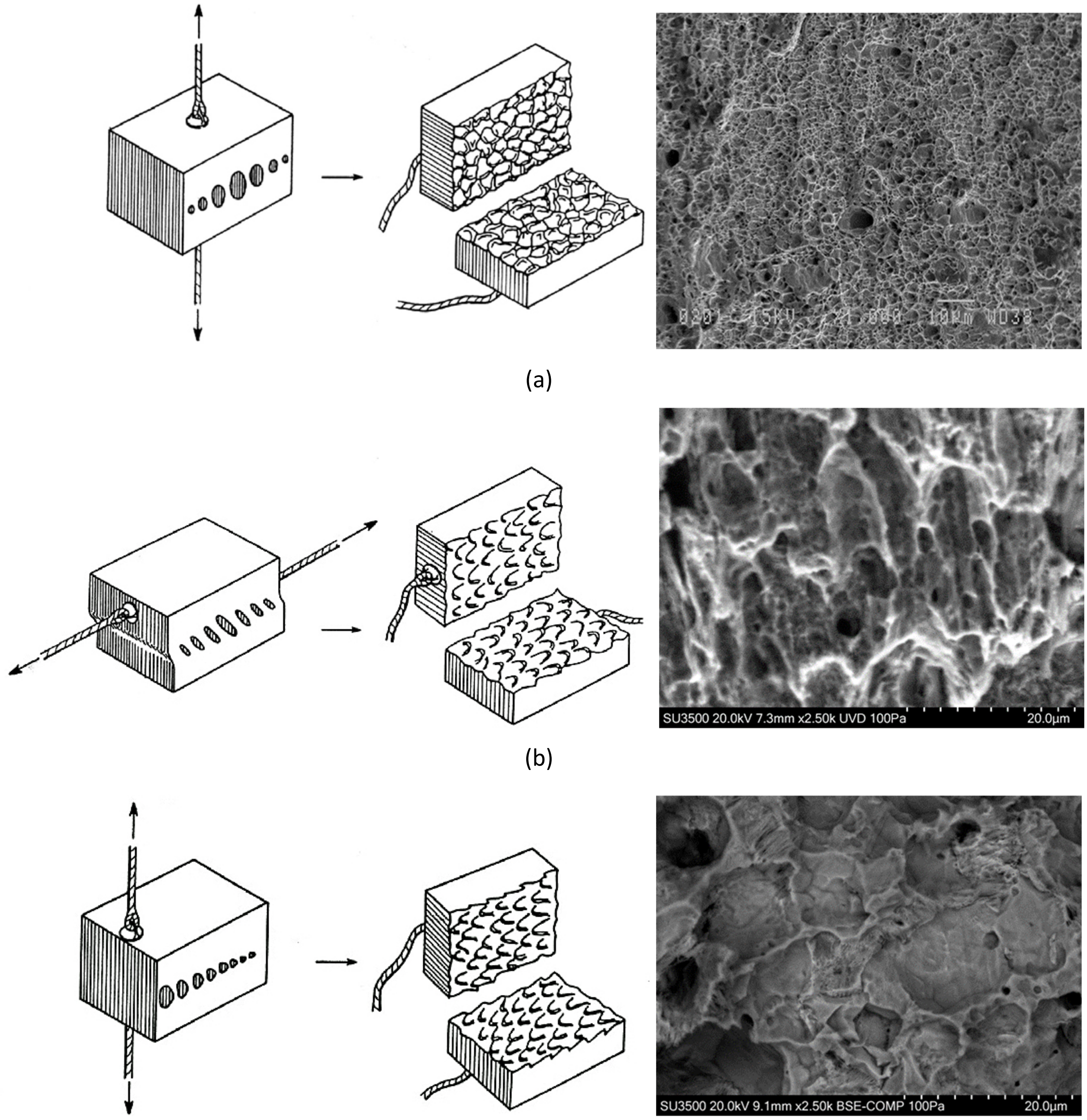
(a)

(b)

(c)

Figure 34 Macro photography of fracture surface for different types of rockbolts. (a) Expandable; (b) Rebar; (c) Paddled energy-absorbing

The next step is the use of a scanning electron microscope to investigate fracture morphology fracture of failed rockbolts. Typical rockbolt fractures are characterised by cleavage, quasi-cleavage, dimpled rupture, and fatigue. Most structural alloys fail by microvoid coalescence where overload is the major cause of fracture. As stress increases, the microvoids grow, coalesce, and eventually form a continuous fracture surface. It is therefore possible to look at fracture morphology and confirm or disprove the interpreted failure mechanism. Figure 35 provides examples drawn from ground support failure investigations in Canadian mines. The corresponding theoretical material transgranular fracture is based on the work of Dieter (1986).



(a)

(b)

(c)

Figure 35 Rockbolt fracture morphology as a function of loading mechanism (Hadjigeorgiou & Thorpe 2020). (a) Tension: equiaxed dimple formation on both fracture surfaces; (b) Shear: elongated dimples pointing in opposite direction of matching surfaces; (c) Tensile tearing: elongated dimples point toward fracture origin on matching fracture surfaces

A metallurgical investigation of failed rockbolts, e.g. Hadjigeorgiou et al. (2002), Hadjigeorgiou & Thorpe (2020), Chen et al. (2018), although useful, is only part of a comprehensive investigation on the root cause of a fall of ground. It may be justified in cases when the consequences of a failure are important or there are concerns on the adequacy of the remaining rockbolts. A major contribution of fracture investigations is to confirm or disprove hypotheses on the dominant failure mechanism of any ground support element.

7 Degradation and failure of ground support

Typically, energy-absorbing ground support is installed during development in areas of anticipated high seismicity. It is not possible to predict when support will be called upon to mitigate or contain potential rockburst events. It is then possible that by the time the ground support is required to act, it may already have significantly degraded. A convenient and simple way to interpret degradation of rock support is the distinction between consumption of capacity due to increased demand and loss of capacity due to damage of support (Hadjigeorgiou 2016). In the first case, the support is working as intended until a threshold is reached where the demand is greater than the capacity, while in the second category, damage to support results in loss of capacity. Table 8 lists contributing factors for degradation of ground support.

Table 8 Contributing factors to degradation of ground support (Hadjigeorgiou 2016)

Increased demand	Damage to ground support
Changes in stress	Static and dynamic loading
Rock mass degradation	Corrosion of support
Increase in excavation dimensions	Blast damage (Flyrock)
Mine-induced seismicity	Equipment damage
Static and dynamic loading	

Figure 36 illustrates two ground support systems susceptible to degradation. A system is considered to have failed when it reaches a critical performance level. In squeezing ground conditions, it is possible to predict the performance of the ground support system as a function of convergence Hadjigeorgiou & Potvin (2023). In a corrosive environment Hadjigeorgiou (2016) this can be predicted to a degree, by monitoring the rate of degradation (Dorion & Hadjigeorgiou 2014).

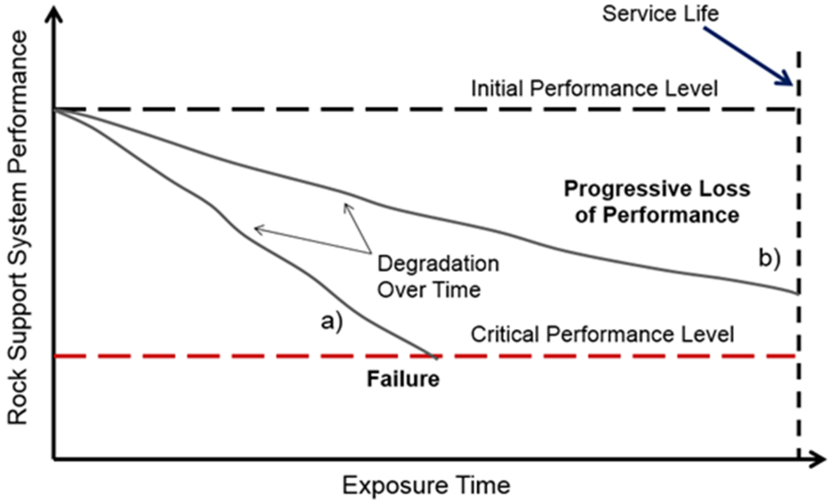


Figure 36 Rock support system performance over time. (a) Degradation resulting in failure; (b) Degradation resulting in loss of performance (Hadjigeorgiou 2016)

It is a considerably more complex process to predict the residual capacity of a ground support system following a seismic event, Figure 37. Laboratory experiments by Knox & Berghorst (2019) noted a correlation between the residual dynamic capacity and the energy absorbed quasi-statically when a tendon is elongated axially but warned that the results could not be extrapolated to other configurations.

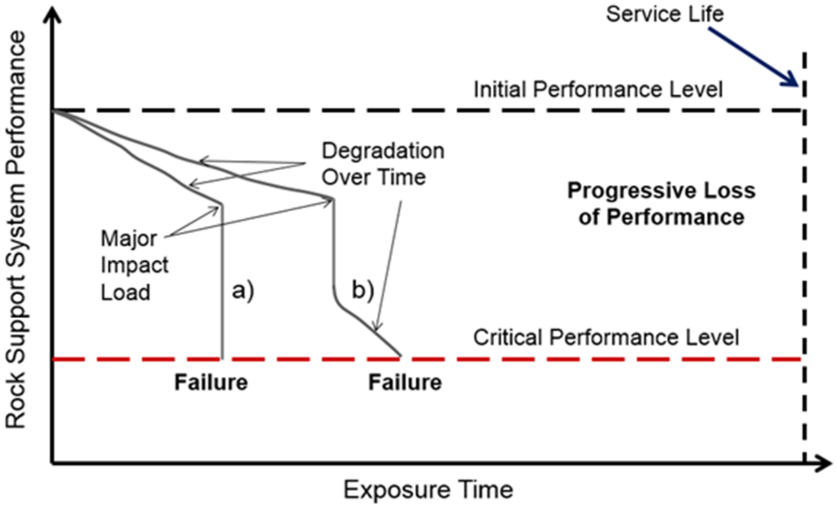


Figure 37 **Rock support system performance over time. (a) Degradation over time, and due to major impact load resulting in failure; (b) Degradation over time, major impact load, and further degradation resulting in failure (Hadjigeorgiou 2016)**

8 Ground support economics for deep and high stress mines

As mining progresses to depth, it is likely that seismicity will become an issue. Recognising that a mine has transitioned from a non-seismic mine to a seismic mine and modifying its ground support strategy often requires the education of all stakeholders. Another challenge is a significant increase in seismicity in an already seismically active mine. Both scenarios require a change in ground support strategies with potentially significant costs. Mercier-Langevin (2019) compared the ground support costs between Goldex and LaRonde mines. At the time of the comparison, Goldex, with relatively better ground conditions and only nascent seismic risk at relatively shallow depths, had ground support material costs that were in the order of CAD 340/eq.m. LaRonde's much more challenging environment, with severe squeezing ground and significant seismic risk, reported almost triple the costs compared to Goldex (CAD 925/eq.m.).

The reality is that the mining industry was very slow to introduce yielding support (Stacey 2016). Although this has changed in the last 15 years, there is still a degree of reluctance to make changes, citing both economic and operational constraints. Examples of operational constraints include the change to #4 mesh in Canadian mines (Punkkinen & Yao 2007) and the necessary effort to bring ground support to the floor (Figure 38).


(a) (b)

Figure 38 **(a) Deterioration associated with lack of support to the floor; (b) Ground support installed to the floor**

Stacey (2016) argued that if rockburst-resistant support had been implemented substantially, rockburst damage, associated direct and indirect costs, and accidents could have been reduced. An interesting comparison metric for ground support systems has been proposed by Louchnikov et al. (2014) who presented costs of surface support as 'dollars per kilojoule of energy absorbed per square metre of surface support'. This allows for a direct cost comparison for each support system, taking into consideration its deformation capabilities.

Although it is relatively easy to compare the costs of ground support elements, this is not adequate to make an informed decision. Stacey & Hadjigeorgiou (2022) proposed a quantified value-created process (QVP) where all costs are quantified in advance of committing to a decision in the selection of ground support strategies. This should consider the value that will be created in the short term, medium term, and long term. This is different than the traditional risk approach, as the QVP should identify the upside to make appropriate strategic decisions. Mercier-Langevin (2019) suggested that the direct consequences of not managing geomechanical risk can range from minor (production delays) to catastrophic (fatalities). In addition, consideration should be given to additional indirect consequences such as damage to a corporation's reputation and loss of community support. Stacey & Hadjigeorgiou (2022) suggested that a proposed decision on upgrading ground support for anticipated seismic conditions may result in short-term value destruction, but that medium-term and long-term value will be substantial, thus promoting a positive decision.

A challenge to implementing the QVP approach is that many hidden costs are difficult to quantify and there is an asymmetry of knowledge between the various stakeholders (Hadjigeorgiou 2020). An inconvenient truth is that often the emphasis at a mine site may focus on addressing the short-term financial and production goals.

9 Conclusion

There are considerable challenges in developing and implementing ground support strategies for deep and high-stress mines. This paper acknowledges the considerable progress in ground support technology in recent years and an improved understanding of the challenges to implement ground support that is both effective and cost efficient. It is suggested that there are some inconvenient truths that should also be recognised and addressed to reduce the sources of error and epistemic uncertainty associated with ground support data, design, and implementation.

Differences in material properties, manufacturing process, configuration, and other details may result in significant variations in performance of 'similar' ground support elements under seismic loading conditions. The various national steel standards employed by manufacturers are not equivalent, therefore there is a need for comprehensive QA/QC to ensure that the end performance of the finished product is as intended. Variations in QA/QC practice between different manufacturing plants should be taken into consideration in purchasing decisions. These should be based on multiple factors beyond unit cost. The current trend towards centralised procuring departments, with sometimes limited communication with ground control engineers is not optimal.

Our understanding of the behaviour of ground support under different loading conditions remains limited. This can only improve by field observations, investigations under controlled testing conditions, and forensic fracture analyses. Existing laboratory investigations do not capture the rockburst mechanisms. In addition, testing facility and methodology bias can make comparisons of published data difficult.

It is only recently that we are beginning to address the knowledge gap in the performance of energy-absorbing rockbolts in shear, and there is even scarcer information on how rock reinforcement elements behave under combined shear and tensile load in quasi-static controlled conditions. All laboratory impact tests assume axial loading which is only one of the possible mechanisms. It is an inconvenient truth that the energy absorption obtained from axial impact tests may not be representative of rockbolt dynamic capacity.

‘Certification’ of new products was a valuable concept in that it drove the development of several impact testing facilities worldwide. The term certification is somewhat misleading, as none of the testing rigs can provide ‘certification’ to a specific standard. At best, they provide an indication on how a particular ground support element or system performs under specific conditions at a specific testing rig.

A QA/QC program of ground support is critical, but it has to be well designed for purpose. It is an inconvenient truth that several mines implement the same frequency of tests for all rockbolt types. This is clearly not optimal as certain rockbolt types, e.g. FRS, are more susceptible to QA/QC issues and a higher testing frequency is necessary. It is not always evident that a mine will replace all ground support elements that failed the defined QA/QC standards. There will always be opposition to overcome if it requires a stop in production, e.g. rehabilitation of a ramp.

In the context of ground support performance under seismicity, both observational and experimental approaches are necessary. Observational studies allow us to understand the performance of ground support under seismic load (e.g. stiff versus yielding ground support) while experimental studies allow the control of different variables (e.g. loading rate and inclination) to provide an indication of cause and effect (e.g. axial versus shear capacity) of any ground support element. It is necessary to reconcile the two approaches.

The lessons that can be taken from rockburst investigations are not fully appreciated. There are significant advantages in ensuring good ground support implementation including connectivity and compatibility of different elements as opposed to focusing in improving a theoretical ground support capacity based on laboratory data under ideal conditions based on quasistatic and impact axial tests. It is extremely difficult to quantify the residual capacity of ground support systems following a rockburst event.

Instead of focusing on calculating a Factor of Safety for an indeterminate ground support problem based on what are at times questionable demand and capacity input data, consideration should be given to establishing safer operations. This would require addressing the asymmetry of knowledge between the various stakeholders that, under seismic conditions, contribute to ground support design, manufacturing, QA/QC, implementation, monitoring, and ground performance.

The economics of ground support for deep and high-stress mines require the use of a QVP that may result in short-term value destruction, but that medium-term and long-term value may be substantial. The inconvenient truth is that this is often counter to financial pressure to address short-term objectives.

It would be amiss if this paper did not conclude with a ‘convenient truth’. Seismic risk management strategies, including ground support, have improved significantly in recent decades. This is reflected in the very few fatalities due to rockbursts in mines in recent years. This paper focused on identifying sources of error and epistemic uncertainty associated with ground support data including material properties, QA/QC, performance under controlled conditions, and field observations. The path forward is to engage all stakeholders to work together in addressing the processes over which we have control.

Acknowledgement

This paper evolved from research projects financed by multiple mining and ground support technology companies and the Natural Science and Engineering Research Council of Canada. The presented commentary is based on observations at mine sites and onsite discussions at deep and high-stress mines. The author is grateful to have had the opportunity to collaborate with outstanding industry and research colleagues over the last 30 years. A number of ground support manufacturers provided access to data and manufacturing facilities, thus making this paper possible. In the preparation of this paper, I have received valuable feedback and suggestions from Professor Yves Potvin, Brad Simser and Greig Knox. Their contributions are genuinely appreciated.

References

ASTM International, *A29 Standard Specification for General Requirements for Steel Bars, Carbon and Alloy, Hot-Wrought*, West Conshohocken.

ASTM International, *A416 Standard Specification for Steel Strand, Uncoated Seven-Wire for Prestressed Concrete*, West Conshohocken.

ASTM International *A572 Standard Specification for High-Strength Low-Alloy Columbium-Vanadium Structural Steel*, West Conshohocken.

ASTM International, *A615 Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement*, West Conshohocken.

ASTM International, *A706 Standard Specification for Deformed and Plain Low-Alloy Steel Bars for Concrete Reinforcement*, West Conshohocken.

ASTM International, *A1011 Standard Specification for Steel, Sheet and Strip, Hot-Rolled, Carbon, Structural, High-Strength Low Alloy, High-Strength Low-Alloy with Improved Formability, and Ultra-High Strength*, West Conshohocken.

ASTM International, *A1018 Standard Specification for Steel, Sheet and Strip, Heavy-Thickness Coils, Hot-Rolled, Carbon, Commercial, Drawing, Structural, High-Strength Low-Alloy, High-Strength Low-Alloy with Improved Formability, and Ultra-High Strength*, West Conshohocken.

ASTM International, *E1019 Standard Test Methods for Determination of Carbon, Sulfur, Nitrogen, and Oxygen in Steel, Iron, Nickel, and Cobalt Alloys by Various Combustion and Fusion Techniques*, West Conshohocken.

ASTM International, *E1479 Standard Practice for Describing and Specifying Inductively Coupled Plasma Atomic Emission Spectrometers*, West Conshohocken.

ASTM International, *F432 Standard Specification for Roof and Rock Bolts and Accessorie*s, West Conshohocken.

Baek, B, Karampinos, E & Hadjigeorgiou J, 2020, 'Understanding the impact of test configuration on welded wire mesh laboratory test results', *Rock Mechanics and Rock Engineering*, vol. 53, pp. 4873–4892.

Barton, N, Lien, R & Lunde, J 1974, 'Engineering classification of rock masses for design of tunnel support', *Rock Mechanics and Rock Engineering*, vol. 6, no. 4, pp. 189–236.

Bieniawski, ZT 1989, *Engineering Rock Mass Classifications*, John Wiley & Sons, New York.

Brändle, R & Luis Fonseca, R 2019, 'Dynamic testing of surface support systems', in J Hadjigeorgiou & M Hudyma (eds), *Ground Support 2019: Proceedings of the Ninth International Symposium on Ground Support in Mining and Underground Construction*, Australian Centre for Geomechanics, Perth, pp. 243–250, https://doi.org/10.36487/ACG_rep/1925_15_Brandle

Brändle, R, Luis Fonseca, R, von Rickenbach, G, Fischer, G, Vallejos, JA, Marambio, E, Burgos, L & Cuello, D 2022, 'Large-scale dynamic testing of ground support systems at the Walenstadt testing facility', in Y Potvin (ed.), *Caving 2022: Proceedings of the Fifth International Conference on Block and Sublevel Caving*, Australian Centre for Geomechanics, Perth, pp. 177–190, https://doi.org/10.36487/ACG_repo/2205_10

Charette, F & Bennett, A 2017, 'The importance of the face plate as part of an engineered holistic ground support scheme in dynamic conditions', in J Wesseloo (ed.), *Deep Mining 2017: Proceedings of the Eighth International Conference on Deep and High Stress Mining*, Australian Centre for Geomechanics, Perth, pp. 709–722, https://doi.org/10.36487/ACG_rep/1704_48_Charette

Chen, H, Ramandi, HL, Walker, J, Crosky, A & Saydam, S 2018, 'Failure of the threaded region of rockbolts in underground coal mines', *Mining Technology*, vol. 127, no. 3, pp. 146–154.

Chen, Y & Li, CC 2015, 'Influences of loading condition and rock strength to the performance of rock bolts', *Geotechnical Testing Journal*, vol. 38, no. 2, pp. 1–11.

Counter, DB 2014, 'Kidd Mine – dealing with the issues of deep and high stress mining – past, present and future', in M Hudyma & Y Potvin (eds), *Deep Mining 2014: Proceedings of the Seventh International Conference on Deep and High Stress Mining*, Australian Centre for Geomechanics, Perth, pp. 3–22, https://doi.org/10.36487/ACG_rep/1410_0.1_Counter

Darlington, B, Rataj, M, Balog, G & Barnett, D 2018, 'Development of the MDX Bolt and In-Situ Dynamic Testing at Telfer Gold Mine', *Rock Dynamics and Applications,* CRC Press, Boca Raton.

Dieter, GE 1986, *Mechanical Metallurgy*, McGraw Hill, New York.

Drover, C & Villaescusa, E 2016, 'Field performance of fully encapsulated reinforcement during violent failure events', *Seventh International Conference & Exhibition on Mass Mining*, Australasian Institute of Mining and Metallurgy, Melbourne.

Drover, C & Villaescusa, E 2015, 'Performance of Shotcrete Surface Support Following Dynamic Loading of Mining Excavations', in Lu & Sigl (eds), *Shotcrete for Underground Support XI*, ECI Symposium Series.

Dorion, JF & Hadjigeorgiou, J 2014, 'Corrosion considerations in design and operation of rock support systems', *Mining Technology*, vol. 23, no. 2, pp. 59–68.

Doucet, C & Voyzelle, B 2012, *Technical Information Data Sheets*, Natural Resources Canada, Ottawa.

European Committee for Standardization 2013, *EN 10149 Hot Rolled Flat Products Made of High Yield Strength Steels for Cold Forming General Technical Delivery Conditions*, Brussels.

European Committee for Standardization 2004, *EN 10025 Hot Rolled Products of Structural Steel,* Brussels.

European Committee for Standardization 1998, *EN 10267 Ferritic-Perlitic Steels for Precipitation Hardening From Hot Working Temperatures*, Brussels.

National Standard of the People's Republic of China 2008, *GB 912 Hot-Rolled Sheets and Strips of Carbon Structural Steels and High Strength Low Alloy Structural Steels*, Beijing.

Hadjigeorgiou, J 2012, 'Where do the data come from?', *Mining Technology*, vol. 121, no. 4, pp. 236–247.

Hadjigeorgiou, J, 2016, 'Rock support: degradation and failure', in E Nordlund, TH Jones & A Eitzenberger (eds), *Ground Support 2016: Eighth International Symposium on Ground Support in Mining and Underground Construction*, Luleå University of Technology, Luleå.

Hadjigeorgiou, J 2020, 'Understanding, managing, and communicating geomechanical mining risk', *Transactions of the Institutions of Mining and Metallurgy: Section A. Mining Technology*, vol. 129, pp. 159–173.

Hadjigeorgiou, J, Ghali, E, Charette, F & Krishnadev MR 2002, 'Fracture analysis of friction rock bolts', in Hammah et al (eds), *NARMS-TAC*. University of Toronto, Toronto, pp. 881–887.

Hadjigeorgiou, J & Harrison, JP 2012, 'Uncertainty and sources of error in rock engineering', in Q Qian & X Zhou (eds), *Proceedings of the 12th ISRM International Congress on Rock Mechanics, Harmonising Rock Engineering and the Environment*, CRC Press, Leiden, pp. 2063–2067.

Hadjigeorgiou, J & Potvin, Y 2007, 'Overview of dynamic testing of ground support', in Y Potvin (ed.), *Deep Mining 2007: Proceedings of the Fourth International Seminar on Deep and High Stress Mining*, Australian Centre for Geomechanics, Perth, pp. 349–371, https://doi.org/10.36487/ACG_repo/711_26

Hadjigeorgiou, J & Potvin, Y 2011, 'A critical assessment of dynamic rock reinforcement and support testing facilities', *Rock Mechanics and Rock Engineering*, vol. 44, no. 5, pp. 565–578.

Hadjigeorgiou, J & Potvin, Y 2011, 'Hard rock ground control with screen and shotcrete*'*, *SME Mining Engineering Handbook*, Society of Mining, Metallurgy and Exploration, Engelwood, pp. 573–594.

Hadjigeorgiou, J & Potvin, Y 2023, 'Ground support guidelines for squeezing ground conditions', *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 123, no. 7, pp. 371–380.

Hadjigeorgiou, J & Stacey, TR 2018, 'Challenges in determining the capacity of mesh', *AusRock 2018: The Fourth Australasian Ground Control in Mining Conference*, The Australasian Institute of Mining and Metallurgy, Melbourne, pp. 280–290.

Hadjigeorgiou, J, Savguira, Y & Thorpe, SJ 2020, 'Impact of steel properties on the corrosion of expandable rock bolts', *Rock Mechanics and Rock Engineering*, vol. 53, pp. 705–721.

Hadjigeorgiou, J, Savguira, Y & Thorpe, SJ 2019, 'Comparative susceptibility to corrosion of coated expandable bolts', Rock Engineering, *Rock Mechanics and Rock Engineering*, vol. 52, issue 8, pp. 2665–2680.

Hadjigeorgiou, J & Thorpe SJ 2020, 'Failure analysis of rock support in hard rock tunnels', *ISRM International Symposium Eurock 2020: Hard Rock Engineering*, Trondheim.

Hadjigeorgiou, J, Thorpe, SJ & Cole, KM 2023, 'Quality assurance considerations for friction rock stabilizers', *Mining Technology (TIMM A)*, vol. 132, no. 1, pp. 17–29.

Hadjigeorgiou, J & Tomasone, P 2018, 'Characterising the behaviour of rockbolts based on in situ pull tests', in Y Potvin & J Jakubec (eds), *Caving 2018: Proceedings of the Fourth International Symposium on Block and Sublevel Caving*, Australian Centre for Geomechanics, Perth, pp. 727–734, https://doi.org/10.36487/ACG_rep/1815_56_Hadjigeorgiou

He, M, Gong, W, Wang, J, Qi, P, Tao, Z, Du, S, Peng, Y, 2014, 'Development of a novel energy-absorbing bolt with extraordinarily large elongation and constant resistance', *International Journal of Rock Mechanics and Mining Sciences*, vol. 67, pp. 29–42.

Heal, D 2010, *Observations and Analysis of Incidences of Rockburst Damage in Underground Mines*, PhD thesis, The University of Western Australia, Perth.

Hoek, E, Kaiser, PK & Bawden, WF 1995, *Support in Underground Excavations in Hard Rock*, A.A. Balkema, Rotterdam.

Hudson, JA, Crouch, SL & Fairhurst, C 1972, 'Soft, stiff, and servo-controlled testing machines: a review with reference to rock failure', *Engineering Geology*, vol. 6, no. 3, pp. 155–89.

International Organization for Standardization 2015, *Quality Management Systems – Requirements (ISO 90011:2015)*, Geneva.

International Organization for Standardization 2019, *Metallic Materials — Tensile Testing (ISO 6892-1:2019)*, Geneva.

Jager, AJ 1992, 'Two new support units for the control of rockburst damage', in PK Kaiser & DR McCreath (eds), *Proceedings of the International Symposium on Rock Support*, A.A. Balkema, Rotterdam, pp. 621–631.

Jones, T, Nordlund, E & Wettainen, T 2019, 'Mining-induced deformation in the Malmberget Mine', *Rock Mechanics and Rock Engineering,* vol. 52, pp. 1903–1916.

Kaiser, PK & Cai, M 2013, 'Critical review of design principles for rock support in burst-prone ground – time to rethink!', in Y Potvin & B Brady (eds), *Ground Support 2013: Proceedings of the Seventh International Symposium on Ground Support in Mining and Underground Construction*, Australian Centre for Geomechanics, Perth, pp. 3–37, https://doi.org/10.36487/ACG_rep/1304_01_Kaiser

Kaiser, PK & Malovichko, DA 2022, 'Energy and Displacement Demands Imposed on Rock Support by Strainburst Damage Mechanisms', *RaSim 10: Rockbursts and Seismicity in Mines*, Society for Mining, Metallurgy & Exploration, Engelwood.

Kaiser, PK, McCreath, DR & Tannant, DD 1996, *Canadian Rockburst Support Handbook*, Canadian Mining Industry Research Organization, Sudbury.

Kaiser, PK & Moss, A 2022, 'Deformation-based support design for highly stressed ground with a focus on rockburst damage mitigation', *Journal of Rock Mechanics and Geotechnical Engineering,* vol. 14, pp. 50–66.

Knox, G 2023, 'Laboratory-based drop testing of rock reinforcement', in J Wesseloo (ed.), *Ground Support 2023: Proceedings of the 10th International Conference on Ground Support in Mining*, Australian Centre for Geomechanics, Perth, pp. 23–38, https://doi.org/10.36487/ACG_repo/2325_0.02

Knox, G & Hadjigeorgiou, J 2023a, 'Performance of conventional and energy-absorbing self-drilling hollow core rockbolts under controlled laboratory conditions', *Rock Mechanics and Rock Engineering*, vol. 56, pp. 4363–4378.

Knox, G & Hadjigeorgiou, J 2023b, 'Performance in shear of mechanical hybrid rockbolts', in J Wesseloo (ed.), *Ground Support 2023: Proceedings of the 10th International Conference on Ground Support in Mining*, Australian Centre for Geomechanics, Perth, pp. 495–506, https://doi.org/10.36487/ACG_repo/2325_33

Knox, G & Hadjigeorgiou, J 2022, ‘Influence of testing configuration on the performance of paddled energy-absorbing rockbolts under impact loading’, *Rock Mechanics and Rock Engineering*, vol. 55, pp. 5705–5721.

Knox, G & Berghorst, A 2019, ‘Dynamic testing: determining the residual dynamic capacity of an axially strained tendon’, in J Hadjigeorgiou & M Hudyma (eds), Ground Support 2019: Proceedings of the Ninth International Symposium on Ground Support in Mining and Underground Construction, Australian Centre for Geomechanics, Perth, pp. 231-242, https://doi.org/10.36487/ACG_rep/1925_14_Knox

Li, CC 2010a, ‘A new energy-absorbing bolt for rock support in high stress rock masses’, *International Journal of Rock Mechanics and Mining Sciences,* vol. 47, no. 3, pp. 396–404.

Li, CC 2010b, ‘Field observations of rock bolts in high stress rock masses’, *Rock Mechanics & Rock Engineering*, vol. 43, pp. 491–496.

Li, CC, Hadjigeorgiou, J, Mikula, P, Knox, G, Darlington, B, Royer, R … & Hosp M, 2021, ‘Performance of Identical rockbolts tested on four dynamic testing rigs employing the direct impact method’, *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 13, issue 4, pp. 745–754.

Li, CC, Mikula, P, Hadjigeorgiou, J, Simser, B, He, M, Canbulat, I & Joughin, W 2024, ‘ISRM Suggested Method for determining the properties of rock bolt assemblies by mass freefall impact testing in the laboratory’, submitted to *Rock Mechanics and Rock Engineering*.

Li, CC, Stjern, G & Myrvang, A 2014, ‘A review on the performance of conventional and energy-absorbing rockbolts’, *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 6, issue 4, pp. 315–327.

Louchnikov, V, Sandy, Watson, O, Orunesu, M & Eremenko, V 2014, ‘An Overview of Surface Rock Support for Deformable Ground Conditions’, *Proceedings of the 12th AUSIMM Underground Operators*’ Conference, The Australasian Institute of Mining and Metallurgy, Melbourne, pp. 57–65.

Marinos, V, Marinos, P & Hoek, E 2005, ‘The geological strength index: applications and limitations’, *Bulletin of Engineering Geology and the Environment*, vol. 64, pp. 55–65.

Martin, CD, Kaiser, PK & McCreath, DR 1999, ‘Hoek–Brown parameters for predicting the depth of brittle failure around tunnels’, *Canadian Geotechnical Journal*, vol. 36, no. 1, pp. 136–151.

Mercier-Langevin, F 2019, ‘Ground support: a mine manager’s perspective’, in J Hadjigeorgiou & M Hudyma (eds), *Ground Support 2019: Proceedings of the Ninth International Symposium on Ground Support in Mining and Underground Construction*, Australian Centre for Geomechanics, Perth, pp. 29–40, https://doi.org/10.36487/ACG_rep/1925_0.03_Mercier-Langevin

Mercier-Langevin, F & Hadjigeorgiou, J 2011, ‘Towards a better understanding of squeezing potential in hard rock mines’, *Transactions of the Institutions of Mining and Metallurgy: Section A – Mining Technolog*y, vol. 120, no. 1, pp. 36–44.

Mercier-Langevin, F & Turcotte, P 2007, ‘Evolution of ground support practices at Agnico Eagle’s LaRonde Division: innovative solutions to high stress ground’, in E Eberhardt, D Stead & T Morrison (eds), *Rock Mechanics: Meeting Society’s Challenges and Demands*, pp. 1497–1504.

Mikula, PA 2012, ‘Progress with empirical performance charting for confident selection of ground support in seismic conditions’. in Y Potvin (ed.), *Proceedings of the Sixth International Seminar on Deep and High Stress Mining*, Australian Centre for Geomechanics, Perth, pp. 71–90.

Mikula, P & Gebremedhin, B 2017, ‘Empirical selection of ground support for dynamic conditions using charting of support performance at Hamlet min’, in J Wesseloo (ed.), *Deep Mining 2017: Proceedings of the Eighth International Conference on Deep and High Stress Mining*, Australian Centre for Geomechanics, Perth, pp. 625–636, https://doi.org/10.36487/ACG_rep/1704_42_Mikula

Morissette, P & Hadjigeorgiou J, 2019, ‘Ground support design for dynamic-loading conditions: a quantitative data-driven approach based on rockburst case studies’, *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 11, pp. 909–919.

Morissette, P & Hadjigeorgiou, J 2017, ‘The development of a ground support design strategy for deep mines subjected to dynamic-loading conditions’, in J Wesseloo (ed.), *Deep Mining 2017: Proceedings of the Eighth International Conference on Deep and High Stress Mining*, Australian Centre for Geomechanics, Perth, pp. 651–665, https://doi.org/10.36487/ACG_rep/1704_44_Morissette

Morissette, P, Hadjigeorgiou, J, Punkkinen, AR, Chinnasane, DR & Sampson-Forsythe, A 2017, ‘The influence of mining sequence and ground support practice on the frequency and severity of rockbursts in seismically-active mines’, *The Journal of the Southern African Institute of Mining and Metallurgy*, vol. 117, pp. 47–58.

Morissette, P, Hadjigeorgiou, J, Punkkinen, AR & Chinnasane, DR 2014, ‘The influence of change in mining and ground support practice on the frequency and severity of rockbursts’, in M Hudyma & Y Potvin (eds), *Deep Mining 2014: Proceedings of the Seventh International Conference on Deep and High Stress Mining*, Australian Centre for Geomechanics, Perth, pp. 165–177, https://doi.org/10.36487/ACG_rep/1410_09_Hadjigeorgiou

Morkel, IG, Mikula, PA & Whiting, RK 2023, ‘A review of ground support mesh testing around the world’, in J Wesseloo (ed.), *Ground Support 2023: Proceedings of the 10th International Conference on Ground Support in Mining*, Australian Centre for Geomechanics, Perth, pp. 373–398, https://doi.org/10.36487/ACG_repo/2325_25

Morton, E, Thompson, A, Villaescusa, E & Roth, A 2007, ‘Testing and analysis of steel wire mesh for mining applications of rock surface support’, in Ribeiro e Sousa, Olalla and Grossman (eds), *11th Congress of the International Society for Rock Mechanics*, vol. 2, pp. 1061–1064.

Ortlepp, WD 1969, ‘An Empirical determination of the effectiveness of rockbolt support under impulse loading’, in TL Brekke & FA Jorstad (eds.), *Proceedings of the International Symposium on Large Permanent Underground Openings*, Universitatsforlaget, Oslo, pp. 197–205.

Ortlepp, WD & Stacey, TR 1994, ‘Rockburst mechanisms in tunnels and shafts’, *Tunnelling and Underground Space Technology*, vol. 9, no. 1, pp. 59–65.

Ortlepp, WD & Stacey, TR 1998, 'Performance of tunnel support under large deformation static and dynamic loading', *Tunnelling and Underground Space Technology*, vol. 13, no. 1, pp. 15–21.

Potvin, Y & Hadjigeorgiou, J 2016, 'Selection of ground support for mining drives based on the Q-System', in E Nordlund, T Jones & A Eitzenberger (eds), *Proceedings of the Eighth International Symposium on Ground Support in Mining and Underground Construction*, Luleå University of Technology, Luleå.

Potvin, Y & Hadjigeorgiou, J 2020, *Ground Support for Underground Mines*, Australian Centre for Geomechanics, Perth.

Potvin, Y & Wesseloo, J 2013, 'Towards an understanding of dynamic demand on ground support', in Y Potvin & B Brady (eds), *Ground Support 2013: Proceedings of the Seventh International Symposium on Ground Support in Mining and Underground Construction*, Australian Centre for Geomechanics, Perth, pp. 287–304, https://doi.org/10.36487/ACG_rep/1304_18_Potvin

Potvin, Y, Wesseloo, J & Heal, D 2010, 'An interpretation of ground support capacity submitted to dynamic loading', in M Van Sint Jan & Y Potvin (eds), *Deep Mining 2010: Proceedings of the Fifth International Seminar on Deep and High Stress Mining*, Australian Centre for Geomechanics, Perth, pp. 251–272, https://doi.org/10.36487/ACG_repo/1074_18

Potvin, Y, Wesseloo, J, Morkel, G, Tierney, S & Woodward, K 2018, S*eismic Risk Management Practices in Underground Mines,* Australian Centre for Geomechanics, Perth.

Player, JR, Thompson, AG & Villaescusa, E 2008, 'Dynamic testing of reinforcement system', in TR Stacey and D Malan (eds), *Proceedings of the 6th International Symposium on Ground Support in Mining and Civil Engineering Construction*, The South African Institute of Mining and Metallurgy, Johannesburg, pp. 581–595.

Punkkinen, AR & Yao, M 2007, 'Change of ground support system and mining practice in the deep at Creighton Mine', *CIM AGM* Montreal.

Roth, A, Cala, M, Brändle, R & Rorem, E 2014, 'Analysis and numerical modelling of dynamic ground support based on instrumented full-scale tests', in M Hudyma & Y Potvin (eds), *Deep Mining 2014: Proceedings of the Seventh International Conference on Deep and High Stress Mining*, Australian Centre for Geomechanics, Perth, pp. 151–163, https://doi.org/10.36487/ACG_rep/1410_08_Roth

Scott, J 1980, 'A new innovation in rock support – friction rock stabilizers', *CIM Bulletin,* February issue, pp. 65–69.

Simser, BP 2007, 'The Weakest Link - Ground support observations at some Canadian shield hard rock mines', in Y Potvin (ed.), *Deep Mining 2007: Proceedings of the Fourth International Seminar on Deep and High Stress Mining*, Australian Centre for Geomechanics, Perth, pp. 335–348, https://doi.org/10.36487/ACG_repo/711_25

Simser, BP 2018, 'Rock burst observations from hard rock mines: failures, successes, lessons learned', in CC Li, X Li & Z-X Zhang (eds), *Rock Dynamics - Experiments, Theories and Applications*, Taylor & Francis Group, London, pp. 3–12.

Simser, BP 2019, 'Rockburst management in Canadian hard rock mines', *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 11, pp. 1036–1043.

Simser, B, Andrieux, P, Mercier-Langevin, F, Parrott, T & Turcotte, 2007, 'Field behaviour and failure modes of modified conebolts at the Craig, LaRonde and Brunswick Mines in Canada', in Y Potvin, TR Stacey & J Hadjigeorgiou (eds), *Challenges in Deep and High Stress Mining*, Australian Centre for Geomechanics, Perth, pp. 351–358.

South African Bureau of Standards 2011, *Steel Bars for Concrete Reinforcement (SANS 920:2011)*, Groenkloof.

Stacey, TR 2012 'Support of excavations subjected to dynamic (rockburst) loading', *Proceedings of the 12th International Congress on Rock Mechanics,* International Society for Rock Mechanics, Lisbon, pp. 137–145.

Stacey, TR 2016, 'Innovative and controversial support for rockbursting conditions' in E Nordlund, T Jones & A Eitzenberger (eds), *Proceedings of the Eighth International Symposium on Ground Support in Mining and Underground Construction*, Luleå University of Technology, Luleå.

Stacey, TR, 2016, 'Addressing the consequences of dynamic rock failure in underground excavations', *Rock Mechanics & Rock Engineering*, vol. 49, pp. 4091–4101.

Stacey, TR & Hadjigeorgiou, J 2022, 'Quantified value-created process (QVP) – a value-based criterion for mine design and operating decisions', *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 122, no. 2, pp. 73–82.

Stacey, TR & Ortlepp, WD 1999, 'Retainment support for dynamic events in mines', *Proceedings of the International Symposium of Rock Support and Reinforcement Practice in Mining*, Balkema, Kalgoorlie, pp. 329–333.

Stacey, TR & Ortlepp, WD 2007, 'Yielding rock support — the capacities of different types of support, and matching of support type to seismic demand', in Y Potvin, TR Stacey & J Hadjigeorgiou (eds), *Challenges in Deep and High Stress Mining*, Australian Centre for Geomechanics, Perth, pp. 411–415.

Stacey, TR, Rojas, E 2013, 'A potential method of containing rockburst damage and enhancing safety using a sacrificial layer', *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 113, pp. 565–573.

Stillborg, B 1993, 'Rockbolt tensile loading across a joint', *Proceedings of The First African Symposium on Mine Drainage and Environment Protection from Mine Waste Water Disposal*, International Mine Water Association, Wendelstein, pp. 587–604.

Stjern, G 1995, *Practical Performance of Rock Bolts*, PhD thesis, University of Trondheim, Trondheim.

Tomasone, P, Bahrani, N & Hadjigeorgiou J 2020, 'Practical Considerations in the modelling of resin grouted rock bolts', *The Journal of the Southern African Institute of Mining and Metallurgy*, vol. 120, pp. 385–292.

Turcotte, P 2014, 'Practical applications of a rockburst database to ground support design at LaRonde Mine', in M Hudyma & Y Potvin (eds), *Deep Mining 2014: Proceedings of the Seventh International Conference on Deep and High Stress Mining*, Australian Centre for Geomechanics, Perth, pp. 79–91, https://doi.org/10.36487/ACG_rep/1410_03_Turcotte

Varden, R, Lachenicht, R, Player, J, Thompson, A & Villaescusa, E 2008, 'Development and implementation of the Garford dynamic bolt at the Kanowna Belle Mine', *Proceedings of the 10th Underground Operators Conference*, Australasian Institute of Mining and Metallurgy, Melbourne, pp. 95–102.

Villaescusa, E, Thompson, AG & Player, JR 2015, *Dynamic Testing of Ground Support Systems: Report 312 Project M417*, Minerals Research Institute of Western Australia, Perth.

Villaescusa, E, Kusui, A & Drover, C 2016. 'Ground Support design for sudden and violent failures in hard rock tunnels', *9th Asian Rock Mechanics Symposium*, Bali.

Wijk, G & Skogberg, B 1982, 'The inflatable rockbolting system', *Proceedings of the 14th Canadian Rock Mechanics Symposium*, Canadian Institute of Mining and Metallurgy, Vancouver, pp. 106–115.

Watt, G, Roberts, T & Faulkner, D 2018, 'Single pass drill, install and inject self-drilling resin bolt applications in poor ground', *Proceedings of The Fourth Australasian Ground Control in Mining Conference,* The Australasian Institute of Mining and Metallurgy, Melbourne. pp 323–343.

Wu, YK, Oldsen, J & Lamothe, M 2010, 'The Yield-Lok Bolt for bursting and squeezing ground support', in M Van Sint Jan & Y Potvin (eds), *Deep Mining 2010: Proceedings of the Fifth International Seminar on Deep and High Stress Mining*, Australian Centre for Geomechanics, Perth, pp. 301–308, https://doi.org/10.36487/ACG_repo/1074_21