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Ground Support for Extreme Conditions

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ABSTRACT

Ground support is routinely employed to maintain the structural integrity of excavations in rock. In extreme conditions, such as observed in seismically active mines, and in excavations in squeezing rock, this can be challenging. In seismic conditions, ground support is required to prevent excessive levels of rock mass dilation, sustain confinement around the reinforcement and absorb kinetic energy released through the process of brittle rock mass failure and ejection. This is only possible if the ground support works as an integrated system to maintain the load distribution between all elements. In extreme squeezing ground the role of support is to maintain access for the working life of the excavations. Recent years have seen the development of yielding or energy absorbing reinforcement and surface support elements that can perform better than conventional support in extreme conditions. An improved understanding of the loading mechanisms, and better data on the capacity of ground support, complemented by field observations, have resulted in improved ground support practice for extreme conditions. The long-term performance of ground support can be hindered when exposed to corrosive environments. In extreme corrosive environments ground support is susceptible to degradation that may severely reduce its capacity to meet its performance goals for the intended service life of the excavations. This requires protective processes to prolong the effectiveness of ground support, or to plan for rehabilitation when a reduction in capacity is deemed critical. This paper reviews recent developments in ground support strategies for extreme conditions, including mine seismicity, squeezing environment and corrosive environments. In this context, the role and timing of rehabilitation of ground support can have significant safety and economic implications.

KEYWORDS

Ground support; mine seismicity; squeezing ground; corrosive environments; rehabilitation strategies;

INTRODUCTION

Ground support is integral in maintaining the structural integrity of excavations in rock for their projected working life. Reinforcement is the process where rock bolts and cable bolts are applied internally to the rock mass, while surface support is a technique in which elements such as shotcrete, steel mesh, straps, are applied to excavation surfaces externally to the rock, Hadjigeorgiou and 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.

Excavations developed at shallow to moderate depth, in relatively competent rock masses, are often characterised by relatively low stress and low convergence. These are often described as “normal conditions” and can be adequately supported by conventional reinforcement and surface ground support. Conventional rockbolts include mechanical bolts, (i.e., expansion shell bolts), fully grouted rebars and frictional bolts (e.g., friction rock stabilisers and expandable rockbolts). Li et al (2014) provided a useful performance comparison between conventional and energy absorbing, or yielding rockbolts, while Hadjigeorgiou and Potvin (2011) reviewed the range of surface support elements.

There are several ways to describe “extreme conditions” in underground hard rock excavations. For the purposes of ground support, extreme conditions are those where the potential failure mechanisms are such that maintaining the integrity of an excavation is challenging. Such conditions include seismically active and rockburst prone ground as well as excavations displaying very large deformations (squeezing rock). Highly corrosive environments that may result in degradation and loss of capacity of ground support, are also considered as extreme conditions.

A more nuanced definition of extreme conditions is one that may have severe safety and economic consequences for the operation. This paper focuses on issues associated with the use of ground support under extreme ground conditions in underground hard rock mines.

1. NORMAL GROUND CONDITIONS

A conventional definition of extreme is any condition that is situated at the farthest possible point from a center of a set of ground conditions. Excavations developed at shallow to moderate depth are often characterised by low stress and low convergence and can be adequately supported by conventional ground support systems. Empirical rock mass classification systems have been successfully employed in these conditions. The Q system by Barton et al (1974) uses six constitutive parameters and captures a large range of ground conditions. It has been successfully employed worldwide for a variety of characterization and design purposes in rock engineering, Barton (2002). The original ground support recommendations, Barton et al (1974), were based on ground support technology available to prior to 1973 that included plain shotcrete, steel-mesh reinforced shotcrete, or cast concrete arches along with conventional rock bolts. The updated ground support recommendations using the Q system, Grimstad and Barton (1993), use fibre reinforced shotcrete which is routinely used in tunneling applications. Although the Q system provides design recommendations for conditions that range from exceptionally poor to exceptionally good, it has been argued by Palmstrom and Broch (2006), its applicability is more limited, Figure 1a. They suggest that it should be used for normal hard rock ground conditions from “very poor” to “good”, i.e., 0.1 < Q < 40, and tunnels or caverns of 3 to – 30 m span or height.

Potvin and Hadjigeorgiou (2016) highlighted that the vast majority of constitutive case studies of the Q system, Grimstad and Barton (1993) were based in tunneling, with a limited number from mining. This is significant, given variations in the choice of ground support between tunneling and mining drives, as well inconsistencies by mining operators in assigning an ESR value. At the same time the Q system is used widely to characterise the rock mass in mining applications. Consequently, Potvin and Hadjigeorgiou reconciled rock mass quality data based on the Q system, with the ground support used for mining drives (4 to 6 m span). Based on an analysis from mines in Australia and Canada, Potvin and Hadjigeorgiou (2016) provided preliminary ground support recommendations for a range of Q values (0.01 to 100), Figure 1b. It was recognised that the developed ground support recommendations were not applicable for extreme conditions such as seismically active and squeezing ground conditions. These extreme conditions would require different ground support strategies.

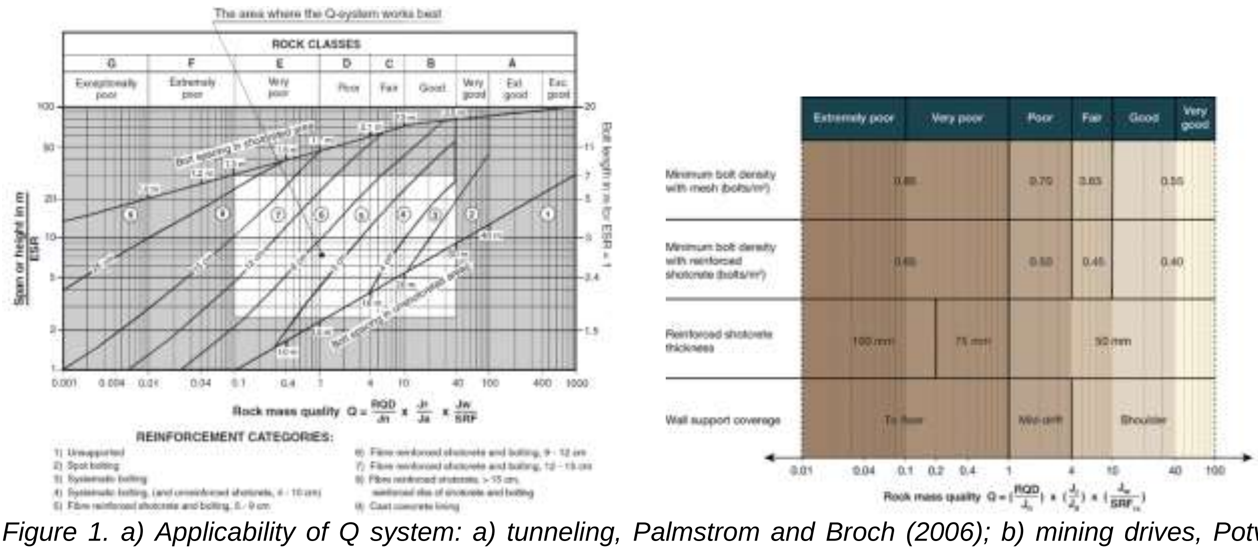

Figure 1. a) Applicability of Q system: a) tunneling, Palmstrom and Broch (2006); b) mining drives, Potvin and Hadjigeorgiou (2016).

Low stress and structurally defined ground are also defined as normal ground conditions. Rigid wedge gravity falls of ground can be routinely analysed using limit equilibrium tools such as UnWedge, Rocscience (2023) or a combination of DFN and limit equilibrium tools, Hadjigeorgiou and Grenon (2017), Figure 2. Both options can assess the impact of ground support to stabilize potentially unstable excavations. As in all design methods, provided the data quality is acceptable and their inherent limitations understood, they are useful. Conventional ground support systems are usually adequate to meet the desired support requirements.

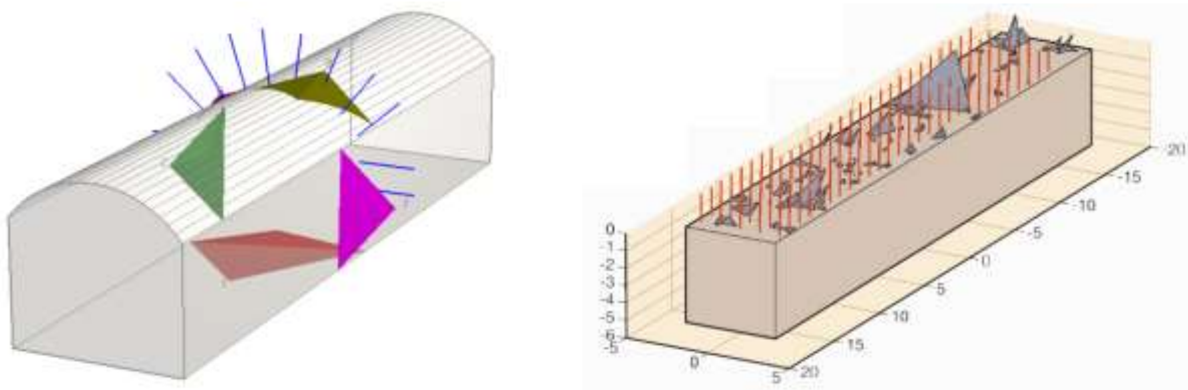

Figure 2. Limit Equilibrium Analysis including reinforcement: a) UnWedge, Rocscience (2023); b) DFN generated rock mass, Hadjigeorgiou and Grenon (2019).

Although high stress conditions can result in stress fracturing of the rock mass, Figure 3a, these are not always considered extreme conditions. The reason for this interpretation is that stress fracturing can be reasonably anticipated using stress modelling, and consequently supported by ensuring the length of reinforcement exceeds the fractured/broken ground zone, Wiles et al (1994). The basic assumption is that the broken/cracked ground has undergone stress driven failure and represents the dead weight that needs to be reinforced, Figure 3b. The use of borehole cameras to determine the extent of fracturing can provide a good indicator of the extent of the fractured zone as well "groundtruth" the results of the numerical models.

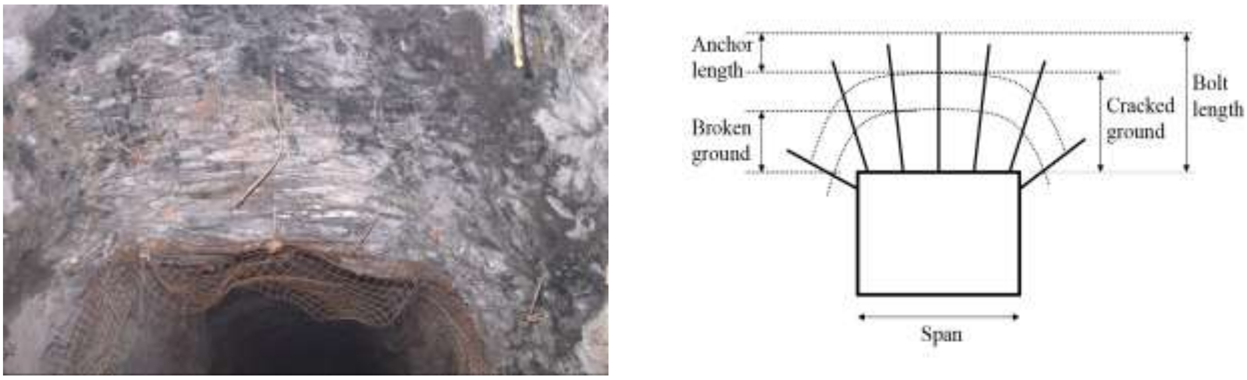

Figure 3.a) Stress fracturing at the back of an excavation, Simser (2023) b) Implicit reinforcement design using numerical modelling tools, Wiles et al (1994).

Several stress analysis tools allow for the explicit representation of ground support and can be used to compare different alternatives or the adequacy of a specific strategy, Sweby et al (2020). The choice of a numerical tool should be driven by the objectives of the analysis and definition of the problem. However, depending on the model requirements (elastic vs elasto-plastic; 2D vs 3D; continuum or discontinuum) the data and calibration requirements can be quite demanding. In several cases, a relatively simpler numerical model, capturing the salient problem requirements, may be adequate for most design purposes in normal ground conditions.

Although all analytical, empirical, and numerical modelling approaches have inherent limitations, there are multiple tools available that can be used with success in normal ground conditions. The recommended conventional ground support can usually be installed without major QA/QC issues and is typically able to maintain the stability of an excavation for its intended working life.

2. EXTREME CONDITIONS: MINE SEISMICITY AND ROCKBURSTS

2.1. Mine Seismicity and Rockbursts

In a rock engineering context, a seismic event may occur because of a movement, or creation of a new fracture within a rock mass. A useful classification of seismic events for underground excavations has been proposed by Ortlepp and Stacey (1994). Table 1. Any of these seismic events can potentially result in damage to the ground support.

Table 1.Classification of seismic event sources with respect to tunnels.

Seismic Event	Postulated Source	First motion from Seismic Records	Guideline Richter Magnitude ML
Strainbursting	Superficial spalling with violent ejection of fragments	Usually undetected; could be implosive	-0.2 to 0
Buckling	Outward expulsion of pre-existing larger slabs parallel to opening	Implosive	0 to 1.5
Face crush	Violent expulsion of rock from tunnel face	Implosive	1.0 to 2.5
Shear rupture	Violent propagation of shear fracture through intact rock mass	Double-couple shear	2.0 to 3.5
Fault-slip	Violent renewed movement on existing fault	Double-couple shear	2.5 to 5.0

A rockburst is a seismic event resulting in significant damage to a tunnel or an excavation of a mine. Although several seismic event mechanisms can cause damage, it is convenient to distinguish between strainbursts, in which the source of the seismicity and the location of the damage are coincident, and events in which the source of the seismicity and the location of the rockburst damage may be separated by substantial distances, Stacey (2016).

There are valuable lessons to be gained by reviewing the performance of ground support under seismic loads. Examples of damage following a strainburst are illustrated in Figure 4. In the first case, the ground support failed, while in the second case the installed ground support successfully contained the fractured material. The challenge from a practical perspective is to establish the remaining capacity of the ground support in the latter case, Figure 4b. This is extremely difficult to quantify but is important in deciding whether it is necessary to trigger rehabilitation of the installed ground support in the affected area.

Figure 4. Strainburst a) ground support failed; b) the support retained the ground, Simser (2023).

A characteristic of very large seismic events is that damage can occur at multiple levels. Boskovic (2022) reports on the extent of damage following the May 18, 2020, M_w 4.2 ± 0.2 seismic event at the LKAB Kiirunavaara mine. The aftershock activity that followed was widespread over a 1,000 m away from the hypocentre of the main event. The May 18, 2020, event damaged several kilometres of drifts on six mining levels and had an impact on several production areas at different levels. Figure 5 illustrates different degrees of damage following the seismic event.

Figure 5. Examples of severity of damage: (a) Heavily damaged area; (b) Area of major damage; (c) Area with the localized damage, Boskovic (2022).

Counter (2014) provides examples of significant damage to multiple levels following a M_N 3.8 seismic event in January 2009 at the Kidd Mine. Damage was significant in intersections which were not heavily reinforced at the time of capital development, Figure 6. An extensive rehabilitation program took approximately 18 months to complete, and upon resumption of mining, another M_N 3.8 event occurred on 13 September 2011, in almost the same location as the event of 2009, on the same poorly developed incipient structure. Damage during the second event was significantly reduced as compared to the first large event, as the density and type of support were modified during the 2009-2010 repairs to better withstand future events of similar magnitude, Figure 7.

Figure 6. Damage following the January 2009 M_N 3.8, Counter (2014).

Figure 7. a) Rehabilitation following the 2009 event; b) Damage following the 2011 event, Counter (2014).

The practical question that a mining operation has to address following a significant seismic event is whether the installed system has sufficient residual capacity. This is not a trivial problem although the use of LiDAR monitoring has shown potential, Jones and Hancock (2020). Counter (2019) provides site specific examples of areas beyond a certain threshold of deformation where the ground support is susceptible to increased risk of failure associated with subsequent seismicity.

An interpretation of the consumption of capacity following an impact load under controlled conditions has been provided by Hadjigeorgiou (2016). Figure 8 is a conceptual representation based on a series of impact loads on a high quality grouted threaded rebar. The first impact load resulted in a split of the tube, but the bolt did not fail. The bolt was subjected to a second impact load and this time failed. This however demonstrates the degradation-failure process in a reinforcement element, under axial loading in a controlled laboratory environment. It is difficult to demonstrate the same phenomenon in the field, where ground support is subjected to more complex loading mechanisms. In seismic mines, failure of the ground support system, is more likely to occur under its weakest link Simser (2007).

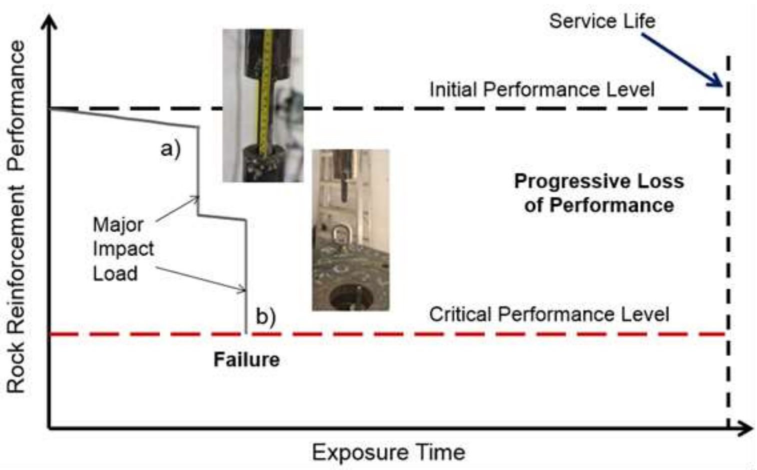

Figure 8. Degradation following an impact load (a) and failure following a subsequent impact load (b), Hadjigeorgiou (2016).

It should be reiterated that ground support is only one of the mitigation strategies in the management of seismicity. Other measures include changes in the mining sequence, destressing the rock mass and the implementation of exclusion protocols where the objective is to reduce the exposure of personnel.

2.2. Design Considerations

The design of ground support in seismic mines does not replace the requirements for maintaining the structural integrity of excavations between seismic events. The traditional design approach has been to extend the factor of safety concept used for static load to dynamic problems. It has been suggested to investigate the resulting factor of safety as a function of displacement capacity and demand, as well as energy capacity and demand, e.g., Kaiser et al (1996), Kaiser and Cai (2012). Other approaches for seismically active mines include the rockburst damage potential approach, Heal (2010), and the Western Australian School of Mines, Villaescusa et al (2013, 2014). Site specific approaches have also been developed by Mikula and Gebremedhin (2017) based on empirical charting, and by Morissette and Hadjigeorgiou (2019) using passive monitoring. All these approaches have merit and can provide useful insights, but they have inherent limitations, Potvin and Hadjigeorgiou (2020).

The performance of ground support, under seismic loads, has been difficult to predict reliably. This is illustrated by case studies where localised failure of the ground support can be observed following a seismic event, while adjacent areas remaining intact, Figure 9. There can be several reasons for these discrepancies, ranging from QA/QC, poor understanding of the seismic loads, inadequate load distribution between surface and reinforcement, yielding vs not yielding ground support, etc. Stacey (2012) concluded that since the dynamic capacity of ground support systems and the demand from seismically induced dynamic loading cannot be reliably quantified, then “…a clear case of design indeterminacy” results, making it “…impossible to determine the required support using the classical engineering design approach”. Furthermore, in a rockburst event, it is essential that no component of the support system fails. This is consistent with the observations of Simser (2007) where a ground support system fails along its weakest link.

Figure 9. Examples of localised rockburst damage.

2.3. Energy Absorbing Ground Support

Under normal ground conditions conventional reinforcement and surface support provide confinement and limit the loosening of the rock mass. In seismically active ground conditions, the rock mass tends to display significant deformation as a result of impact loads. Under these conditions, energy absorbing ground support can better match the anticipated rock mass failure mechanism.

There is plethora of energy absorbing systems that have been introduced in the last twenty years. Examples of these include the use of debonding agents with threaded bars, debonded bars with anchors that are designed to slip or plough through the chemical bonding agent, and paddled energy absorbing rockbolts. Developments in surface support technology include applications using chainlink mesh, straps etc. The objective being to develop a system that can accommodate large deformations.

The development of new ground support elements for seismic ground conditions created the need for specialised testing facilities to quantify their “dynamic” performance. Hadjigeorgiou and Potvin (2011) provided a critical review of such facilities identifying variations in testing rigs and followed procedures. Most testing rigs currently use the direct impact method. In this configuration a free-falling mass impacts on a plate attached to the sample, thereby applying a load, Potvin and Hadjigeorgiou (2020), Li et al (2021). A different testing set-up is used by the WASM rig, Villaescusa et al (2014), where both mass and bolt free-fall at the beginning of the test. In this arrangement the bolt is then abruptly stopped, and the momentum of the mass is transferred to the rockbolt.

There are two fundamental configurations used during impact tests of rockbolts: continuous tube which simulates the application of an impact load directly applied onto the bolt plate; and split-tube used to reproduce the loading condition by impact thrust ejection on the rockbolt. In both setups, the energy dissipated per impact is equal to the area under the impact load and plate, Figure 10. Li et al (2021).

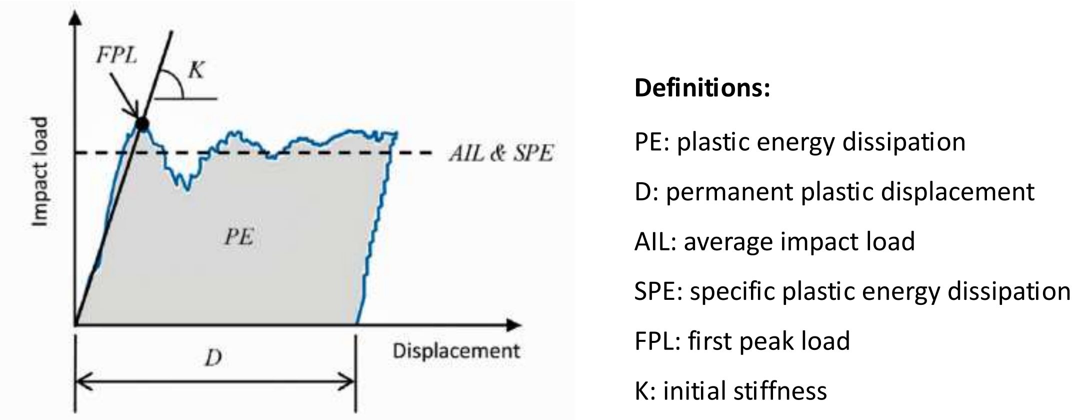

Figure 10. A typical impact load - displacement curve of a rockbolt, Li et al (2021).

Several authors have compiled the results from impact testing for various rigs, e.g., Potvin and Hadjigeorgiou (2020). Villaescusa et al (2014) compiled the results from the WASM rig. In results from both testing configurations, performance trends between yielding and non-yielding ground support elements are evident. The specifics of individual elements under impact loads should be subjected to greater scrutiny given the wide variety of ground support products and testing protocols. Li et al (2021) reported on a series of impact tests of identical rockbolts carried out using the direct impact method on the rigs in four laboratories. It was concluded that there was a degree of testing rig bias when comparing results from different laboratories.

Another useful source of information is through large-scale impact tests that can also investigate the interaction between reinforcement and surface support. The Walenstadt testing rig (Figure 11) has been used to investigate the relative performance under specific loading conditions of different ground support systems, Brändle and Luis Fonseca (2019, 2021). In this case it was possible to investigate the performance of a ground support system used at a specific mine site, providing an insight into the load distribution between reinforcement and surface support elements.

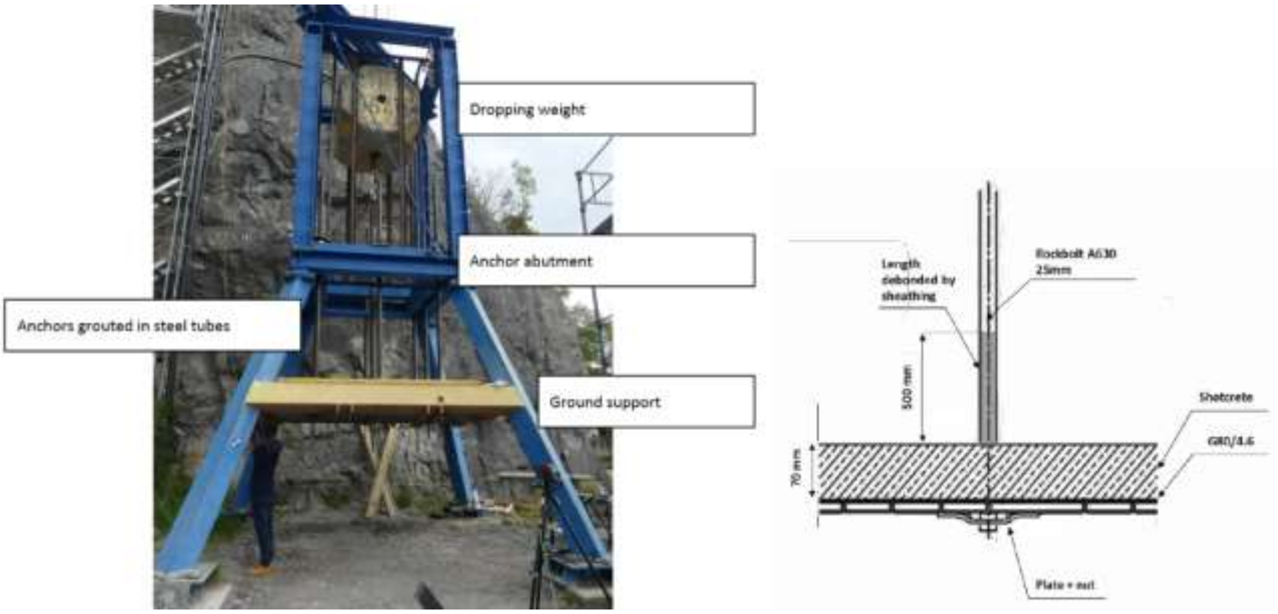

Figure 11. Walenstadt test arrangement (left), tested configuration (right), Brändle and Luis Fonseca (2021).

Although none of the testing systems can fully reproduce the rockburst mechanism they can still provide valuable insights and improve our understanding of ground support behaviour under impact loading. For example, Knox and Hadjigeorgiou (2022) explored the influence of both the presence and location of the split in a continuous tube for paddled energy absorbing rockbolts. Five split configurations were used (Figure 12) and the results are summarised in Table 2. The energy dissipated per impact is equal to the area under the impact load and plate, Li et al (2021). Figure 13 is longitudinal cross-section of a sample after testing using the indirect impact paddle split tube configuration and the location of a rupture point in the paddle set relative to the split in the host tube.

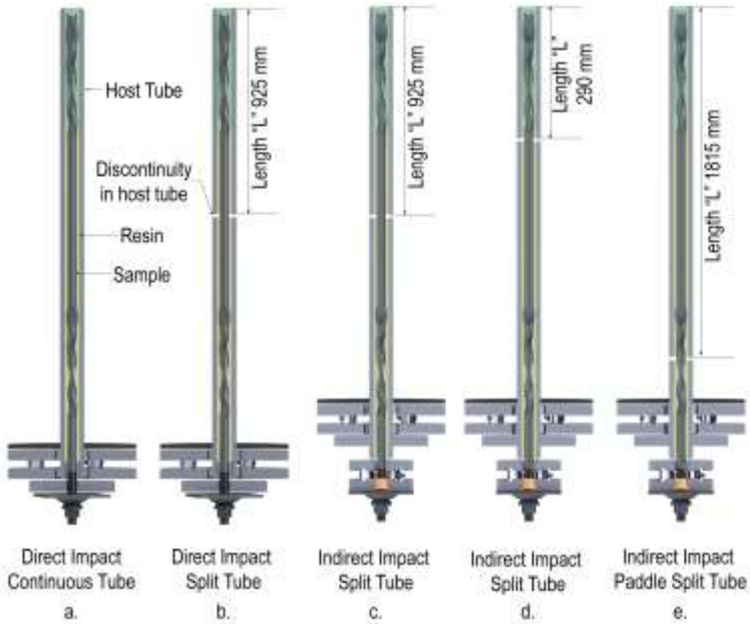

Figure 12. Illustration of split location along the tube for both direct and indirect impact test configurations, Knox and Hadjigeorgiou (2022).

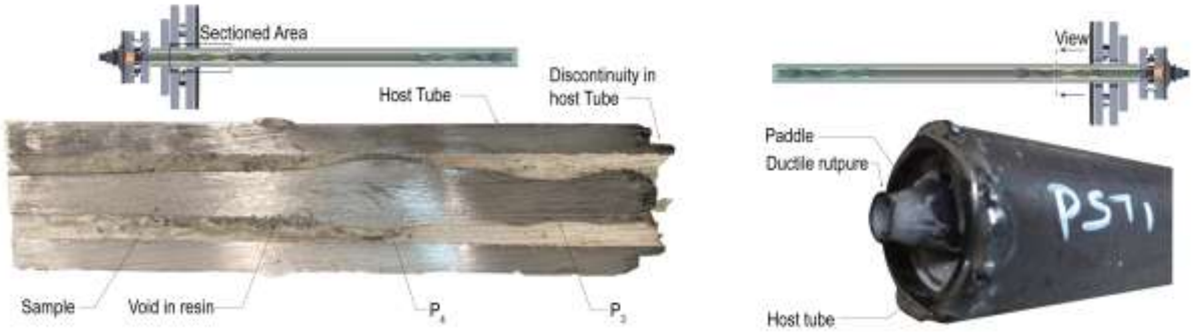

Figure 13. Cross-section of the proximal side of the split through the proximal anchor where the split was located; rupture of the bar on the distal side of the split, Knox and Hadjigeorgiou (2022).

Table 2. Testing Configuration and Results, Knox and Hadjigeorgiou (2022).

Sample	Split position	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

These experiments demonstrated that the split location, had a significant influence on both the maximum plate displacement and dissipated energy recorded prior to the rupture of paddled energy absorbing rockbolts. This has significant implications on the use of laboratory testing results to understand the field performance of energy-absorbing rockbolts under more complex seismic load mechanisms.

3. EXTREME CONDITIONS: SQUEEZING GROUND

Large deformations and squeezing ground conditions result in major operational problems often requiring major rehabilitation of existing support. Figure 14 illustrates examples of structurally controlled squeezing in mining drives at two Canadian hard rock mines, Hadjigeorgiou et al (2013). In general, after very large deformations the mines have to purge the broken rock mass and rehabilitate the area in order to keep the mining drives operational.

The last 15 years have seen significant developments in how mines manage large deformations. These include access to tools to anticipate the level of deformation, e.g., the Squeezing Index, Mercier Langevin and Hadjigeorgiou (2011) and increased use of numerical models. The Squeezing Index, in particular, was shown to facilitate proactive modifications to a mine’s ground support strategy, Marlow and Mikula (2013), Wooley and Andrews (2015).

Figure 15 highlights the influence of the angle of interception (ψ), defined as the angle between the normal to the foliation planes and the normal to the drive wall of interest, on the resulting total strain at the LaRonde and Lapa Mines. It is important to note that the observed severe squeezing at these mine sites would not have been tolerated in a tunneling project where values of 10% strain, are not acceptable.

Numerical models have been used frequently to predict the anticipated levels of squeezing as well to explore the influence of the type and time of installation of ground support as part of a mitigating strategy, e.g., Vakili et al (2013), Karampinos et al (2015, 2016), Bouzeran et al (2020). The complexity and assumptions of these models differs significantly for the given applications. This should be taken into consideration when interpreting the results and interpretation.

No squeezing

Low squeezing: rockbolts take load

Moderate squeezing: convergence

Extreme squeezing

Rehabilitated drift

Purged drift

Figure 14. Examples of structurally controlled squeezing, Hadjigeorgiou et al (2013).

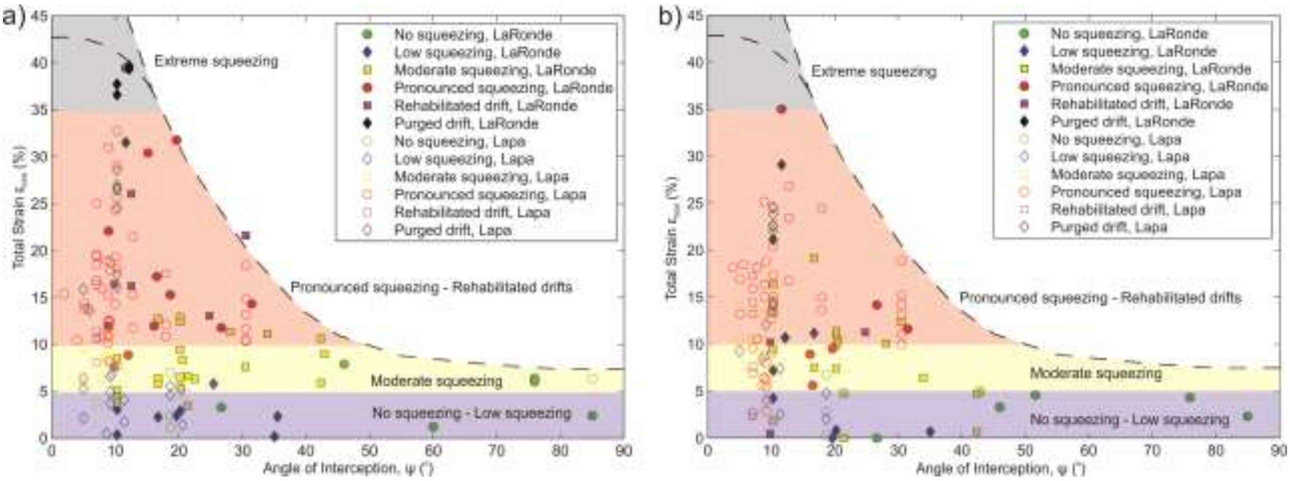

Figure 15. Influence of angle of interception (ψ) on resulting total strain at the LaRonde and Lapa Mines; (a) total wall-to-wall strain; and (b) total back-to-floor strain, Karampinos and Hadjigeorgiou (2018).

Both Lapa and LaRonde managed the high level of deformations (> 35% strain) over time by timing the installation of its reinforcement, using yielding ground support, and bringing the surface support close to the floor to prevent unravelling of the lower walls, Turcotte (2010), Mercier-Langevin and Wilson (2013).

3.1. Ground Support Strategies

In a benchmarking study Potvin and Hadjigeorgiou (2008) observed significant differences in ground support strategies between tunneling and mining. Applying some of the ground support strategies from tunneling to mining was deemed as prohibitively expensive and would result in significant delays in development and production. At the time it was also observed that Australian mines favoured the use of fibre reinforced shotcrete as the principal surface support while Canadian mines relied on welded mesh as part of their ground support to manage large deformations. As shown in Figure 16a, the fibre reinforced shotcrete keeps the rock mass together, is initially stiff until it cracks and the overlaying mesh restrains the large shotcrete plates produced by the excessive wall deformation. The use of weld mesh, Figure 16b, allows the rock mass to deform and shatter before retaining the rock fragments. Although mesh can accommodate considerable deformation it has more limited overall strength capacity. The use of straps is often used with mesh in extreme squeezing conditions.

Figure 16. a) mesh overlaying fibre reinforced shotcrete; b) welded mesh, Potvin and Hadjigeorgiou (2008).

Following a recent benchmarking study Hadjigeorgiou and Potvin (2023) provided a series of guidelines for a range of squeezing conditions. Mines now have access to the same range of energy absorbing ground support elements as for seismic conditions. A further characteristic of best practices includes the use of long reinforcement and installing ground support to the floor.

The influence of stiffness and time of installation of reinforcement to optimise its effectiveness in squeezing ground has been demonstrated by several people, including Turcotte (2010). Installing the hybrid bolt as a secondary support at LaRonde, resulted in significant reduction in rehabilitation.

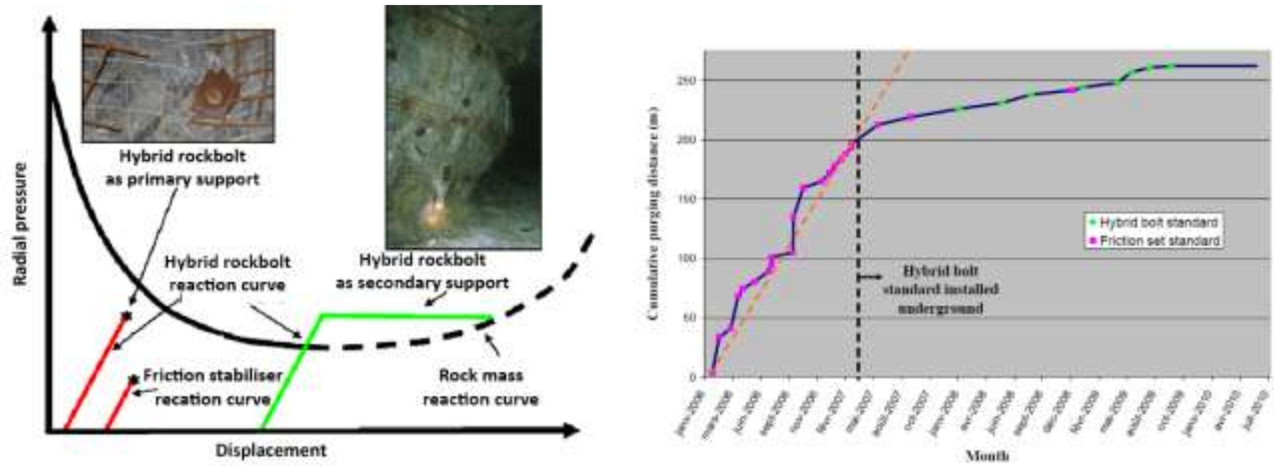

Figure 17. Conceptual reaction curve for the wall (left); cumulative distance purged under the 215 Level (right), Turcotte (2010).

Hadjigeorgiou and Potvin (2023) suggested that there are two fundamental ground support strategies available to mines experiencing very large deformations. The first one uses a sacrificial support, and the second requires a planned rehabilitation. The decision process is illustrated with reference to Figure 18 differentiating between convergence during development of the drive (phase 1), operational stage (phase 2) and phase 3 when mining of nearby stopes results in an increased rate of convergence.

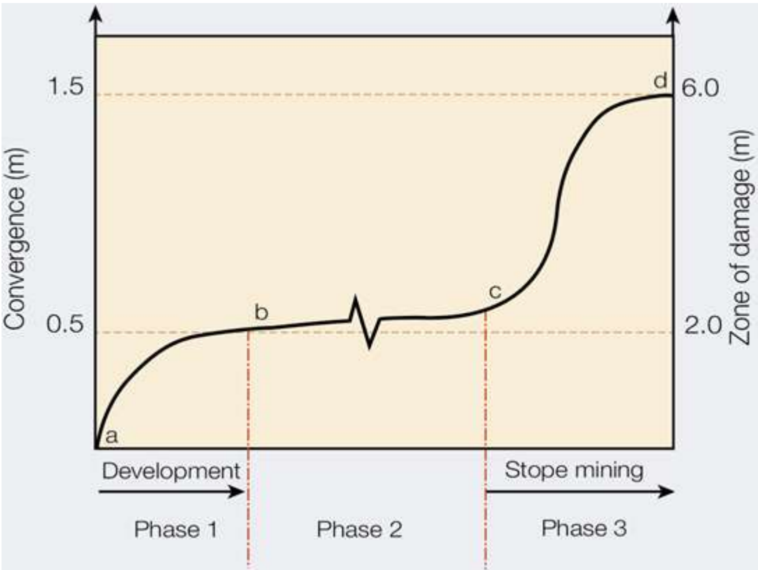

Figure 18. Mining-induced stress changes caused by the development of the drive followed by the mining of stopes nearby resulting in distinct deformation profiles, Hadjigeorgiou and Potvin (2023).

Sacrificial support is used to manage the convergence triggered by development mining. The convergence rate is relatively high immediately after the first development round and then slows down (Phase 1). Ground support is subsequently stripped towards the end of phase 1 and replaced with a system that can sustain the increased deformations associated with stope production (Phase 2 and 3). The convergence is relatively stable during Phase 2 and controlled by the ground support. Stope mining in the vicinity of the mining drive (Phase 3) results in increased convergence and damage within the rock mass. A planned rehabilitation strategy requires rehabilitation of the ground support just before the nearby stopes are extracted (Phase 3). The initial support must be able to manage convergence until just before the stope extraction phase.

4. EXTREME CONDITIONS: CORROSIVE ENVIRONMENTS

The preceding discussions focused on two types of extreme ground conditions, seismically active and squeezing ground. The challenge is to match the most appropriate ground support to these challenging conditions. A further consideration is degradation of a ground support system due to a multiple of extraneous factors including: material quality and the presence of manufacturing flaws; installation issues such as bolt orientation, grout quality; blast damage associated with explosive gases and flyrock; overload of individual reinforcement or surface support elements; damage to reinforcement and support caused by equipment; mine induced seismicity resulting in rockbursts, and corrosion of support systems.

A corrosive environment may invariably result in loss of capacity of installed ground support. However, its impact in seismically active and squeezing ground, can be greater as there is already the potential for reduced capacity due to increased demand, and damage to the ground support as well. Characterizing the corrosive environment is consequently important to evaluate the potential for degradation of different ground control elements. Atmospheric corrosion is the degradation of rock bolts exposed to air and pollutants present in an underground. The rate of atmospheric corrosion is a function of the relative humidity, temperature, and the presence of pollutants such as gas and particles. Aqueous corrosion is an electrochemical reaction that results in deterioration of the material and is influenced by both the characteristics of the solution and the material properties. Microbiologically influenced corrosion (MIC) is the condition where microorganisms present in the water can facilitate or inhibit corrosion.

Different types of ground control elements, exposed to the same corrosive environment, can have varying resistance to corrosion. For example, friction rock stabilisers are perceived to have higher corrosion rates than other ground support elements when exposed to atmospheric and aqueous corrosion, Figure 19.

Figure 19. Friction rock stabilizers showing signs of a) atmospheric corrosion; b) aqueous corrosion.

What is often overlooked are variations in corrosion rates between “similar” rockbolts. For example, it is possible for specific rockbolt types to have similar mechanical properties but different resistance to corrosion. This was demonstrated in accelerated corrosion studies where three similar expandable rockbolts, from different suppliers, exposed in an aggressive electrolyte, showed significant variations in their calculated corrosion rates, Hadjigeorgiou et al (2020). The benefits of corrosion inhibiting coating on rockbolts must be carefully addressed case by case. In an in-situ investigation of six coated expandable rockbolts completely immersed in two aggressive mine waters, there were clear signs of corrosion, Figure 20. A comparison of the performance of these rockbolts is provided in Figure 21 summarising the frequency of pitting attack (by colour) and the estimated corrosion rate, Hadjigeorgiou et al (2019). Although there were significant variations, all bolts performed much better in the less corrosive solution (site A). The other takeaway is that use of some of these rockbolts in these environments would result in premature failure and necessitate earlier rehabilitation of the ground support.

Figure 20. Observed corrosion types along the bolt length: a) general corrosion, b) pitting corrosion and c) pinpoint rusting, Hadjigeorgiou et al (2019).

Type	Site A	Site B
SA-CoatA2-12t	60 µm (120 µm/year)	30 µm (60 µm/year)
SA-CoatA1-24t	120 µm (240 µm/year)	750 µm (750 µm/year)
SB-CoatB1-12t	85 µm (170 µm/year)	470 µm (940 µm/year)
SB-CoatB2-12t	40 µm (80 µm/year)	1,980 µm (3,960 µm/year)
SC-CoatC1-12t	55 µm (110 µm/year)	1,655 µm (3,310 µm/year)
SC-CoatC2-24t	145 µm (290 µm/year)	295 µm (590 µm/year)

Note: **Pit Depth** µm; **Corrosion Rate** (µm/year)

Coating Condition (Pit Density)

- Light – Only few corrosion sites are present, typically due to mechanical damage
- Moderate – Some corrosion sites are present, typically due to mechanical damage
- Heavy - Many corrosion sites distributed on the entire surface of the bolt, closed blisters
- Severe – The whole surface covered with pits, open blisters

Figure 21. Performance of expandable bolts exposed in two solutions, Hadjigeorgiou et al (2019).

Although the long-term performance of ground support in corrosive environments is a complex process, it is still possible to provide some guidelines on when to trigger the rehabilitation process based on field observations, Figure 22. A good example of an effective use of the corrosion level chart is illustrated in Figure 23 where site inspections were used to zone areas of similar corrosion levels. This information allowed the mine to develop and prioritize its rehabilitation strategy. The same approach has been employed at another site by Dorion (2019), to develop a decision matrix to establish the mine's rehabilitation strategy, also considering the consequences of not achieving its production goals due to ground control issues. The mine then issues a rehabilitation plan.

Corrosion Level	Description	Corrosion rate	Loss of capacity	#6 Mesh diam.	Required Intervention
	**C1: Negligible corrosion** Steel is in excellent condition and corrosion evident only on the surface. A few localized spots, less than 10% of the surface is corroded.	< 0.02 mm/yr	< 10%	> 4.75 mm	None
	**C2: Localized corrosion** Corrosion is characterized by localized spots on the surface. Between 10% and 75% of the surface is corroded. Steel is in good condition.	0.02 to 0.04 mm/yr	10 to 20%	4.50 to 4.75 mm	None
	**C3: Surface corrosion** Corrosion over 75% of the surface. Corrosion is only on surface. If a corrosion crust is present, it is very thin. Can identify blisters.	0.04 to 0.15 mm/yr	20 to 35%	4.00 to 4.50 mm	None to follow up.
	**C4: Advanced corrosion** 100% of the surface is corroded. Can identify blisters. Thin corrosion crust (< 1 mm) easily removed.	0.15 to 0.30 mm/yr	35 to 50%	3.50 to 4.50 mm	Follow up. If installed over 12 months, it will display signs of severe corrosion.
	**C5: Very advanced corrosion** 100% of the surface is corroded. Thick corrosion crust (> 1 mm) and flaky.	0.30 to 0.60 mm/yr	50 to 75%	2.50 to 3.50 mm	Consider replacement of installed units.
	**C6: Extreme corrosion** Corrosion goes through the steel. Integrity of steel has been damaged. Pieces are easily breakable by hand.	>0.60 mm/yr	>75%	<2.50 mm	Reconditioning. May require immediate intervention.

Figure 22. Linking on site observations to resulting loss of capacity and required intervention, after Dorion and Hadjigeorgiou (2014)

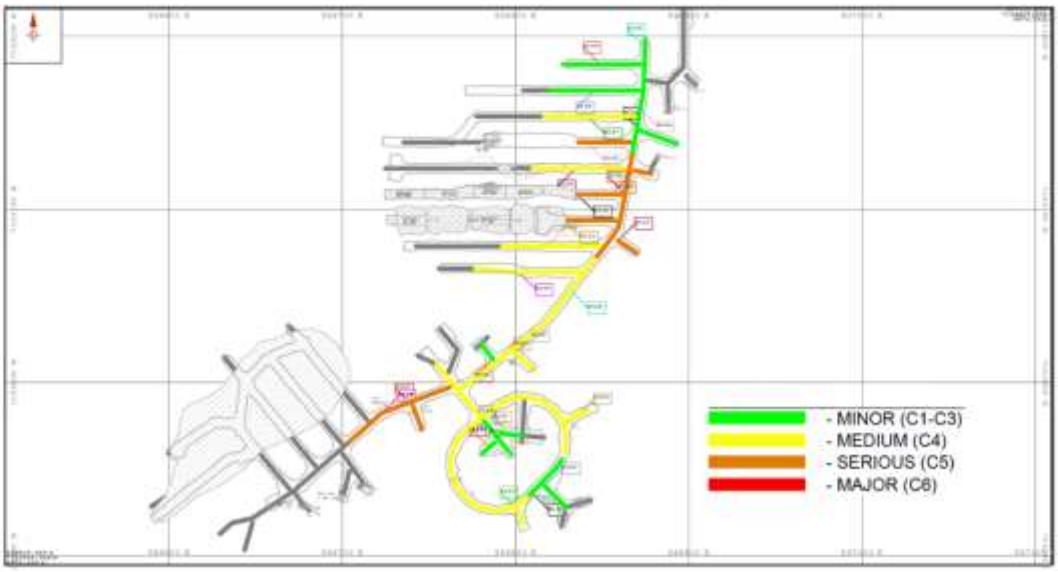

Figure 23. Observed level of ground support corrosion in an underground hard rock mine.

4.1. Interaction of degradation with other extreme conditions

The preceding discussion focused on the degradation of ground support when exposed to corrosive environments. In operating mines, exposed to mine seismicity or extreme squeezing, a corrosive environment can be detrimental to the long-term performance of ground support. For example, a corroded ground support may limit its capacity to withstand a seismic load. This is illustrated conceptually in Figure 24 where a degraded support can fail following a major impact load. This has been observed in field investigations following falls of ground, but it is very difficult to quantify the degree of influence of degradation in the process.

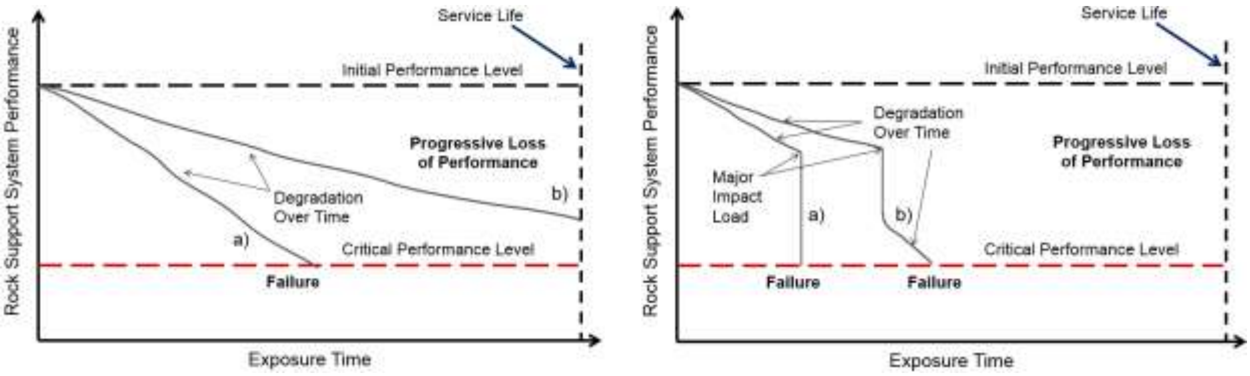

Figure 24. a) Degradation over time resulting in failure; b) Degradation over time, major impact load, and further degradation resulting in failure, Hadjigeorgiou (2016).

Localised corrosion of ground support may also result in developing a weakest link in the system. This can further compromise the structural integrity of the system under additional loading.

5. CONCLUSIONS

Excavations developed at shallow to moderate depth, in relatively competent rock masses, are often characterised by relatively low stress and low convergence. These are often described as “normal conditions” and there are several analytical, empirical, and numerical tools that can be used for the design of ground support. Conventional reinforcement and surface support elements are typically adequate to ensure the structural integrity of excavations in normal ground conditions.

Designing for extreme ground conditions poses significant challenges given the complexity of the loading mechanisms, as well as determining the ground support system capacity. Conventional ground support systems are often inadequate for seismic and squeezing ground, necessitating the use of energy absorbing ground support systems capable of accommodating large deformations. Even when installing energy absorbing ground support systems, it may be necessary to rehabilitate under extreme conditions. The case is made in this paper that determining the threshold and planning for rehabilitation should be an integral part of a ground support strategy for extreme ground conditions.

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