Geotechnical Risk and Risk Mitigation in Deep Underground Mines in Hard, Brittle Rock

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Abstract. The paper reviews the challenges, and in some cases, extreme risks commonly encountered when mining at great depth in hard, brittle rock masses. For context, mining at great depth is assumed to imply mining at depths in excess of 1.0 to 1.5 km below ground surface. The paper focuses primarily on rock engineering risks to mine personnel and equipment [e. g. very high rock stresses; mine induced seismicity; rock bursting; ground support failure; falls of ground; etc.]. The paper also addresses risk due to extreme temperatures, [e. g. heat stroke; extremely hot water; etc.], commonly associated with mining at great depth as this can also pose serious risk to mine personnel. Potential risk mitigation measures, [e. g. robust mine design, numerical modelling, instrumentation; dynamic support; exclusion zones; re-entry times; destress blasting; automation; etc.], and the present limitations of such techniques, are discussed. Associated risks [e. g. infrastructure damage; cost control; etc.] are also briefly discussed. The author has also encountered many of these same risks in much shallower mines where an appropriately robust mine design has not been implemented.

Keywords: Deep mining · geomechanical risks · risk mitigation measures

1 Introduction

1.1 What Constitutes a Deep Underground Mine?

While there is no hard definition of what constitutes a 'Deep Underground Mine', it is generally accepted today that mines operating at depths ≥ 1.0–1.5 km below ground surface would be considered as Deep Mines. There are a limited number of such operations worldwide. The deepest underground mines in the world today are approaching or at 4,000 m below ground surface [South Africa]. The deepest Canadian underground mine, the Agnico Eagle La Ronde Complex near Val D'Or Quebec, is presently operating at ~ 3,200 m below ground surface. Two other mines in Ontario are at or near 3,000 m depth. There are at least two deep mines in development in the USA. All such existing mines tend to encounter similar risks and challenges as discussed below.

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Mine induced stress. It is well understood that overburden rock mass loading increases linearly with the mine depth as:

$$\sigma_v = \gamma D \quad (1)$$

where: σ_v = vertical stress; γ = unit weight of rock; and D = depth below ground surface.

Ground stress is mathematically a tensor and Eq. (1) is often assumed to represent one of the principal stresses, although this is not necessarily the case. The other two principal stresses [σ_H (maximum horizontal stress) and σ_h (minimum horizontal stress)], while a function of σ_v do not increase in a similar fashion to σ_v. Normally the ratio of the horizontal principal stress components to the vertical stress is denoted by the letter 'k' such that:

$$\sigma_h = k\sigma_v = k\gamma D \quad (2)$$

As k is only very rarely unity, the horizontal stress components are much more difficult to estimate than the vertical stress and normally must be measured in-situ or established in some other fashion. The ratio of horizontal to vertical stress components can vary significantly in different geological domains and is impacted by the local and regional geology, tectonic history, local structural domains, glacial history, etc. Surface terrain can also significantly influence the far field stress conditions. In mountainous terrain, if the mine is situated above the valley bottom the 'k' value is often < 1.0 due to lateral relaxation during the mountain building processes. Once the mine passes below the valley bottom however conditions would normally be expected to change dramatically [Fig. 1].

Far Field stress represents one of the most critical input parameters required for geomechanical mine design and risk management. Obtaining good, scale appropriate, estimates of far field stress, however, is both technically and financially challenging.

Mining locally alters the far field stress regime and may result in increase or decrease in the local mine induced stresses. Nonlinear 3D modelling used to assess this provides critical input to mine risk assessment. Results, however, are critically dependent on the input stress assumptions and require detailed calibration to be effective. Kalenchuk (2022) provides a good discussion on alternate methodologies to estimate and calibrate the mine wide stress field.

Managing the impact of mine induced stress change, particularly at great depth, often represents a significant component of mine operating costs and in some cases can exert the ultimate control, from both an economic and safety perspective, on practical mine life.

It is important to remember that mining challenges do not increase linearly with depth but rather are proportional to the square of depth. This, combined with practical limitations in ground support capacity, are key factors controlling the ultimate practical depth of mining operations.

High in-situ rock temperatures. Exposure to extreme temperatures, depending on the length of exposure, can result in serious health issues to mine personnel [e. g. heat cramps, heat fatigue, heat stroke, etc.]. In the worst-case heat stroke can result in death.

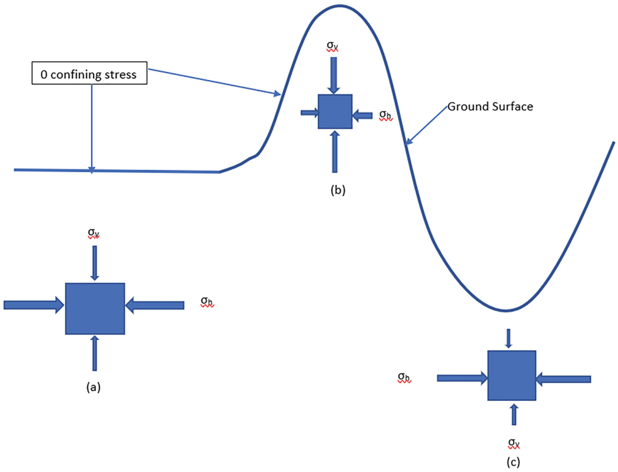

Fig. 1: Stress conditions under varying terrain: (a) $\sigma_v \neq \sigma_h$; (b) $\sigma_v > \sigma_h$ due to stress relaxation of valley walls; (c) $\sigma_v << \sigma_h$ due to stress concentration below valley

In wet mines under high geothermal gradient conditions exposure to extremely hot water poses another significant health and safety risk to underground mine personnel.

Other challenges in deep underground mines. Deep underground mines face a myriad of other challenges, including logistics, ore haulage, waste rock disposal, communications, etc. From a rock engineering perspective however high rock stress and temperature factors generally dominate risk with the potential to force premature mine closure.

2 Engineering Behaviour of Intact Rock and Rock Masses Under Stress

Rock mass constitutive behaviour depends on both the intact rock and the detailed nature of any discontinuity systems that dissect it into discrete blocks. Advancements in laboratory testing [i. e. stiff test machines; Hoek-Brown triaxial cells; full triaxial test cells], and particularly test monitoring [i. e. acoustic emission monitoring], have provided a much more detailed understanding of the failure processes with intact rock. With sufficient, and sufficiently detailed, laboratory testing the constitutive behaviour of each rock type can be determined by fitting the test data using the Hoek – Brown criteria for intact rock [Hoek and Brown, 1980].

Behaviour of the field scale rock mass(es) however for everything except perhaps the most massive formations, is generally dominated more by the detailed properties of the fracture systems [i. e. fracture spacing, persistence, surface conditions] than by the behaviour of the intact blocks as illustrated in Fig. 2. For the purpose of this paper, the focus will be on the risks associated with rock mass behaviour as indicated in the right-hand column highlighted in Fig. 2.

All materials respond to stress change by deformation or, in engineering terms, strain. Depending on the local UCS, the modulus ratio, the local structural domain and mine induced stresses, the resulting rock mass behaviour can vary widely, from completely brittle to perfectly plastic or strain softening [Fig. 3]. Most deep mine rock masses exhibit strain softening behaviour to varying degrees. It is now commonly accepted that rock mass yield and associated seismicity begins when mine induced $\sigma_1 >$ ~0.3 Unconfined Compressive Strength (UCS) (crack initiation) and that damage becomes severe when mine induced $\sigma_1 >$ ~ 0.5 UCS (crack coalescence). Accumulated plastic strain is now commonly used as a proxy for rock mass damage in numerical modelling. Accumulated plastic strain however depends on details of the assumed constitutive model [Fig. 3] which are, at best, semi-empirical. The assessed risk and risk mitigation measures also vary in the extreme and depend on the reliability of the modelling output. It is always important to remember the well known saying that all models are wrong; some however are useful. The remainder of this paper will focus on high stress/brittle and strain softening rock mass behaviour and high rock temperature risks and associated risk mitigation measures.

2.1 Input Parameter Uncertainty

A combination of financial and technical constraints on the evaluation of far field stress inputs combined with uncertainty associated with the empirical evaluation of field scale fractured rock mass constitutive behaviour [Fig. 3] represent significant challenges to deep mine risk assessment.

3 Major Rock Stress Related Risk Factors in Deep Mines in Strong, Brittle Rock Masses

Hard, strong, brittle rock resists deformation and as a result stores mine induced strain energy. In such cases initial failure is normally exhibited as spalling [i. e. tensile failure at the (near) surface of the excavation]. Figure 4 shows an example of such failure at the borehole scale [well bore breakout]. Figure 5 shows similar behaviour at the stope scale. At the mine development scale, if the stored strain energy reaches a critical level, such failure may exhibit as a local rock burst or ‘strain burst’. Rock bursts occur as a violent, instantaneous failure where the stored strain energy, if not appropriately contained, can eject rock into the mine opening at very high velocity resulting in high risk to both mine personnel and equipment. Depending on the detailed local conditions rock burst damage can exhibit various forms [Fig. 6].

Underground structures are not damaged by natural earthquakes unless the displacing portion of the fault directly intersects the underground opening. The reason for this is that the wavelength of natural earthquakes is so large that the entire structure moves and does not generate shear strain on the structure. Rock bursts however have their epicenter in the near field of the underground mine openings and the resulting seismic waves can impart significant differential strain on the excavation surface. If these deformations cannot be contained, then damage to the mine openings will occur. In the most severe cases this can result in ejection of rock from the boundary of the excavation.

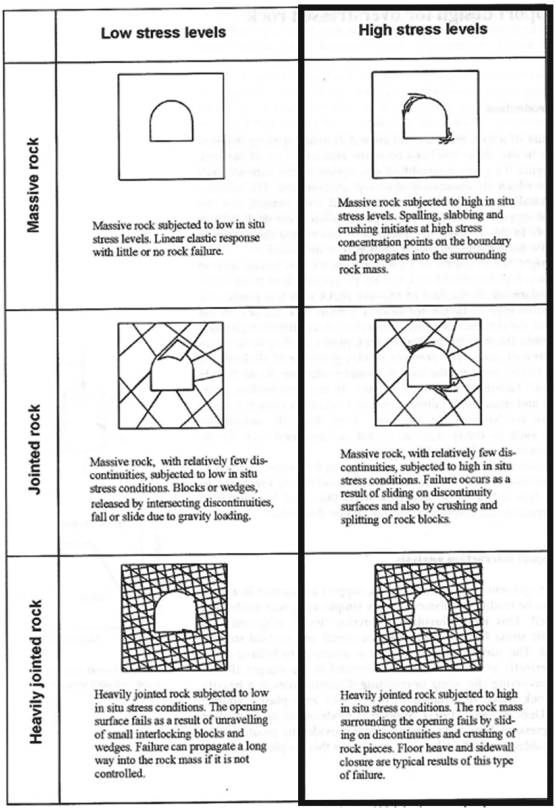

Fig. 2: Types of rock mass failure which occur in different rock masses under low and high in situ stress levels [Hoek, Kaiser & Bawden (2000)]

Depending on site specific characteristics [e. g. Richter magnitude (M_L); epicenter distance, rock mass brittleness, ground support, etc.] damage can vary from none to extreme. Figure 7 shows an approximately 350 t rock displacement in one of several intersections from the back of a 5 m square mine development opening due to an ~3M_L event [Bawden & Jones (2003)]. This event was unexpected, and no burst resistant support was in place. Severe damage occurred over 5 levels [~ 150 m vertical and approximately 150 m on strike] resulting in abandonment of the most severely damaged level. The failure extended > 4 m in the back and completely overtopped the ground support on that level.

Figure 8 shows a more local fall of ground [FOG] from an ~1.5 M_L event. Both of the above incidents occurred without warning and could have resulted in serous injury and/or fatalities had mine personnel been present. In fact, due to the brittle nature of hard rock there is seldom any warning of an impending damaging rock burst. It is therefore imperative that other measures be employed to protect mine personnel and equipment as discussed later in this paper.

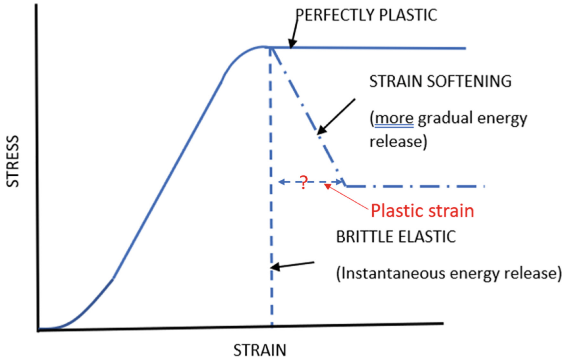

Fig. 3: Intact rock and rock mass failure modes

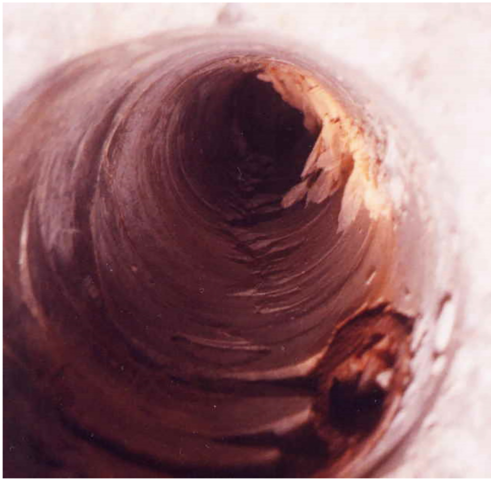

Fig. 4: Brittle spall of a bore hole wall

Both of the above burst related failures occurred at depths ≤ 1,000 m in only moderately brittle rock. In terms of deep mining, it is important to repeat that stored strain energy does not increase linearly with depth (D) but rather with D^2. Seismic risk therefore also increases with D^2 and for each 1.0 M_L increase in rock burst magnitude released energy increases by a factor of 32. A 3.5 M_L event releases the equivalent energy of ~73 tonnes of TNT.

In weaker and/or more highly structured rock masses at great depth rock mass performance is more often dominated by extreme closure [i. e. squeezing] conditions. While high closure conditions generally present less immediate risk to mine personnel and equipment it can still have serious negative impact on mining costs, ultimate mine life, etc.

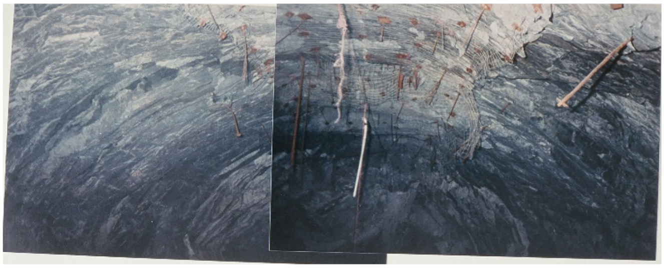

Fig. 5: Brittle spalling at the production stope scale (15–20 m span)

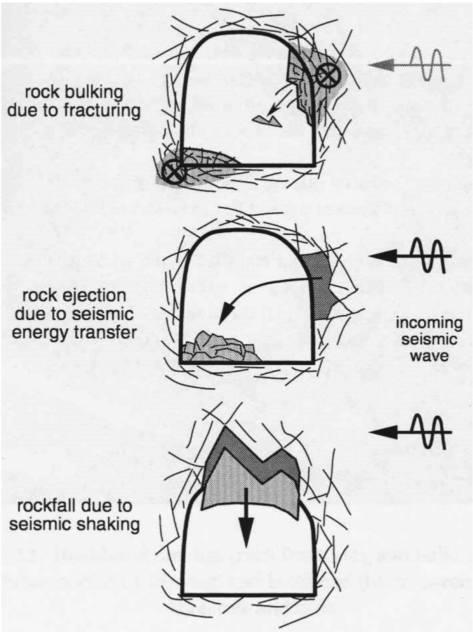

Fig. 6: Modes of rock burst damage [Canadian Rockburst Research Handbook (1990–1995)]

4 Major Rock Temperature Related Risk Factors in Deep Mines

Rock mass temperature always increases with depth. The rate of increase however depends on the local geothermal gradient. As a general rule, away from plate boundaries, the crustal temperature rises at between 25–30 °C/Km depth. Very deep mines therefore always suffer from high temperatures. If not effectively countered these high temperatures adversely impact both human and in some cases equipment performance. In fact, in the common case of underground diesel equipment, the heat generated by the equipment further exacerbates the heat stress due to the rock temperature. Exposure to extreme heat can result in occupational illnesses and injuries. Heat stress can result in heat stroke, heat exhaustion, heat cramps, or heat rashes. Heat can also increase the risk of injuries to workers as it may result in sweaty palms, fogged-up safety glasses, and

Fig. 7: Back collapse resulting from an ~M_L 3.0 mine induced seismic event

Fig. 8: Damage from a ~1.5 M_L near field event – note that FOG largely between support elements

dizziness. Heat stroke is a serious and potentially fatal medical condition. Controlling temperatures to which mine personnel are exposed is therefore critical to the wellbeing of mine personnel and the overall mine performance. The presence of groundwater under such conditions exacerbates the risk to mine personnel. For example, drillers may need to wear additional Personal Protective Equipment [PPE] to protect from potential scalding injury. In virtually all cases, high rock temperatures impair mine personnel performance.

5 Other Risk Factors

Numerous other risk factors impact performance in deep mines. A non-inclusive list includes logistics, critical mine infrastructure [e. g. ore passes, ventilation raises, shafts, etc.], communications, dewatering, etc. These are not strictly geotechnical in nature and are therefore beyond the scope of this paper.

6 Risk Mitigation Measures

6.1 Highly Stressed Ground

Seismicity resulting from excessive mine induced rock stress presents one of the most serious risks to deep underground mines. Stress induced rock mass failure in hard, brittle rock is accompanied by seismic energy releases. If the seismic energy release results in damage to the surrounding mine openings, it is classified as a rock burst. Risk mitigation measures can include optimized (robust) mine design, instrumentation, dynamic ground support systems and equipment automation and robotics as discussed below.

Robust Mine Design. Basic mine design forms a critical element of risk control in all seismically active mines. Utilizing a chevron mining layout is a common stress control technique. Figure 9 shows an example of a pillarless overhand chevron mine layout. This design pushes stress onto the abutments, eliminates the risk of pillar bursts and provides for more uniform stress conditions on each level simplifying ground support design. This however comes with operational penalties [e. g. necessity to often move equipment between levels, etc.]. Chevrons can also be designed using a primary-secondary approach, but the lead/lags must be carefully controlled to achieve the desired pillar behaviour.

Underhand mining [i. e. mining under cemented backfill] is another rockburst control technique commonly employed in steeply dipping orebodies [e. g. Lucky Friday Mine, USA] and can be coupled with chevron mining fronts. This method attempts to push the yield font down such that mining can occur in yielded (i. e. destressed) ground, thus reducing rockburst risk. Multiple chevrons are often required for production reasons. Merging adjacent chevrons usually results in local areas of very high stress and hence risks that require careful management. These mining methods also require highly disciplined mining as rigorous adherence to the design sequence is critical to success with the method.

This discussion is not meant to be comprehensive and other mine design approaches [e. g. destress blasting, etc.] can also be utilized, although the effectiveness of such techniques is highly controversial.

Instrumentation. Instrumentation is critical to risk management in seismically active mines. Most seismically active mines employ mine wide seismic monitoring systems. These are very extensive and employ both micro and macro systems incorporating single and three-component geophones and accelerometers normally complimented with one or more large motion [1 Hz] geophones in order to cover the wide frequency spectrum that occurs with mine induced seismicity. The mine wide seismic systems allow location of the seismic events in 3D within the mine along with the relative magnitudes [Fig. 10]. This allows operators to easily visualize the high-risk areas for seismic activity

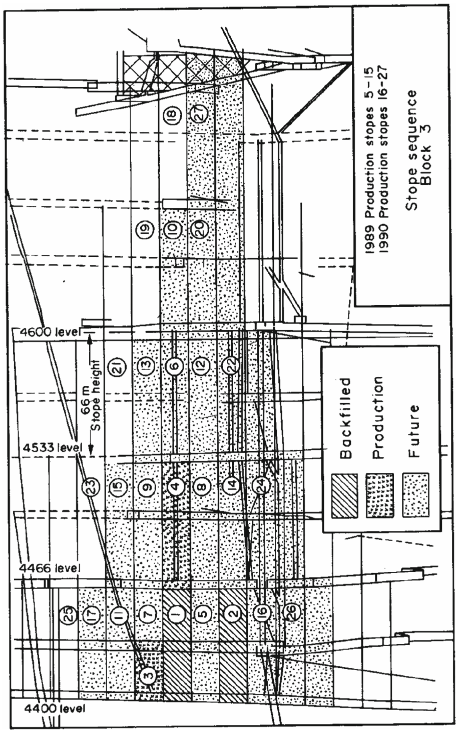

Fig. 9: Pillarless overhand chevron mine layout

and provides a means to estimate the potential seismic risk. Areas of significant seismic clustering are generally interpreted as indicating the zone of active rock mass yield [i. e. the yield front] and hence areas of increased risk to mine personnel and equipment.

Modern mine seismic systems collect the full seismic waveforms for each event that allows more in-depth analysis of aspects such as source mechanism, energy release rate, etc. Seismic data further provides a very useful tool in calibrating the 3D numerical models commonly employed as part of both tactical and strategic mine planning. For example, one method to achieve qualitative calibration of complex non-linear numerical models is to overlie the measured seismic clustering over the model predicted yielded [i. e. destressed] zone [Fig. 11], and then to adjust rock mass parameters to improve the fit if necessary.

Two additional very important seismic analyses used in mine seismic risk mitigation are: (i) Omori (event rate – time) plots and (ii) Gutenberg-Richter [event rate – magnitude] plots. Omori plots [Fig. 12] indicate the time following a blast or large seismic event for seismic event rates to return to background levels and is commonly used to set re-entry times for mine personnel. Gutenberg-Richter event density – magnitude plots [Fig. 13] are used to estimate the maximum likely event size and return rate. These plots are used to assist in ground support design for seismically active areas and in extreme cases to help determine the feasibility of continued mining.

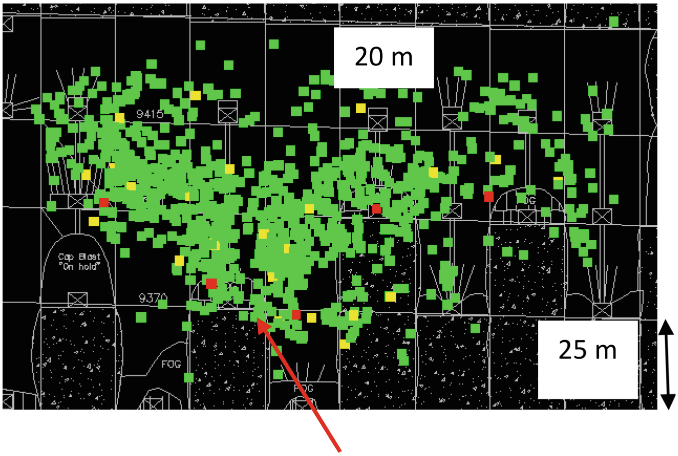

Fig. 10: Seismic event clustering in a highly stressed sill pillar in a Canadian mine.

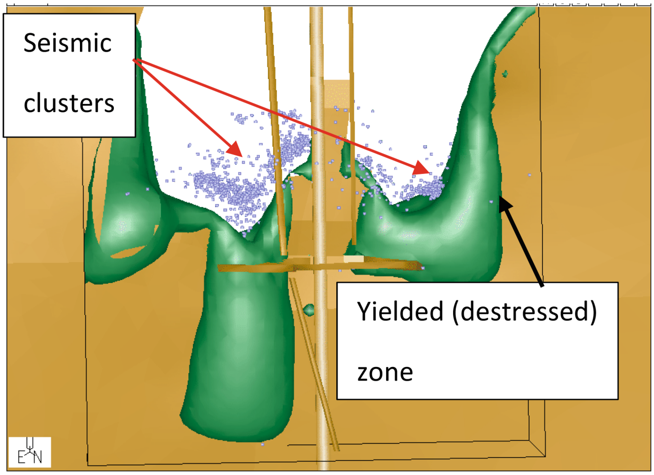

Fig. 11: Mine induced seismicity overlain on numerically interpreted yield front [after McMullan et al. 2004]

Conventional instrumentation is equally important as seismic instrumentation for risk mitigation. Such instrumentation normally includes instrumented 'SMART' cable bolts, Multi Position Borehole Extensometers [MPBX's], sloughmeters, contractometers and laser scanners. Smartcables allow direct measure of the strain, and hence inferred load, that the deep ground support elements have been subject to. Other instrumentation passively measures ground deformation from which support load, etc., can in some cases be inferred.

Today borehole-based instruments are normally monitored remotely using wireless underground telecommunication systems with data being available to the engineer and management in real time. Laser scanning devices, under high seismic risk conditions, are operated robotically.

Bawden and Jones [2003], demonstrate the use of seismic monitoring combined with SMARTcables to optimize rehabilitation of areas damaged by rock bursts in a highly stressed sill pillar. In this case Smartcable output Data was used to maximize rehabilitation efficiency by only replacing consumed support capacity resulting in significant improvement in safety and rehabilitation cost savings [Fig. 14].

Dynamic Ground Support. In relatively low stress environments underground, support systems are normally designed to be strong and stiff so as to minimize any

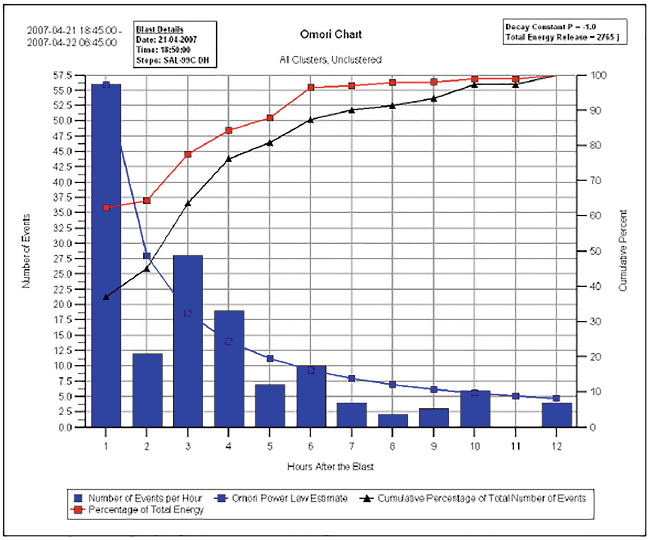

Fig. 12: Omori plot from mine induced seismic data

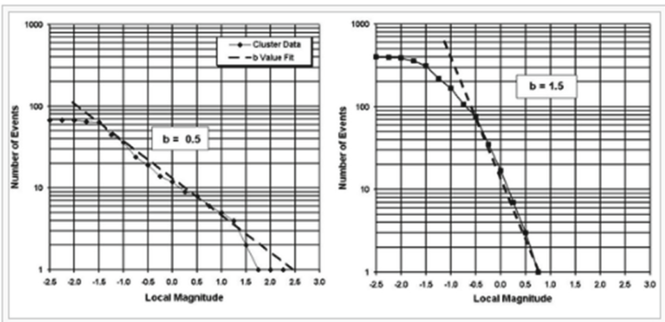

Fig. 13: A Gutenberg-Richter event – magnitude plot showing maximum potential event size ['b' values related to likelihood of a seismic event. Smaller 'b' values [< 1.0] indicative of fault slip; larger 'b' values [1.2–1.5] indicative of failure mechanisms related to stress change (After https://minewiki.engineering.queensu.ca/mediawiki/index.php/Mining_induced_seismicity)]

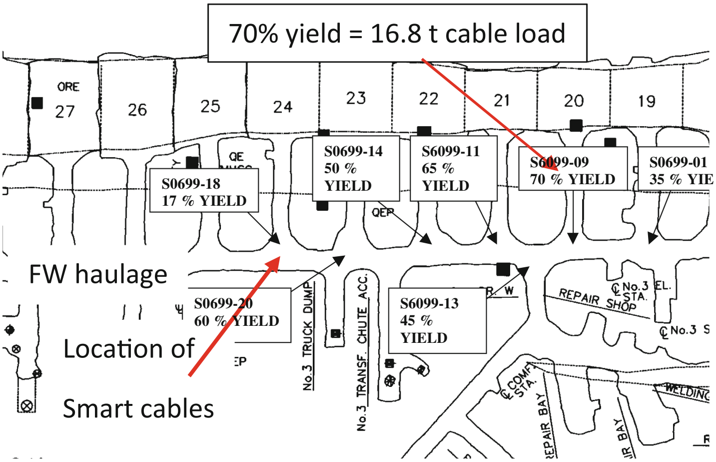

Fig. 14: Level plan showing impact on Smart cable Loads due to 1.8 M_L event.

displacement or dilation on local structures and thus preserve the inherent strength of the rock mass. At depth, however, strong, stiff rock masses tend to store mine induced strain energy that can then be released instantaneously as violent seismic events [rockbursts] that damage underground openings.

Damage occurs due to the response of the excavation surface to the incoming seismic strain wave(s). The seismic wave(s) cause accelerated displacement of the excavation surface into the mine opening. If the ground support system is not capable of dissipating the seismic energy and containing the displacing ground, rock materials will be ejected into the opening posing significant risk to exposed personnel and equipment. In order to prevent this the ground support must be able to allow sufficient displacement to dissipate the seismic energy without failing. Dynamic support systems are meant to accomplish this and therefore should be designed using 'displacement support design' rather than 'load support design' methods (Kaiser & Moss, 2022). Mine induced seismic data is particularly critical to displacement support design.

Dynamic ground support systems are composed of a number of independent elements [e. g. short primary support; deep secondary support; and surface support]. In order to be successful these 'independent' elements must act as a 'system'. The capacity of such a system is that of the weakest element. Over the past ~20 years numerous options have been developed for each of these elements. Table 1 presents an abbreviated list of available independent support elements. The details of deformation and load capacity for each element is provided in the manufacturer's specifications.

Figure 15 shows an idealized dynamic ground support design, while Fig. 16 shows details of the surface support design. An incoming seismic wave causes the surface of the excavation to move into the opening. The surface support must contain this often highly fractured rock and transfer this load to the deep support elements to dissipate the energy. Because such systems fail at the weakest elements, the surface support design is critical and must be both strong and tough. The most common mode of failure in such systems occurs along the mesh overlaps (Fig. 17). To help alleviate this the optimal design is to

Table 1: Abbreviated list of dynamic support elements

PRIMARY SUPPORT	
	MODIFIED CONE BOLTS
	'D' BOLTS
	GARFORD DYNAMIC BOLTS
	NCM BOLTS
	FRICTION BOLTS*
SECONDARY SUPPORT	
	DEBONDEED CABLE BOLTS
	GARFORD DYNAMIC BOLTS
	NCM CABLE BOLTS
SURFACE SUPPORT	
	SHOTCRETE; FIBRECRETE
	WOVEN WIRE MESH
	WELD WIRE MESH
	GEOBRUGG MESH
	'0' GAGE STRAPS
	OSRO STRAPS

*Extremely weak in shear and therefore generally not used in dynamic support systems

first apply plain shotcrete or [preferably] fibrecrete to the surface of the opening and then bolt through the shotcrete with appropriate mesh installed in intimate contact with the shotcrete. Shotcrete is a brittle material and fractures upon any significant displacement. The fractured shotcrete blocks however tend to be much larger than the normally much more finely fractured underlying rock, therefore allowing a more uniform loading to the mesh and hence the bolt elements. This helps prevent point loading of bolts and failure along the mesh overlaps. Geobrugg mesh and Osro straps, combined with fibercrete, offer the highest combination of strength and deformability in surface support.

In dynamic support design it is important to attempt to match the deformation characteristics of the various support elements, with the exception of shotcrete, as closely as possible. The total system capacity is the total energy absorption capacity determined as the summation of the energy capacity of all of the combined elements. Further details on dynamic ground support design can be found in the Canadian Rock Burst Research Program 1990–1995.

Other Measures. A guaranteed method to reduce risk is to reduce exposure. Automation and robotics of mine equipment offers the potential to largely eliminate the risk for mine personnel. While these technologies have advanced significantly over the past 20 years, for many reasons they have not yet reached to stage where personnel risk can be completely eliminated.

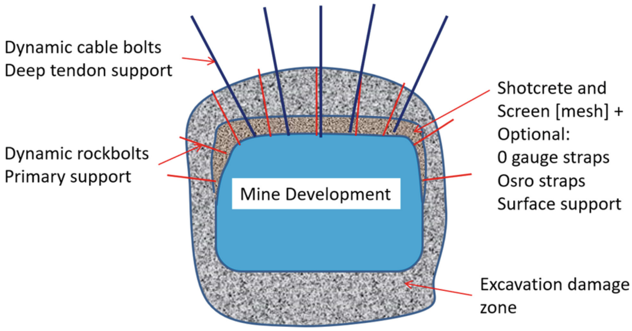

Fig. 15: Dynamic ground support design

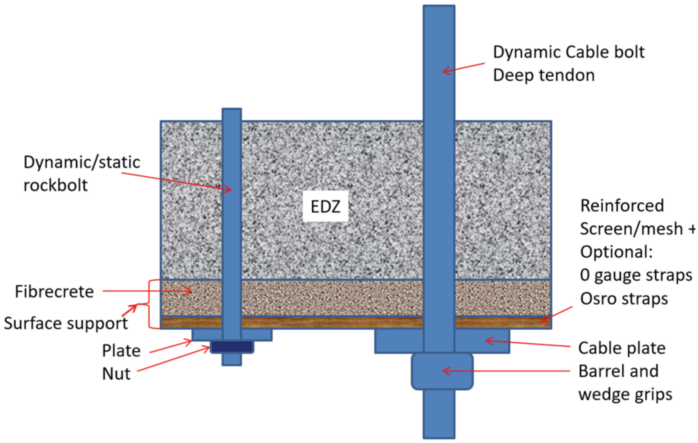

Fig. 16: Dynamic surface support design

7 High Rock Mass Temperature

Excessive temperature can present a health and safety risk to humans. Ventilation in underground mines is used primarily to displace air contaminated with rock dust, diesel particulate matter [DPM], noxious gases, etc., that present serious health risk to underground personnel. Where high rock temperatures exist, the incoming ventilation air is often also chilled to help control temperature. In some cases, individual chilling vests are also provided to underground personnel. Due primarily to power cost, ventilation represents one of the major underground mining costs. While the temperature control measures discussed above represent a further cost escalation, the alternative is to significantly reduce personnel face time. Electrification of underground equipment, along with equipment robotics and automation, by reducing personnel exposure, holds the potential to significantly reduce both high stress and temperature risks while significantly reducing ventilation requirements, usually one of the highest direct mining costs. This of course introduces other potential risks such as how to access and extract equipment affected by mechanical/electrical failures or damaged by falls of ground.

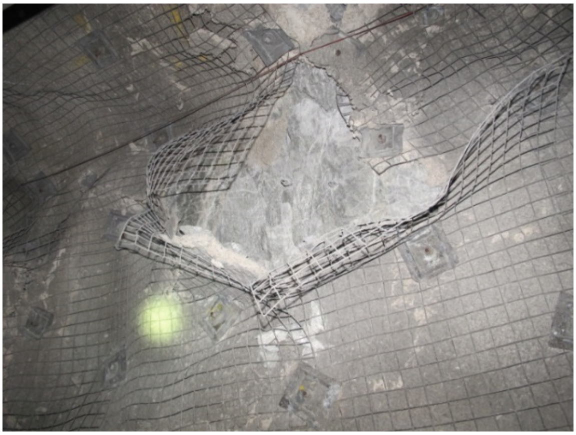

Fig. 17: Failure at mesh overlap

8 Conclusions

Mining at depths at or approaching 3–4 km below surface, presently the deepest mines in the world, has only been made feasible through the application of continued cutting edge technological advances. The demand to significantly reduce/eliminate greenhouse gas [GHG] emissions is entirely dependent on significant additional advances in system electrification and energy storage among other technologies. The secure supply of critical minerals [e. g. nickel, copper, cobalt, lithium, etc.] required for the above technologies presents an existential risk to the climate change control global endeavour. For many reasons [e. g. environmental, geopolitical, national security, etc.] deep mining will be central to the global challenge to control climate change. Success in these endeavours will depend on our ability to develop innovative, environmentally acceptable and economically feasible solutions to the issues discussed in this paper.

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