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The ground support life cycle considering real time ground-consumption monitoring

W Bawden *Mine Design Technologies, Canada*

Abstract

Ground support, in its various forms, serves primarily to maintain ground integrity and hence, personnel safety and operational integrity over the operating life of the excavation/s. Ground support damage occurring during mine production and the requisite support rehabilitation represent major risk and cost factors impacting underground mines. These factors become more severe as mining depths and extraction ratios increase. This paper suggests a methodology to better manage both the increased risk and cost issues through near real-time monitoring of ground support consumption through the full extraction cycle.

Keywords: *mine safety, ground support, support design, support consumption, instrumentation, numerical modelling, risk management*

1 Background

1.1 Basic ground support functions

Ground support, in its various forms, serves primarily to maintain ground integrity and hence, personnel safety and operational integrity over the operating life of the excavation/s. The two of the most basic factors impacting ground support behaviour are:

1. Stress relaxation (i.e. mine-induced stress reduction due to factors such as excavation stress shadowing, local rock mass yield etc.).
2. Excessive mine-induced compressive stress increase.

The case of stress relaxation is, in principle, quite simple. As stresses relax, the natural confining stress holding rock block surfaces in intimate contact reduce, allowing dilation (opening) to occur between rock block surfaces. Such dilation, if allowed to proceed, reduces the intimate interlock of the inter-block interfaces resulting in significant loss of rock mass shear strength that can lead to gravity failure and 'unanticipated' falls of ground into the excavation/s. The function of the ground support is to restrain the dilation and maintain the natural rock mass shear strength. In this case, it is critical that the potential for relaxation is recognised early such that appropriate ground support is installed in a timely manner to control dilation.

The case of increasing mine-induced compressive stress is also, in principle, simple. Rock masses respond to increased stress (loading) by deformation toward the mine opening. This deformation occurs through displacement of existing fractures and nucleation and extension of new fractures, both of which require dilation. It is this dilation-driven deformation that then deforms (stretches and may shear) the embedded ground support (steel) tendons and associated surface support. Shearing presents a more complicated support response issue depending on the details of the support tendons employed. For the case of friction bolts, shear resistance should be considered negligible due to the very thin-walled nature of the bolts. Solid bar tendons offer a much higher shear resistance depending on the bar diameter and type of steel. Cable bolts accommodate shear most effectively (Hutchinson & Diederichs 1996, Section 2.8) but in so doing allow additional deformation of the excavation surface. No ground support tendons are designed specifically for shear loading but can be oriented such that anticipated shear places the support tendons in tension.

Other than point anchor rockbolts, ground support elements do not deform uniformly. Rather, deformations are localised within the zone of maximum compressive stress concentration and resulting rock fracture is often located, at least initially, immediately adjacent to the excavation surface.

The underground mining domain is very complex (e.g. varying lithologies, local and regional structures etc.). The mine-induced, stress driven, ground deformations and resulting ground support loadings are equally complex and virtually impossible to predict in detail, at least at the local (i.e. mine drift) scale. An excellent overview of rock reinforcement behaviour, anchoring mechanisms and specifications is provided in Potvin & Hadjigeorgiou (2020).

The fundamental issue, often misunderstood, is that embedded support tendons do not respond to changes in mine-induced stress. Rather, they respond to what changes mine-induced stresses induce, which are local ground deformations. It is the coupling between the local rock mass to the immediate ground support elements that controls support capacity consumption. It is therefore not 'stress' but 'strain' that dictates ground support performance. It is equally important to recognise that, for many reasons (e. g. imperfect rock mass-support bonding), the local rock mass 'strain' will not necessarily be reflected in the local ground support 'strain'. It is the ground support strain that controls ground support capacity consumption and hence, ultimate support system performance.

1.2 Ground support behaviour

The ultimate ground support behaviour is controlled by the ratio of support capacity (P_{Sup}) to demand (D) ((P_{Sup})/D). Support capacity, generally given in terms of ultimate load bearing capacity, is provided by the manufacturer and is normally based on various laboratory test procedures. In situ P_{Sup}, depending on the type of ground support element utilised and local geological conditions, can vary dramatically from manufacturer suggested guidelines since the in situ loading mechanism/s normally varies dramatically from laboratory tests. In the case of dynamic support, the tendon deformation limits are also provided. Once again, these are based on laboratory dynamic tests (e.g. drop tests) and generally indicate the maximum deformability under ideal conditions. Hence the importance of observation and instrumentation as discussed later in this paper.

2 Case study examples

As noted above, the local embedded ground support element behaviour is dictated by the local in situ ground deformation profile.

2.1 Monotonic increase in compressive stress

As mine development occurs, mine-induced stress levels increase and resulting rock mass deformations are normally restricted to very near the excavation surface. Associated ground support element loading is also restricted to this area (Figure 1). If stress becomes sufficiently high, ground support damage is commonly observed in terms of fracturing and dilation of the rock mass, fracturing and spalling of shotcrete if applied, deformed bolt plates, broken bolts and bagged mesh. Figure 2 shows an extreme example of such behaviour with highly deformed and ruptured bolt plates. This behaviour is easily understood and in many cases, routine visual monitoring (damage mapping (discussed in later sections of this paper)) can provide sufficient warning of ground support distress.

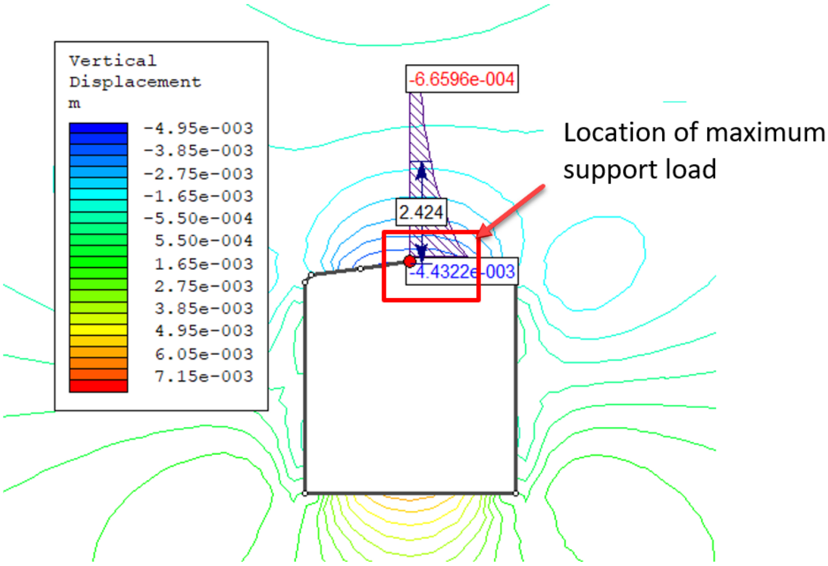


Figure 1 Elastic analysis showing typical location of maximum vertical displacement and therefore, maximum local primary support load

(a) (b)

Figure 2 Highly loaded primary support. (a) Bolt plates on floor; (b) Highly deformed plate

With continued mining, mine-induced stress levels along with their associated induced deformations and ground support loads, extend deeper into the orebody and may result in either (i) insufficient remaining support element embedment length (i.e. support pull out), (ii) support element rupture, or (iii) deformations exceeding the length of the primary support, potentially resulting in 'unanticipated' falls of ground (FOG).

The need for, and timing of, deep secondary support is an important tactical decision during ongoing mining. While numerical modelling can be helpful to this process, providing the model is reasonably well calibrated, instrumentation and observation provide the ultimate decision-making tools. Quantitative calibration of large numerical models is extremely difficult to achieve. A combination of LiDAR survey-based closure measurements, microseismic clustering (assumed to roughly map the existing yield zone at any given mining stage) and damage mapping (e.g. using a typical five-stage visual damage classification scheme), maintained in an ongoing database of damaged and yielded ground versus non-damaged elastic ground and capable of being interrogated by 3D mine rendering software offers the potential to achieve a level of qualitative calibration, fit for purpose, to provide an increased degree of confidence in model predictions. This can have a significant impact on ground support and rehabilitation decisions and costs, and on location and timing of additional instrumentation. The required instrumentation and observational methods are discussed further in Sections 3 and 4 of this paper.

2.2 Stress shadowing

Stress shadowing can also cause serious issues with ground support. Stress shadowing occurs where multiple stopes are mined in relatively close proximity on the same level (e.g. a series of hanging wall–footwall lenses), or where horizontal excavations (stopes or development) can stress shadow underlying supported excavations causing relaxation and loss of support confinement and therefore capacity. Fully embedded ground support tendon behaviour depends on the frictional-based shear resistance developed at the interface between the tendon and the embedment material. In the case of friction bolts, it is the interface at the intimate contact between the support tendon itself and the immediate borehole wall that governs the development of the friction-based shear resistance to movement. Any combination of poor quality embedment materials (e. g. poor quality grout or resin), low stiffness of the immediate borehole rock mass and reduction of the local mine-induced stress generated confining pressure will allow relaxation of the immediate borehole wall causing reduced support tendon friction-based capacity. This can result in stripping failure where the support tendon pulls out of the embedment material resulting in FOG. This issue, in the case of cable bolt support, is summarised in Hutchinson & Diederichs (1996, Section 2.6.2). The case study below provides one example of the significant risk that may occur under conditions of stress shadow induced reduction in support tendon capacity.

Figure 3b shows local development at a mine site. The ramp was driven first. Ore access drive (1) was then driven about 10 m above the ramp. Finally, a second oredrive (2) was driven between the ramp and (1). Back failure of the ramp intersection (Figure 3a) occurred about three weeks later. Critically, the two oredrives were stacked vertically above the ramp intersection. Basic (cartoon level) modelling conducted post-failure (Figure 4), suggested that the combined span from the two ore dives and their proximity (red box in Figure 3a) would largely de-stress the ramp intersection.

The mine is located in a vertical maximum stress field (gravitational) regime. The topography is mountainous and the mining area sits well above the valley floor. No in situ stress measurements have been done but it is evident from historical, mine-wide ground behaviour that the horizontal stress is less than vertical. This, combined with the location above the valley floor, suggests that horizontal stress is likely well below the vertical. The ramp and ramp intersection had been in place and stable for some time (1–2 years) prior to the oredrive development. This author's interpretation, based on the limited observational evidence available, was that the small pillar thickness between the ramp and the second oredrive, combined with development blast damage from the two openings, resulted in any significant 3D increase in horizontal stress increase through the pillar arching to the more massive ground below the ramp, resulting in the observed FOG. Fortuitously, there were no injuries or equipment damage and hence, no detailed back-analysis was conducted by the operation.

The local area was structurally complex with several intersecting faults. This author's interpretation was that the stress shadowing resulted in loss of confinement and inter-block shear strength which then triggered the time dependent, unanticipated FOG (Figure 5). The failure occurred with no warning (i.e. no rock noise, signs of support load etc.), consistent with gravity-driven failure under relaxation conditions. Additionally, no instrumentation had been installed such that small movements that are assumed to have occurred as precursors to the failure were not recognised, although the magnitude of such movement may have been too small to raise alarm. A small sump on Level 2 was drained, but this was not registered until after the FOG and the water inflow into the ramp was not sufficient to raise concerns. It is possible that the existing primary ground support never experienced any additional loading and hence, it is assumed that support capacity was not degraded, but simply collapsed with the destressed rock mass (no evidence of broken support). After this event, mine planning rules were altered to prevent vertical stacking of development.

For an FOG to occur in a stress shadow or relaxation zone, fractures must be able to dilate sufficiently that friction-based shear resistance on wedge bounding structures become severely compromised. Such dilation is normally visually evident and should raise an alarm to an experienced practitioner. In cases of stress shadowing and relaxation, it is critical that the potential for adverse ground conditions are identified at the design stage as simple visual warning signs, as discussed earlier, are likely to be subtle and therefore easily missed by operations personnel. Mine-wide numerical models represent a critical planning tool for identifying stress relaxation zones. Planners, however, must either be trained on interpretation of such tools or the geotechnical department must flag these issues for them. It is for these reasons that borehole MPBX instrumentation is recommended to monitor such areas. Instruments must be anchored beyond the limits of any potential failure zone such that any incipient movements are recorded with confidence. Even relatively small movements of a few millimetres should trigger alarms under these conditions. Such small movements may be too small to raise alarms in standard repeat LiDAR surveys. Under these conditions, the support consumption concepts discussed later would be critical to any risk assessment

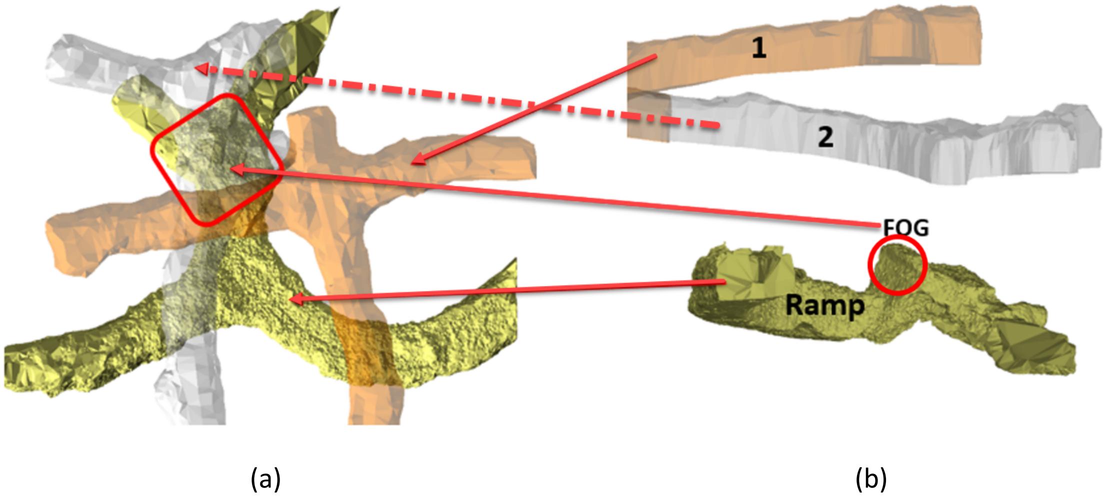


Figure 3 Case study mine development at FOG location. (a) Top view; (b) Perspective view

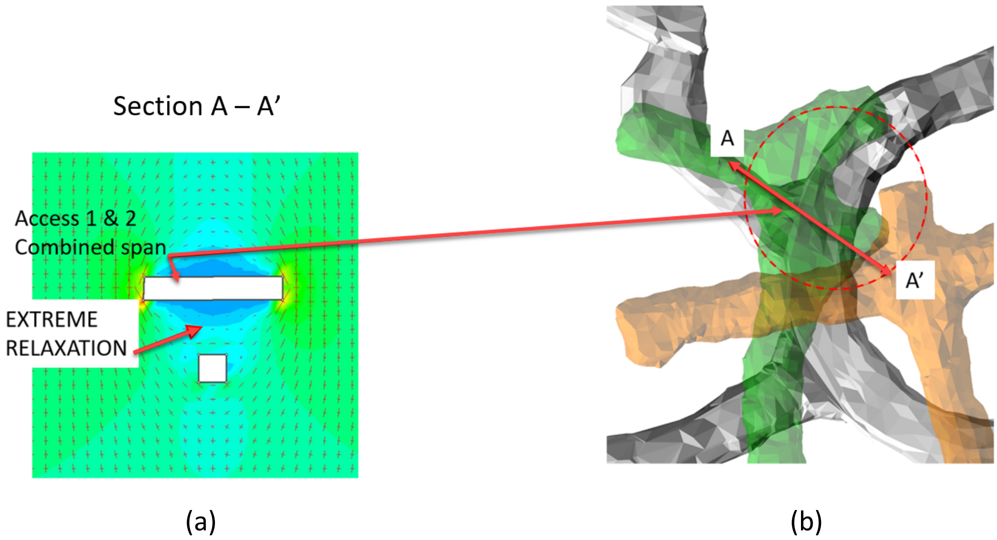


Figure 4 (a) Top view of overlapping drives; (b) Simple illustrative de-stress model

Figure 5 Fall of ground

2.3 Dynamic loading

In March 1999, a very large seismic event (~3.0 M_N) occurred unexpectedly at the Williams Mine in northern Ontario, Canada (Bawden & Jones 2002). Prior to that time, no significant seismic event had occurred at the mine. Key elements of this case study are summarised below because of its direct relevance to the ground support capacity consumption discussion that forms the core of this paper. Additional details of this and subsequent events can be found in Crowder et al. (2006).

Figure 6 shows the seismic event location and the extraction conditions that had led to the Block 3–4 sill being under very high mine-induced compressive stress. The maximum principal stress at that time was about two-times vertical oriented perpendicular to the longitudinal section shown at near 1 km depth. At the time of the seismic event, the mine did not have a seismic system nor any instrumentation in the affected area. Extensive damage occurred on the 9415 footwall (FW) drive (25 m below the Block 3–4 boundary) leading to abandonment of that drive through the sill. Two levels below 9415 were also damaged but remained intact. They were, however, observed to be under very high stress (audible rock noise, spalling and spitting from the excavation surface) and assumed to be seismic related risk.

Although evidence suggested that additional large seismic events were highly likely, a corporate decision was made to attempt to mine as much of the remaining sill pillar as possible. As such, a completely revised ground support design was required. A mine-wide microseismic system was commissioned, and a new dynamic support system was designed including conventional instrumentation (SMART cables). Unlike today, dynamic support elements were almost non-existent in Canada at that time and the concepts were poorly understood at the operational level. Dynamic support was therefore designed using twin-strand, debonded cable bolts – a unique solution at the time – augmented with deep super Swellex type friction bolts. Surface support consisted of resin rebar with weld mesh reinforced shotcrete. Because of the evidence of high mine-induced stress levels and associated seismic risk, rehabilitation had to be conducted with extreme caution.

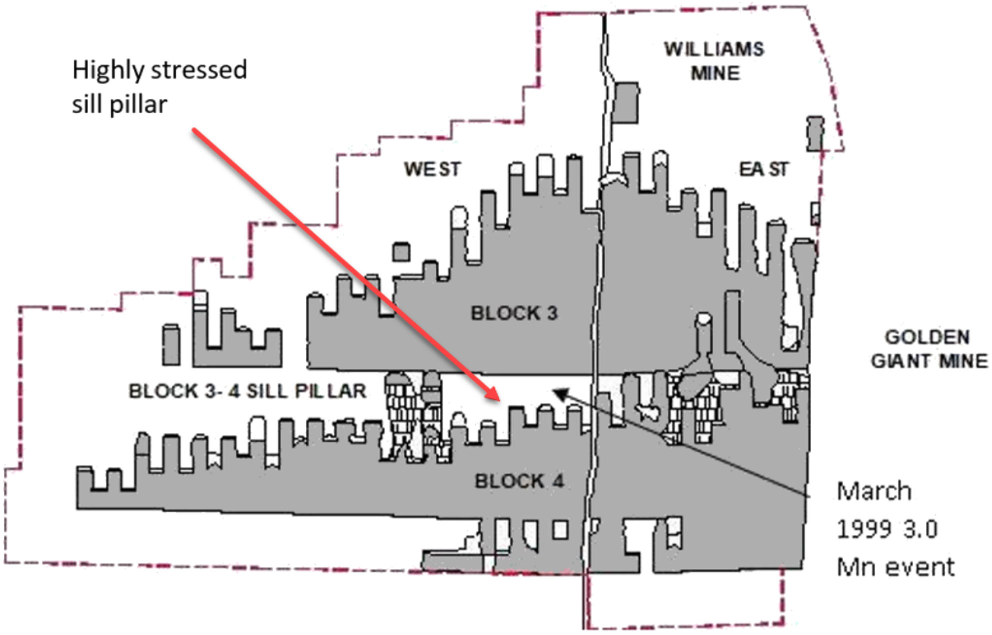


Figure 6 Williams Operating Corporation. Longitudinal view of 'B' zone looking north (modified after LeBlanc & Murdoch 2000)

As discussed earlier, additional large seismic events were anticipated and the first of these occurred in December 2019 as a M_N 1.8 event. An initial local eight-channel microseismic system had been commissioned and all rehabilitation and conventional instrumentation on the levels were in place. Subsequent to this second major seismic event, inspection showed no visible damage (e.g. no cracked or spalled shotcrete etc.). Figure 7, however, shows the SMART cable data as recorded immediately following the event.

The seismic data indicated that the event epicentre was located approximately at the stope 20/21 location. The cable bolt yield data shown on the figure documented the amount of cable bolt support capacity consumed by this single seismic event and how this dissipated with distance from the estimated epicentre. This instrumentation further showed that the major deformation was located 3–4 m into the back, well above the primary support. As noted on the figure, this data allowed the operator to restrict rehabilitation to the immediate area impacted and to restrict rehabilitation to replace only the support capacity consumed by the seismic event. Production was able to continue uninterrupted.

It is important to remember that surface support damage (e.g. cracking and spall of shotcrete) is caused by differential strains at, or near, the excavation perimeter. If the strain occurs at significant depth, and particularly above the top of the primary support elements, then little to no differential strain may be registered at the excavation surface. In this case, the entire primary bolted beam can deflect very uniformly into the excavation with little to no evidence of surface support damage and hence, no visual warning to operators, as evidenced in this case study.

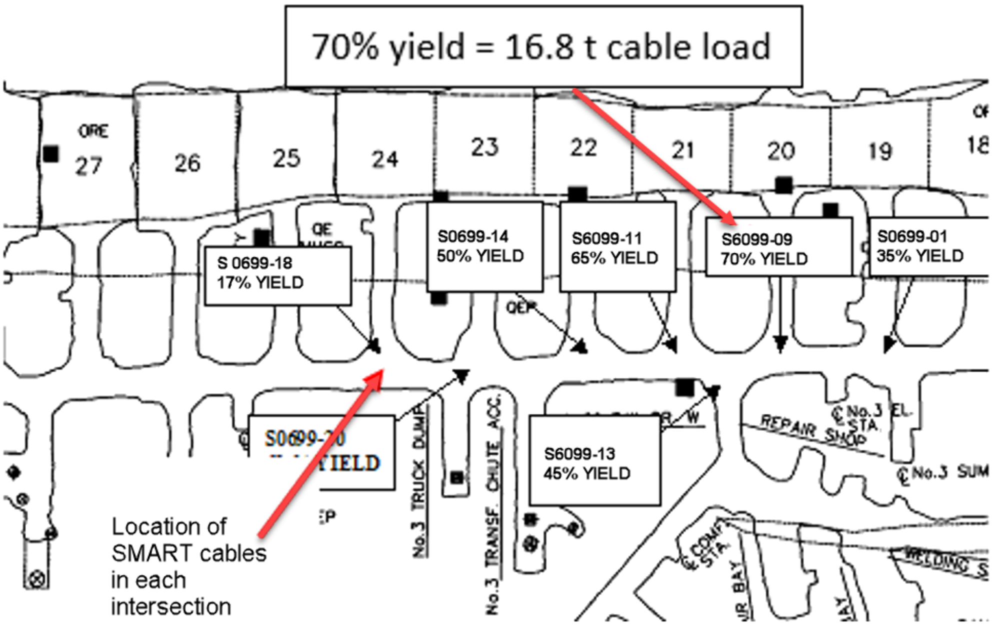


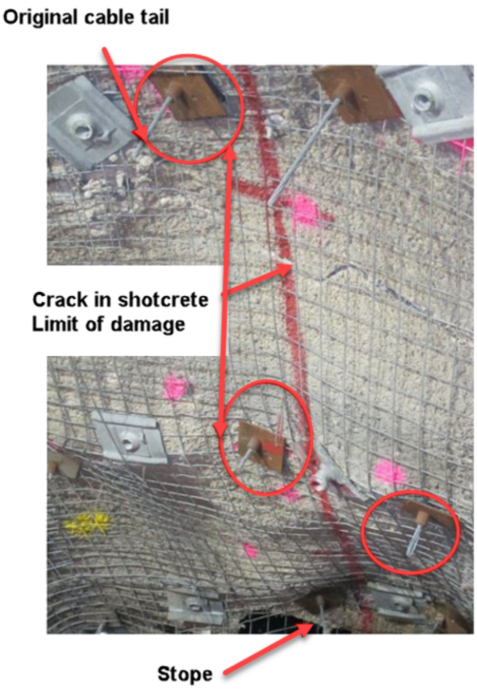
Figure 7 9390 Level plan showing impact on SMART cable loads due to a M_L1.8 event. Data used to maximise rehabilitation efficiency by only replacing consumed support capacity

2.4 Importance of deep in-hole instrumentation

The importance of deep in-hole instrumentation cannot be overstated. At another case study mine where a longitudinal, longhole retreat mining method was employed, in-ore development was supported with primary support along with mesh-reinforced shotcrete. As the mining front approached, secondary cable bolt support was installed to about 20 m ahead of the face. It was noted by the operators that cracking and some bulking of the shotcrete occurred several metres ahead of the face. In this case, no deep in-hole instrumentation was installed and the laser scanning technology did not yet exist. Although no surface indication of corrosion was observed and the mine was considered to be dry, it was concluded, based in site observations presented later in the paper, that corrosion had occurred between the inner surface of the barrel and outer surface of the wedge of the barrel and wedge assembly securing the surface support plates to the cable bolts. This resulted in lockup of the barrel and wedge assemblies with all plate assemblies sliding off the cables when loads exceeded the seating load of about 5 t. A serious collapse of the access development could easily have occurred. Figure 8 shows in situ evidence of slip of the barrel, wedge and plate assemblies down the cable tensioning tails.

Although the problem of cable stripping was easily evident to a highly experienced observer by observation of the cable tail length within and in front of the damage limit, the underlying concept of cable barrel and wedge corrosion-based lock up was not broadly understood. Had routine laser scanning been available, the significant closure in the damage zone with no evidence of cable load should have raised an alarm. Instrumentation available at the time (combined SMART cables and MPBXs) would have immediately indicated the problem since the MPBX displacement (i.e. ground strain) and SMART cable deformation (i.e. support strain) in the damage zone – that should be almost identical if the ground support was functioning properly – would not have matched to an acceptable degree.

Corrosion-based cable plate assembly slip problems are easily solved by the application of an agent such as copper-coat grease to the inner surface of the barrels and outer surface of the grips at installation to prevent the corrosion that causes expansion of the metal and the observed lock up of the barrel and wedge assembly.



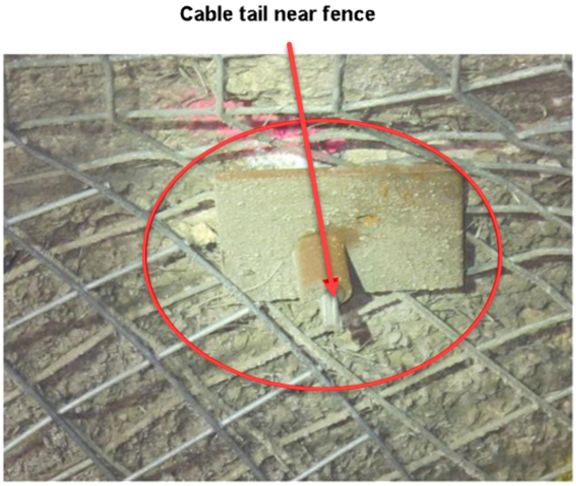


Figure 8 Corrosion-induced cable bolt grip slippage

2.5 Case study learnings

Gravity loading cases are normally simple to manage provided reasonably well-defined structural and stress models are available. In such cases, a combination of empirical and numerical design tools are generally adequate for purpose and easy to use. The mine-induced stress relaxation case is unique and deserves special attention. In the absence of highly experienced geotechnical personnel, such situations require pre-emptive numerical modelling for proper assessment since failure can occur with limited to no visual or audible warning.

Under monotonically increasing compressive stress in hard rock, observable rock mass damage and deformation generally begins when the maximum compressive stress (σ_c)>~30% of the unconfined compressive strength. As compressive stresses increase further, the rock mass damage increases and gradually extends to greater depth. The ground support response to this depends on the detailed nature of the primary and secondary (if installed) support elements utilised and the detailed local geology. The surface support used also plays a critical role in the ultimate behaviour of the embedded support elements. Both well-designed instrumentation programs and appropriate empirical and numerical analyses are required to adequately understand and manage this complex ground support behaviour.

Empirical analysis (e.g. Barton–Bandis [Hoek et al. 1995], Potvin & Hadjigeorgiou [2020], and other empirical charts) continue to provide a good starting point for a mine support design but are ultimately limited by the extent of the database upon which they are based. Highly focused numerical programs (e.g. Unwedge) are very useful for local, site-specific design, provided a sufficiently detailed local structural model is available. Incorporating ground support elements in a large numerical mine model (e.g. FLAC3D, RS3 etc.), in the experience of this author, is of little to no benefit due to limitations (e.g. limitations inherent in support constitutive models, the strong dependence of support behaviour on the very local [e.g. drift scale] structural domain and the discretisation scale used in the model). Such models, however, remain critical to the design process since, if properly executed, they will indicate those areas in the mine predicted to become highly stressed and therefore likely to experience increased deformations in both magnitude and depth. These areas should then be instrumented, at a minimum, using damage mapping with repeat LiDAR scans complemented with strategically located MPBXs to define the initial rock mass strain profile and provide guidance as to when additional resources (e.g. secondary support) should be deployed.

Currently, instrumentation and observation remain the most critical input to understanding and managing ground support behaviour. The ongoing acceleration in numerical model capabilities appears positive for advancement in this area, however, models, no matter their impressive capabilities, remain models with their output dependent on the quality and abundance of relevant input data. It is this latter aspect that presents one of the most stringent constraints and challenges to the adequacy of ground support design today.

Dynamic (i.e. rockburst) loading represents a step change in the complexity of ground support behaviour requiring both much more extensive and complex instrumentation and analysis for effective ground support management. The importance of deep hole instrumentation under such conditions was illustrated in the Williams Mine case study in Section 2.3). This study illustrates how mine stress-induced deformations can easily exceed the depth of primary ground support and, for the case study in question, show no surface evidence of ground support distress. Without the deep secondary ground support, additional drift collapse in this case was entirely possible.

Requisite instrumentation should include, at a minimum, microseismics, ongoing LiDAR scans, instrumented ground support element/s, where available and practical, plus ground deformation monitoring (e.g. MPBX) extending beyond the upper limit of the deepest ground support by 1–2 m depth to ensure that deformations are not exceeding the support depth.

3 Ground support design and risk management incorporating real time support capacity consumption

3.1 Introduction

The basic concepts around ground support capacity consumption were discussed with examples in Sections 1 and 2. For fully embedded steel ground support elements, 'support load' is a flawed metric with which to measure ground support consumption. As noted in the introduction, the fundamental issue is that embedded support tendons do not respond to changes in mine-induced stress. Rather, they respond to what changing mine-induced stresses induce which are local ground deformations (i.e. strain).

For both primary support (rockbolts) and deep secondary support (cable bolts and deep super Swellex [or equivalent]), limited support element instrumentation is available and has achieved varying degrees of industry acceptance as discussed below.

3.2 Typical general ground support element characteristics

3.2.1 Primary support

Primary support element length is normally restricted to less than ~3 m due to equipment and geometric constraints. Embedded ground support elements classically fall into one of two categories – either 'brittle' or 'ductile'. Figure 9 provides a (dated) representation of 'typical' embedded ground support tendon load– deformation behaviour. In Figure 9, this author has re-categorised this into three general behaviour types. Load–deformation can be used as a proxy for stress–strain but depending on the details, can be misleading.

The odd shape of the load–deformation curve of the expansion shell anchored bolt (Figure 9) is likely a result of anchor seating during the laboratory test. In the field, such bolts are tensioned to about 60% of yield on installation to prevent such behaviour.

The deformation 'd' in Figure 10 is the causative action resulting in 'loading' of the bolt. Since, in this case, the bolt shaft is not bonded to the borehole wall, such deformation – that could be due to one or multiple dilating fractures – affects the entire bolt length. As such, the critical bolt strain is d/L expressed as a per cent. This low bolt strain explains the 'soft' behaviour of this bolt type and why these bolts require pre-stressing to be effective. In fact, today, point anchor bolts are seldom used as ground support elements in underground mines due to their many limitations. Two of the major limitations with mechanically anchored bolts are (1) corrosion which may occur relatively quickly or very slowly over time and (2) rock spalling from behind the plate rendering the bolt completely ineffective (Figure 11).

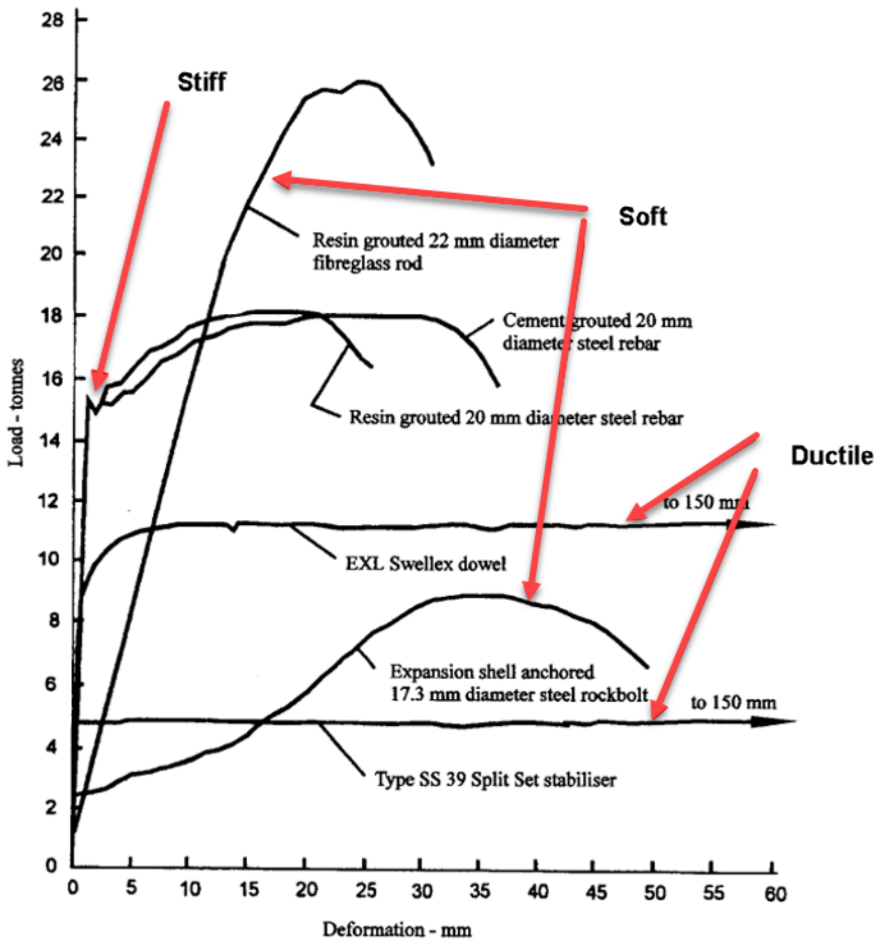


Figure 9 **Load–deformation results obtained by Stillborg in lab tests carried out using high-strength concrete blocks (after Hoek et al. 1995)**

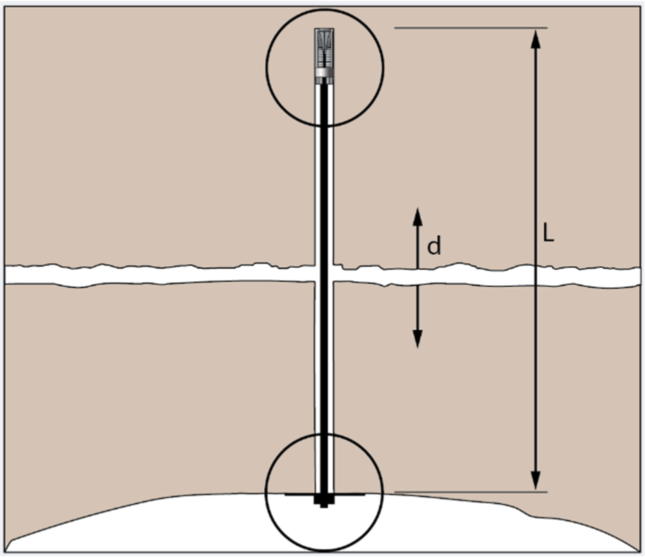


Figure 10 Schematic showing the point anchor principle where the bolt is bonded to the rock only at the toe and collar of the bolt (after Potvin & Hadjigeorgiou 2020)

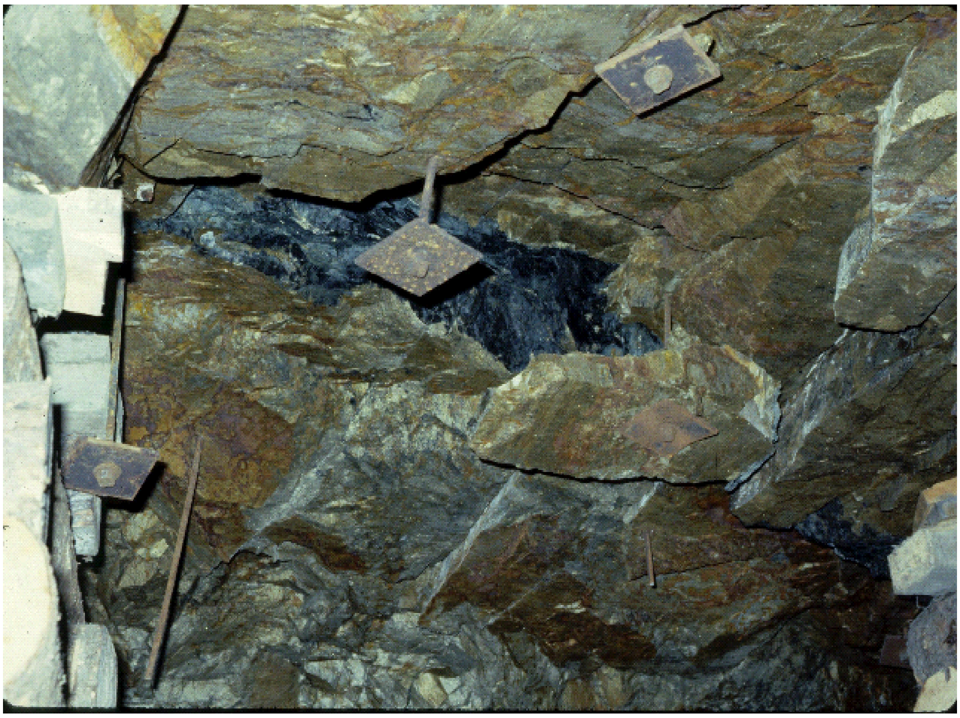


Figure 11 Rock spalled from behind the plates of mechanically anchored bolts

Resin and grout embedded solid bolts are known for their inherent stiffness (Figure 9). Rebar has designed surface roughness to facilitate steel–bond agent interface shear strength. For smooth bar, or poor bond agent quality, debonding normally happens over the full bolt element length. Although, depending on ground conditions (this can be either beneficial or detrimental), it is seldom the original design objective. The cause of this behaviour is normally a QA/QC limitation of fully bonded steel bar support that requires careful management. Figure 12 shows a schematic view of a fully encapsulated solid bar support element. As in Figure 10, a single fracture is shown dilating due to the impact of local mine-induced stress. In this case, however, the entire bolt length does not 'feel' this effect. For the fracture to dilate, it must first penetrate the bonding agent to the support element–bond interface. Due to shear resistance considerations, the weakest link is then at the steel–bond agent interface. For the rock mass to dilate, debonding along some length of the solid bar must occur such that the bar can deform and resist the ground dilation (Figure 12).

As indicated, at least initially, this response will be restricted to specific location/s along the bar and there may be no visual evidence at the bolt plate. In Figure 12, the bolt strain is local to the dilating joint/s and is given by (d/l [%]). This strain, and hence local bolt capacity consumption, is much higher than that indicated in Figure 10 for a point anchor bolt at the same deformation. It is therefore possible for fully encapsulated bolts to rupture at some depth along the bolt element without necessarily showing significant evidence of damage at the face; specifically plate deformation or bolt rupture at the threads (case study 2.1).

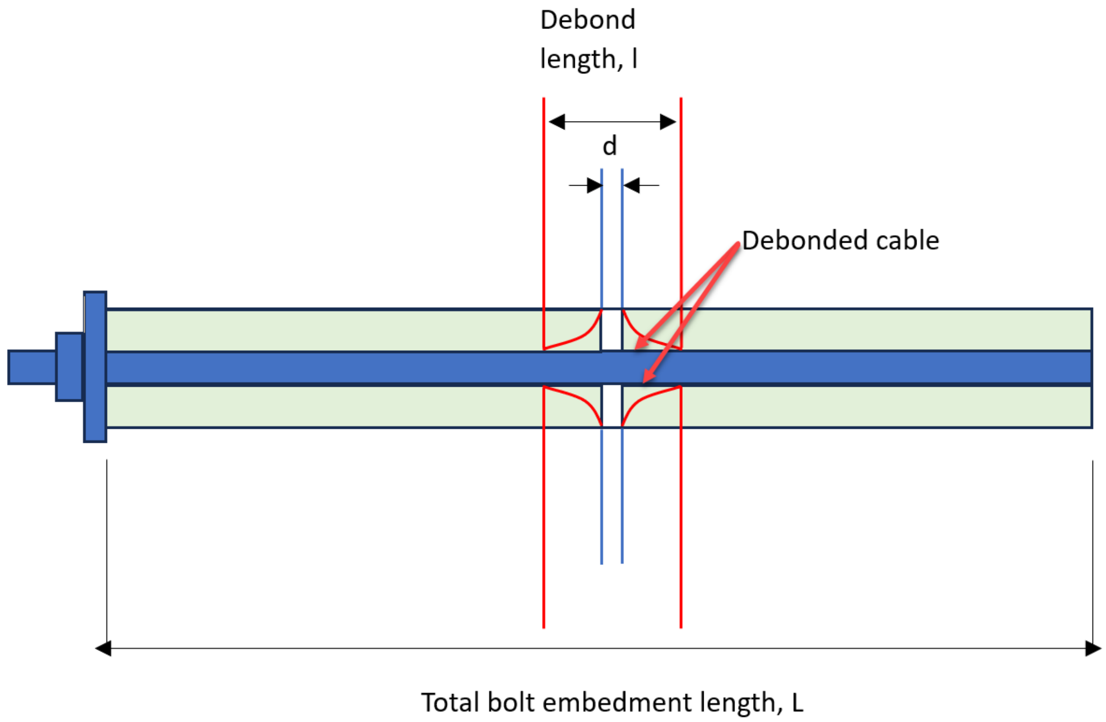


Figure 12 Loading mechanism for a fully bonded solid bar support element (L = full bolt length, l = debond length, d = local ground dilation)

Figure 9 also shows the lab test behaviour of the two common friction bolts. For in situ conditions the highly ductile behaviour indicated in Figure 9 can be misleading. For both bolt types, under field conditions, minor borehole wall dislocations can lock up the bolt well short of the full bolt length, leading to premature bolt failure with greatly decreased ductility.

Additionally, these bolt types have almost zero shear capacity. A final drawback is critical embedment length which, in the case of split set bolts, under ideal conditions, is about half the bolt length, while for Swellex is about 0.5 m depending on rock mass conditions.

3.2.2 Primary support instrumentation

Numerous approaches to instrumenting primary ground support elements have been attempted. A comprehensive review of instrumentation options is given in numerous publications (e.g. Dawn 2019; Roach et al 2019; Vallati 2020). For a variety of reasons, some of which are discussed later in the paper, to date, none have achieved broad industry implementation.

Mechanically anchored bolts can be successfully instrumented using simple load cells attached at the bolt collar. Because of the limitations associated with mechanical bolt support, however, these are now seldom employed, except in very limited circumstances, in underground mines.

Attempts to instrument fully encapsulated bolts have included attaching load cells at the collar, attaching strain gauges directly to the rebar surface, machining grooves along the edges of rebar and instrumenting these in various ways (Hoehn et al. 2020), ultrasound monitoring (Sun et al. 2019) and others. Each of these suffers from specific technical and/or cost limitations (e.g. high uncertainty in interpreting results with fully encapsulated bolts using conventional collar load cells due to bolt loading mechanisms (Figure 12), very short monitoring base length (conventional strain gauges), high manufacturing cost (machining and instrumenting grooves in rebar), and licencing issues for potential manufacturers with patented technologies).

Attempts have been made to instrument split set friction bolts but due to the violence of the bolt installation technique, this was abandoned. Swellex bolts can be tested for potential corrosion by simply reinflating the bolt, which provides an indirect assurance of some level of remaining bolt capacity but no measure of capacity consumption.

Thousands of primary ground support elements are installed in almost all underground mines annually. Instrumenting even a small percentage of these, unless this occurs seamlessly with support installation, would require a major increase in personnel and other costs. The lack of any serious application of the aforementioned technologies in operating mines today indicates the difficulty of making a business case for such an investment. An additional problem in monitoring primary support revolves around the number of units to be monitored and issues (including personnel, infrastructure, and cost) in implementing wireless telecommunication of results to surface. While many of these can be resolved now or in the near future, the issue of developing a cost-effective and pragmatic fully instrumented primary support that is installed seamlessly during the initial support cycle is not expected to be resolved in any near term.

3.2.3 Pillars

Pillars remain a common primary support method in many mining scenarios (e.g. vertical rib pillars separating draw bells in cave mining and horizontal sill pillars used to separate mining blocks) and may be permanent or temporary. Conventional vertical pillars normally only have primary support installed whereas sill pillars commonly have both primary and deep secondary support. Conventional vertical pillars are occasionally cable wrapped to provide confinement. Yanagimura & Hadjigeorgiou (2022) provide an interesting case study using SMART cables to instrument cable wrapping in a block cave mine in Canada.

SMART cables, MPBX instruments and sloughmeters are commonly used to instrument sill pillars and the first two can be used to monitor support consumption. Repeat LiDAR surveys will provide a measure of pillar rib deformation and, if complemented with horizontal MPBX instruments (assuming vertical pillars), will provide the complete pillar strain profile that can then be used to estimate support capacity consumption and help guide any additional required rehabilitation.

3.2.4 Secondary support

Under monotonic loading, deep secondary support normally consist of cable bolts with varying cable configurations and/or connectable super Swellex bolts. Cable bolts can be installed in either single- or twin-strand configuration and as either plain or bulb strand. Plain strand cables undergo the same debond process when loaded as described for fully bonded rebar. Depending on the local rock mass stiffness, these cables can also suffer ‘stripping’ failure where the theoretical cable capacity is never mobilised. Bulb cables tend to anchor the cable at each bulb such that stripping failure does not occur. Cable support system stiffness can be engineered by suitably altering cable bulb spacing. There are also point anchor cable bolt configurations where the cable can be pre-tensioned prior to grouting but these are not instrumented. Bonding agents can be either cementitious grout or pumpable resin. In both cases the properties and installation details of the grout or resin are critical to cable bolt behaviour.

Deep super Swellex support behaviour is similar to that described for primary Swellex support but with higher ultimate capacity. The lack of any real shear resistance for super Swellex bolts combined with the tendency for these bolts to lock up and fail prematurely means that the potential for dramatic loss in theoretical ductility remains the same as discussed for primary friction bolts.

3.2.5 Instrumented secondary support

To date, the only directly instrumented deep secondary support are 18 mm diameter, ASTM 416 steel cable bolts. Instrumented cable bolts can be either plain or bulb strand, can be installed in any configuration, and can be bonded using either cementitious grout or pumpable resins. Other deep support element strain profiles must be inferred using nearby passive ground deformation instruments such as MPBX or alternate instruments. Only instrumentation that provide a direct, quantitative measure of passive ground strains are applicable for this and must be in reasonably close proximity to the support element/s in question. There will, however, always be uncertainty as to how accurately these measures reflect the inferred support consumption.

3.2.6 Dynamic support

Over the past ±20 years, significant advances have been made in the area of dynamic support for both primary and secondary applications. While the list of commercially available dynamic bolts is too extensive to be covered in this manuscript, there are a limited number of mechanisms that are routinely employed to achieve the design objectives. These include:

1. Ploughing where a cone-shaped wedge attached to a smooth bar is pulled through the bonding material at a fixed load less than the yield load of the bar. Maximum deformability depends on the details of the wedge design, bonding material, site effects and installation.
2. Pulling an end anchor through a mechanical mechanism for a fixed distance at which point the end mechanism locks up and if deformation continues, takes the bolt to rupture. These bolts are often fully encapsulated for corrosion protection but debonded from the encapsulating material. The maximum deformation of the mechanical toe fixture is normally about 250 mm, although this is not always achieved.
3. High-strength, high-ductility specialty steels used for the bar element. Such bolts may be end-anchored or have multiple anchors. In either case, they rely on the ductility of the bar element itself to achieve the required deformability.

All of the above mechanisms are employed in various dynamic primary support elements. Secondary support relies on two primary mechanisms:

1. Debonded cable bolts. With this method, a section of bulb cable is normally applied at the collar and at the toe. A fixed length of debonded plain strand cable designed for the desired deformability (35 mm maximum deformation per metre of debonded cable) is then employed between the anchor lengths. Cables can be deployed in single- or twin-strand configurations (case study in Section 2.3 provides an example). Measured cable strain can also be used to guide rehabilitation timing.
2. Mechanism (2) stated earlier has also been employed for single-strand dynamic cables (e.g. the Garford dynamic cable, maximum deformation 250 mm].

The functional mechanism of all the dynamic support elements discussed is to allow but control ground deformation up to the deformability limit, after which, with increasing deformation, full capacity consumption of the dynamic support element/s in question occurs.

4 The use of support consumption as a risk management tool in underground mining

4.1 Introduction

Since ground support elements do not respond to mine-induced stress change, but rather to the resulting rock mass strains, ground support capacity consumption cannot, at this time, be determined to sufficient accuracy *a priori* by any method (numerical modelling or other) known to this author. Rather, it must be evaluated in semi-real time using various forms of highly coordinated, multi-instrumentation input.

4.2 The value of numerical and empirical modelling

Both numerical and empirical modelling have an important role in the upfront design of the requisite ground support system/s. For reasons discussed in Section 2.5, however, neither can provide reliable predictions of real time in situ ground support performance under operating conditions at the scale required for both safety and secure operational management.

4.3 How to incorporate support capacity consumption into real time geomechanical risk management

In order to quantitatively measure ground support consumption for use as a risk management tool, operators are required to develop a methodology to reliably measure the total mine development deformation profile in near real time. Traditionally, this was almost impossible to achieve in underground mines due to instrumentation limitations and the fact that it was effectively impossible to create stable reference points in a drift floor. The recent development of laser scanning tools that allow repeat 3D scans of underground development to a high degree of resolution allows determination of total and differential drift closure along any desired axis following each scan. The closure data, coupled with in-hole deformation measures using MPBXs or other suitable instrumentation, can then provide the complete rock mass deformation profile at each location where requisite instrumentation is installed.

Due to the extremely complex and locally variable nature of almost all mine-specific geological domains, it is not possible to recommend how many MPBX (or alternate) instruments would generally be needed for such an application. For the majority of mine sites, however, commonly accepted practice is to use standard geotechnical mapping and rock mass classification to define geomechanical domains (i.e. zones of similar rock mass geotechnical characteristics in which a 'standard' ground support design is considered acceptable). Even within such a domain, however, strain profiles can vary, often to a significant degree. Total closure monitoring using repeat LiDAR surveys allows identification of anomalous areas where additional instrumentation (MPBX and/or observation holes) should be installed. This approach can be used to manage additional instrumentation deployment. Defining what constitutes as an 'anomalous area' in a closure profile will be very site-specific. One approach would be to conduct borehole camera surveys of each MPBX instrumentation hole prior to instrument deployment to provide an initial borehole fracture database. Subsequently, when a local area begins to show an elevated degree of closure, additional monitoring holes should be drilled (number of monitoring holes dependent on scale of abnormal closure). Additional MPBX instruments can then be installed in those locations of which some or all should be camera surveyed. In this manner, the borehole camera survey provides an estimate of the initial strain the local support had been subject to which can simply be added as an initial reading to further strains measured by the MPBX (or other) instruments and used as a rehabilitation guide based on support consumption.

The in-hole instruments can be suitably tagged at the collar so as to be easily georeferenced to the laser scans in order to cross-check the various deformation measures. The addition of deep secondary instrumented ground support, where possible, allows ongoing assessment of ground support capacity consumption through the direct measure of support element strain. Ground support efficiency can then be assessed by direct comparison of support element strains to passively measured rock mass strains measured using nearby MPBX or equivalent instruments. Any significant divergence between the passively measured rock mass strains and those recorded by the instrumented deep support normally indicate a problem with support performance, commonly bond or anchor slippage.

The above requires a combination of multiple instrumentation types, as reviewed earlier and summarised below. Ideally, this data would be combined with ongoing re-calibration of 3D numerical models in order to enhance model prediction capabilities as mining progresses. At a minimum, the instrumentation should include:

1. Mine-wide microseismic monitoring: the major limitation today is that such systems must be hard wired due to bandwidth limitations in underground wireless communications (a maintenance issue). While the impact of this limitation depends on the amount of data communication

interruption due to instrumentation wiring damage at a specific operation, the issue could be resolved by building intelligence into the sensors themselves such that the data could be communicated wirelessly. This, however, would probably entail a significant increase in cost plus increase in uncertainty since the raw data would no longer be available for scrutiny by the operator, which for many reasons should raise red flags with any instrumentation program. Continuous monitoring and post-processing today provide a generally acceptable alternate.

2. Mine-wide damage mapping: routine damage mapping of mine development and infrastructure provides an invaluable qualitative tool to assist with qualitative calibration of mine-wide microseismic clustering data (used as a proxy for the yield zone [Section 2.2]) against 3D numerical model simulations of progressive yield. Such data, that documents surface damage and deformation, should be displayed on available site 3D mine rendering software to facilitate cross correlation with other instrumentation data bases.
3. Laser scanning of underground development: such surveys are routinely conducted today. Repeat scans can provide complete 3D closure data in semi-real time. Under high-risk scenarios, surveys can be conducted robotically.
4. Open observation holes with routine borehole camera surveys: borehole camera surveys of open observation holes allow direct measure of ongoing, deep fracture development and dilation to assist in interpretation of instrumented support and passively measured ground strains.
5. Conventional instrumentation (e.g. MPBXs; SMART cables; contractometers etc.): application of such instrumentation was discussed in previous sections of this paper. This instrumentation is widely available today. Ease of installation, instrumentation robustness, client support etc., and the requirement, to the highest degree possible, that instrumentation be agnostic to third party wired or wireless communication systems, while critical, are original equipment manufacturer supplier dependent.

The final piece in this puzzle concerns which of the many available systems a particular mine uses to assimilate, display and interpret their data. While a discussion of these myriad of systems is beyond the scope of this paper, it is a quintessential issue mines must address when procuring and implementing their IT system/s. Too often instrumentation, communication, analysis and display systems are procured on an ad hoc basis in communication silos within each individual department. Mine-specific IT restrictions also often lead to additional delays and roadblocks with deployment of the instrumentation and data acquisition systems described earlier. This can lead to significant inefficiencies and additional costs that exacerbate the communication problems inherent in all underground mines.

5 Concluding remarks

The deep, dynamic ground support described in the Williams Mine case study (Section 2.3) was installed in a reactive mode. As such the ground around the immediate development was already highly damaged. No MPBX instruments were installed in this case and hence, cable slip cannot be totally ruled out. The use of bulb cable for the anchor zones, combined with the instantaneous large cable displacements at significant depth coincident with the seismic event, suggest that this was unlikely to have occurred.

To be truly effective as a risk management strategy, however, it is critical that deep secondary support and associated instrumentation are installed in a much more proactive manner, such that there is confidence that the calculated support capacity consumption is accurate. Any significant deviation between simple rock mass deformation and nearby support strains should trigger immediate further investigation as this could lead to unanticipated support failure and FOGs.

All mine operations strive to minimise ground control costs while maximising efficiency. Numerical models allow forward prediction of areas most likely to require ground support upgrades and at approximately what mining stage. Because clustering microseismicity provides a strong indicator of rock mass yield, this offers a real time feedback loop allowing qualitative validation of model predictions that can be fine-tuned and enhanced over time. The problem is that enhanced ground support needs to be installed well before microseismic clustering indicates yield. Visual damage mapping (i.e. crack initiation in shotcrete etc.) in mine development, combined with repeat 3D laser scans that provide a direct measure of wall-to-wall closure and closure rates, can provide an early indication that support upgrades, (normally deep and potentially dynamic in-hole support), are likely to be required and should be installed proactively.

Utilisation of the ground support capacity consumption methodology described in this paper should, if properly executed, result in significant reduction in support rehabilitation costs and more importantly help minimise potential production interruptions resulting from ground support failures and associated infrastructure damage. The Williams Mine case study offered an early indication of the effectiveness of this approach. At that time, most of the tools necessary to put this approach in practice did not yet exist. Today, however, all required technologies are available in some form.

Mine operators simply need to assess which products are best suited to their specific environment and then to work with suppliers to ensure that the system ultimately deployed provides maximum return on investment. Operators should, however, anticipate a learning period before the processes become familiar to all requisite mine personnel and they become comfortable with the systems.

A final limitation to the direct measure of support capacity consumption is that most deep in-hole ground support elements cannot today be instrumented in any pragmatic, cost-effective manner, although this may change with future technological advances. One way to overcome this is to install MPBX instruments with suitably spaced anchors in close proximity to some of the deep support elements, as illustrated in Figure 13. Such instrumentation can be used to estimate support element consumption based on the closest measured rock mass strains. This inherently assumes no bolt slip, which may not be correct. Load cells can also be placed at the support element collars but must be interpreted with caution.

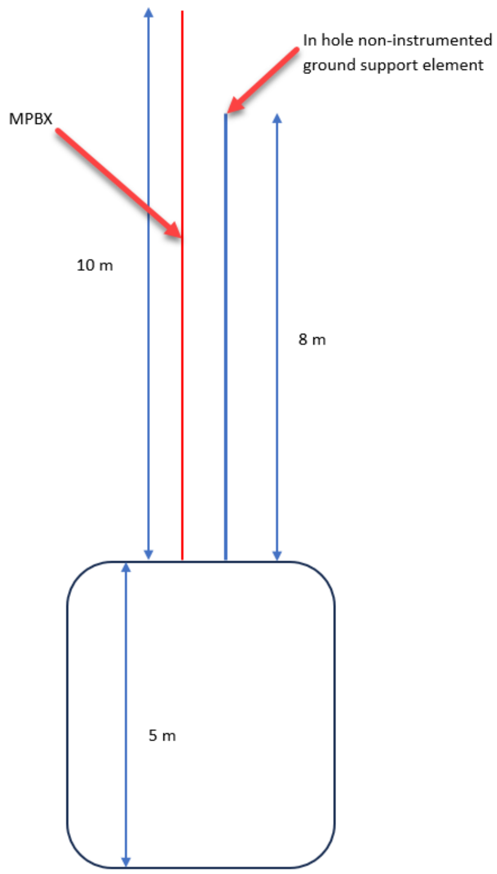


Figure 13 A typical six anchor, 10 m long MPX has a regular anchor spacing of 1.25 m. If two 5 m MPBX instruments are stacked, the anchor spacing reduces to 0.83 m providing mush higher strain resolution

Finally, it is always recommended to instal instrumentation in wide intersections and critical, large span infrastructure (e.g. crusher stations etc.) during development as it is often very difficult to access such areas later. This instrumentation can also provide an early indication of the potential need for support upgrades.

Future technological developments can be expected to provide at least incremental improvements to the issues discussed in this paper. There are, however, some significant challenges to overcome:

- Numerical modelling: while continued development and improvement in the numerical tools used in mining is to be expected, the ultimate practical utility of these tools will continue to be constrained by the lack of sufficient quantity and quality of appropriate geomechanical input data, resulting in varying levels of uncertainty in the results.
- Instrumented ground support elements: the lack of available instrumented versions of most primary and secondary support elements, combined with the limited industry take up of the limited available instrumented support, makes it very difficult for instrumentation original equipment manufacturers to make a business case for investment in new research and development in this area.
- Highly qualified personnel: the reduction and, in some cases, closure of tertiary education institutions for mining and geological engineers in many advanced economies, even mining reliant ones, is resulting in a severe shortage of appropriately trained and experienced mining technical personnel. This is particularly evident in the geomechanics field. Such key personnel represent the first line of defence for any mining operation against 'unanticipated' events that can severely impact mine safety and operations. There are no apparent quick or easy solutions to this dilemma.
- Artificial intelligence (AI): while, in a surficial review, AI may appear to have the potential to overcome many of the obstacles referenced above, it must be remembered that the utility of AI relies on the input of very massive databases that the technology uses to provide answers to queries. In the field of rock engineering, and particularly at an individual mine level and considering how ground conditions change with extraction level and depth, such very large databases generally do not exist. This represents a significant challenge to adaptation of this technology in the ground control area.

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