Deep Mining 2024 – P Andrieux & D Cumming-Potvin (eds)

doi:10.36487/ACG_repo/2465_21

Forgotten critical limitations on cable bolt reinforcement design and guidelines for instrumentation deployment to monitor support behaviour and capacity consumption

William F Bawden [a,b,*]

[a] *University of Toronto, Canada*

[b] *Mine Design Technologies, Canada*

Abstract

Cable bolt ground support has been used in mining since the 1970s. The key factors controlling cable bolt support element behaviour and cable bolt pattern support were resolved by the late 1990s. This information was widely disseminated at numerous mining conferences and well summarised in the book by Hutchinson & Diederich (1996). Since then, the author has noted a disturbing increase in the lack of basic understanding and application of these fundamentals by many practitioners around the world. As part of the same research, instrumented cable bolt elements (SMART Cables) were invented and gradually achieved wide acceptance in the industry. While this development was welcome and offers significant benefits from both safety and economic perspectives, the author continues to see a lack of basic understanding on the proper application of instrumentation for ground support monitoring and assessment of support capacity consumption.

The first part of this paper provides a review of the critical factors that must be understood and carefully assessed in:

1. *the selection of appropriate cable bolt element design*
2. *critical field conditions that must be assessed as part of a cable bolt support pattern design*.

While some of the factors in point 1 may seem minor, they can, and often do, dictate the success or failure of a cable bolt program. The factors discussed are equally applicable to any scale of underground excavation (e.g. drifts, stopes, etc.).

The second part of this paper discusses the rules and limitations that must be followed for the proper deployment of instrumentation (SMART Cables, multi-point borehole extensometer, etc.) for cable bolts and more general ground support monitoring program design.

Keywords: *ground support, cable bolts, cable bolt behaviour, cable bolt design, instrumentation, SMART Cables*

1 Introduction

The use of cable bolts as ground reinforcement elements roughly coincided with the evolution of underground mining from methods reliant on small scale, handheld drills and dedicated rail haulage to bulk mining methods utilising mobile rubber-tired equipment. This development facilitated much higher productivity mining but also required much larger underground openings at all scales. Cable bolting was critical to this step change evolution in underground mining technology as it permitted the installation of long ground support elements from development opening of limited size.

The earliest cable bolt applications used degreased hoist ropes for cables. Not surprisingly, these were found to not function well. Cable bolting practice then advanced to use seven strand steel reinforcing cables (ASTM

* Corresponding author. Email address: will.bawden@utoronto.ca

International 1980). Early cable bolt performance was very erratic with the success appearing random, as observed by this author in the 1980s. Industry concern with this erratic ground support behaviour led to several independent research initiatives primarily in Canada, Australia and the United States of America to attempt to better understand and resolve the cable bolt support issues. The core results (successes and failures) from these research initiatives and the impact on cable bolt design and behaviour is discussed in the following sections of this paper.

One key outcome of this research was the development of the instrumented SMART Cable that provides a direct measure of the cable bolt support element behaviour in situ (Hyett et al. 1997). In the author's experience, there is often a critical lack of understanding concerning the rules governing the optimal pragmatic utilisation of this instrumentation, and often instrumentation in general, in the monitoring of cable bolt performance. This is discussed in second portion of this paper.

2 Fundamental conditions controlling cable bolt ground support behaviour

2.1 How do cable bolts function as ground control elements?

A cable bolt is a frictional, fully coupled tendon. Load is transferred from the rock to the grout at the borehole perimeter and is then transferred from the grout to the cable via a frictional interface at the grout/cable boundary (Figure 1). Load can be transferred along the entire length, unless debonded due to design or quality control problems.

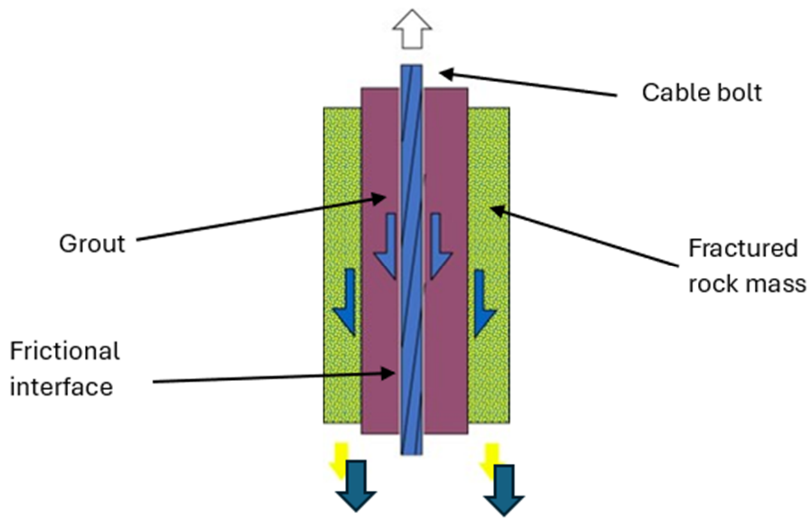


Figure 1 Section view of installed cable bolt in grouted borehole (modified after Hutchinson & Diederichs 1996)

As the rock mass displaces inward into the mine opening (Figure1), the grout moves with the rock mass since shear capacity of rock/grout interface is much greater than the grout/cable interface due to geometric configurations and differences in surface roughness. For the grout to displace with the rock, it must either move away (dilate) from the cable (reduces bond strength [BS]) or the cable crushes the small grout flutes (increases BS). Two different, commonly used cable configurations are shown in Figure 2: modified strand bulb cable (A) and plain strand (B).

Dilation is the critical factor controlling cable BS (Figure 2). The modified strand provides a much greater mechanical interlock with the grout in comparison to the plain strand cable and this strongly impacts the interface dilation pressure and hence interface shear resistance (i. e. BS) with the following potential impacts:

- Bulb strand requires dilation ~6 mm for BS to reduce to near 0.
- Plain strand requires dilation of ~100–200 µ (0.1–0.2 mm) for BS to reduce to near 0.

Fundamentally, interface dilation pressure controls friction that then controls BS and hence pull-out load (i.e. cable capacity).

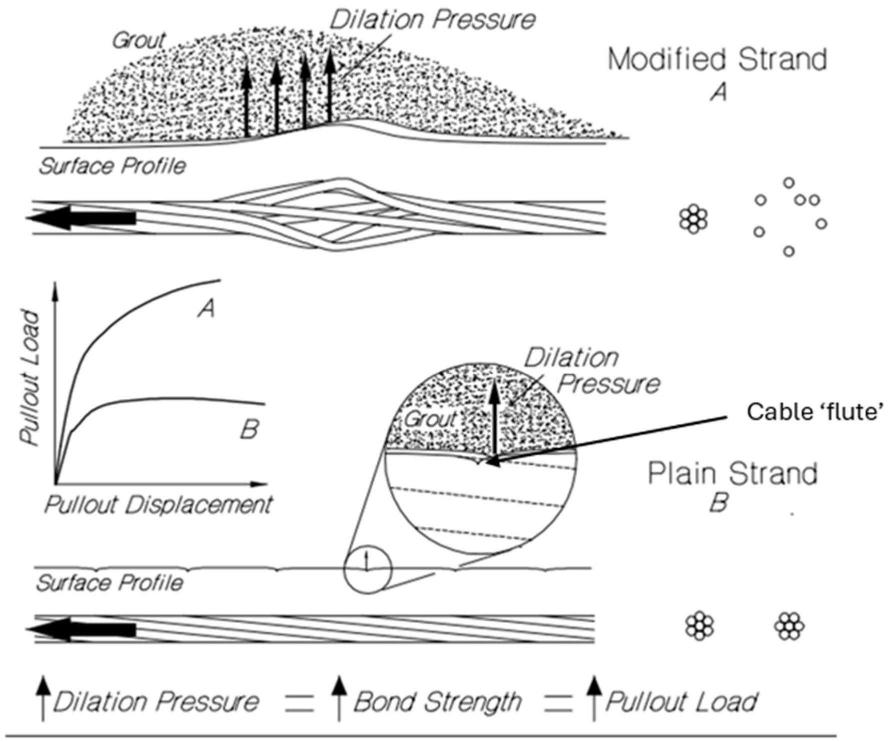


Figure 2 Dilation, the key to bond strength (modified after Hutchinson & Diederichs 1996)

The cable condition at installation also impacts the BS. If cables are laid out on the floor of the drive and pulled through slimes or mud on installation without cleaning, then slimes or mud can fill the flutes (particularly for plain strand cable) such that cable interface dilution is severely restricted and BS approaches 0. Highly corroded cables (i.e. pitted) should also not be installed.

The combined research initiatives discussed earlier were completed in the early 1990s and provided a comprehensive understanding of all factors that critically impact cable bolt behaviour, including site-specific rock mass conditions (strength and stiffness), mine induced stress changes (increased confinement versus relaxation), cable type, grout quality (strength and stiffness), grout equipment quality and installed cable conditions (open breather tubes, dirty cables, etc.). This work was widely published in numerous mining and geomechanics journals and conference proceedings. The work was eloquently summarised in the book by Hutchinson & Diederich (1996).

2.2 How do cable bolts fail?

There are two basic conditions controlling cable bolt failure:

1. Cable stripping failure.
2. Cable rupture.

The second failure mode results from load demand (D) on the support that exceeds the support capacity (C) resulting in cable rupture. The engineering response to this condition is simple: add more cable capacity.

The first case (cable stripping; Figure 3) is much more complex and requires a fundamental understanding of grouted cable bolt behaviour in the underground environment, including how cable bolts function and the major factors controlling load transfer from the in situ fractured rock mass to the cable elements. These issues were briefly reviewed in the previous section.

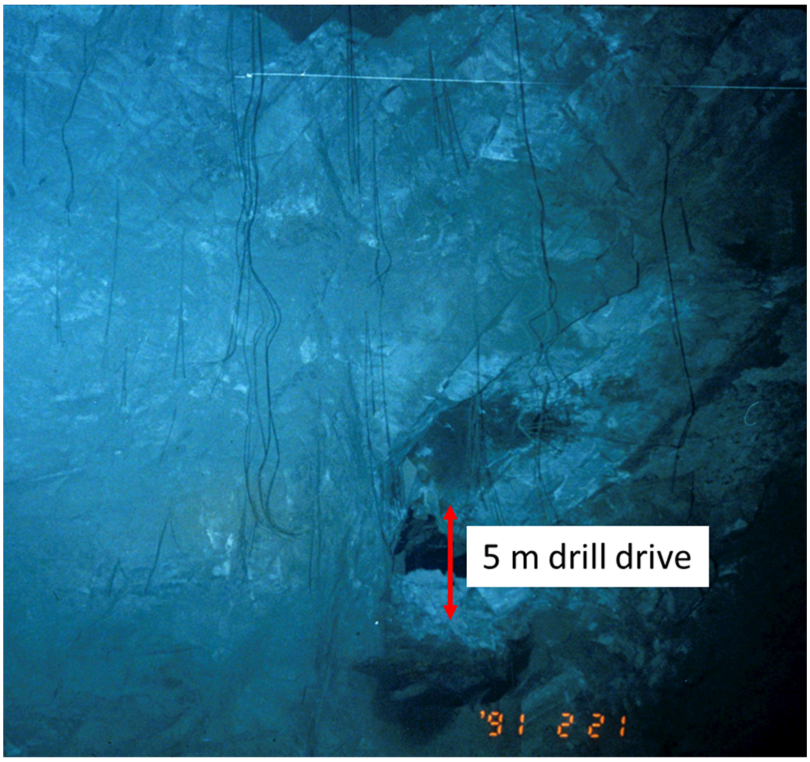


Figure 3 Cable bolt stripping failure in an historic open stope mine in Eastern Canada. Note: cables have been stripped clean with no grout left on cables; no ruptured cables observed hence actual cable loads unknown

Stripping failures were common in the 1980s. This was a result of the limited understanding at the time of the numerous parameters that interact to control cable bolt behaviour (Section 2.1). At that time, only plain strand cable was available. Grout pumps commonly used were not capable of pumping high-quality grout (0.35 to 0.4 water:cement [w:c] ratio) and small diameter breather tubes were normal. Common practice was to place the free end of these breather tubes in a pail of water and once the air bubbles stopped, the hole was assumed to be fully grouted. What was not recognised was that this created a hollow inclusion the entire length of the borehole. When the rock loaded the cable, the grout dilated and crushed the empty breather tube. The combination of low strength/stiffness grout and/or empty breather tube allowed the grout to dilate away from the cable reducing the BS to near zero. The negative impact of a highly deformable rock mass allowing increased grout dilation was another factor that in very weak rock masses strongly inhibited development of cable BS. Finally, the impact of site-specific mine induced stress change on cable BS (i.e. change in confinement at grout/cable interface) was not yet recognised.

2.3 Results from cable bolt research programs

Laboratory and field cable bolt research programs discussed earlier resolved all of the issues impacting cable bolt behaviour. Additionally modified geometry cables (birdcage, nutcase and bulb) were also developed as part of or in parallel with these research programs. For reasons primarily related to manufacturing efficiency, the bulb cable emerged as the dominant modified cable geometry. The combination of the above factors resulted in drastic improvement in the performance of cable bolt ground support in hard rock mines globally.

2.4 Pragmatic implications from the cable bolt research programs to cable bolt design and implementation

The major factors that largely dictate the success or failure of a cable bolt support program are summarised in this section.

2.4.1 Cable bolt grouting options

There are two accepted techniques for cement grouting of cable bolts:

1. Toe to collar grouting: With this technique, a grout tube (nominally about 25 mm diameter) is attached about 30 mm below the cable toe. Once the cable is inserted in the bore hole, a 0.35 w:c grout (Figure 4a) is pumped. This grout is a non-Newtonian fluid (i.e. paste) and must be pumped down the borehole from the toe to the collar. No surface plugs should be used.
2. Breather tube grouting: With this technique, a 17 to 25 mm diameter breather tube is attached near the toe of the cable. Once the cable is inserted in the bore hole, a short 25 mm diameter grout tube is installed at the collar and secured using a collar plug. A 0.4 w:c grout (a Newtonian fluid) (Figure 4b) is then pumped from the collar to the toe until the grout flows freely from the breather tube which is then crimped off.

Grout w:c = 0.3 (Figure 4c) is too stiff for the majority of grout pumps and can result in incomplete hydration and highly erratic strength results. Alternately, any grout with w:c > 0.4–0.45 is too weak to generate sufficient cable BS to mobilise full cable capacity (Figure 4d).

For details of toe-to-collar versus breather tube cable installation methods see Hutchinson & Diederichs (1996). Toe-to-collar grouting is the preferred method as this removes the need for any additional grout QA/QC efforts (i.e. if the grout stays in the hole with no collar plug it is at least 0.35 w:c).

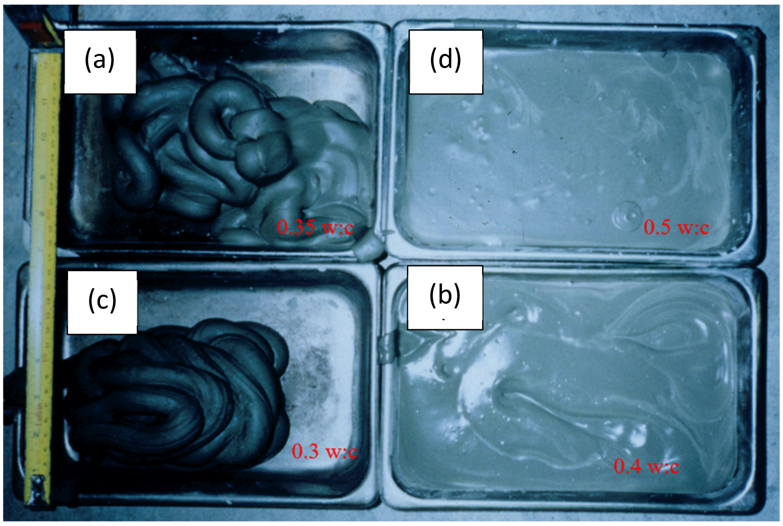


Figure 4 Grout quality versus water:cement (w:c) ratio: (a) w:c = 0.35; (b) w:c = 0.4; (c) w:c = 0.3; (d) w:c = 0.5

2.4.2 Grouting equipment

Providing operators with the highest possible quality pumping equipment is essential to achieving successful and efficient cable bolt installation and performance. Progressive cavity or positive displacement pumps are generally considered optimal. Thorough cleaning of such equipment at the end of each shift is essential to the success of any cable bolt program (Hutchinson & Diederichs 1996).

2.4.3 Impact of grout and rock mass quality on cable bond strength

Figure 5 illustrates the extreme importance of rock mass quality in terms of rock mass modulus (Figure 5 top) and grout quality in terms of w:c ratio (Figure 5 bottom). It is essential that these factors are given careful consideration in the design of any proposed cable bolt support program.

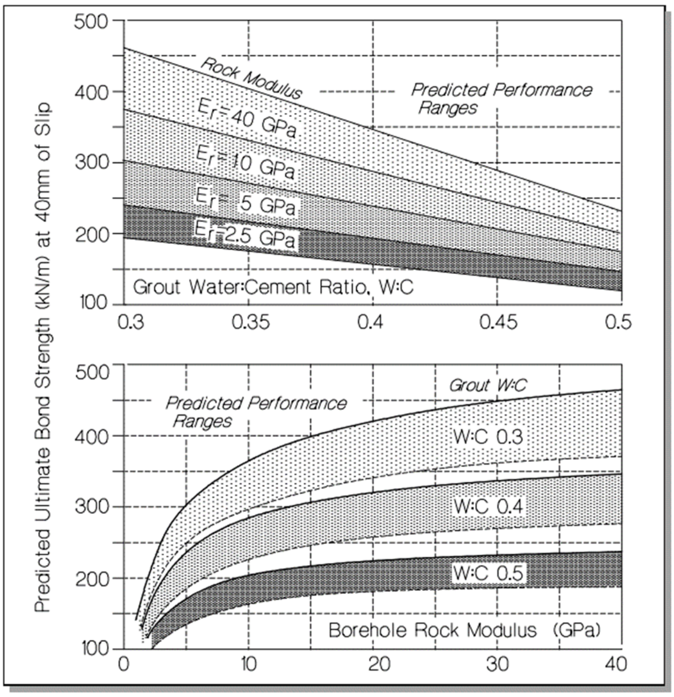


Figure 5 Ultimate bond strength as a function of grout quality and rock modulus. Note actual system capacity may be limited by strand tensile strength (after Hutchinson & Diederichs 1996)

2.4.4 Impact of modified strand on cable capacity

The two cable configurations commonly used in underground mining are plain and modified geometry 15.6 mm ASTM 416 strand (Figure 6). Both can be installed as single or twin strand. The choice of strand exerts a powerful influence on the ultimate cable capacity (Figure 6) and stiffness. In the case of modified strand, each bulb (or flare out) acts as an anchor and can mobilise the ultimate cable capacity even in very weak ground.

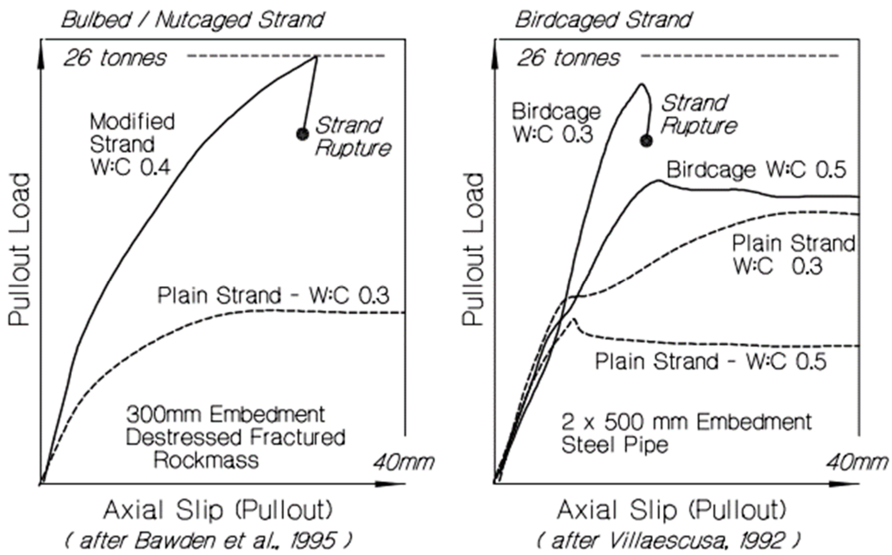


Figure 6 Examples of increased bond performance of modified strand (pullout) (after Hutchinson & Diederichs 1996)

2.4.5 Case study

A gold mine in Northwestern Ontario, now closed, was hosted in relatively weak sericite schist formations (GSI ~ 50–70; Er ~ 10–35 GPa). Field cable bolt testing indicated that for plain strand cables the maximum achievable capacity was ~16 t, in agreement with commonly observed stripping failures at the mine. Replacement of the plain strand with bulb cables in a test stope resulted in cable rupture. The mine subsequently changed to bulb cables for all applications and with minor adjustment to the cable density achieved stable stope back conditions for the majority of situations.

2.4.6 Engineering cable bolt stiffness

Modifying the bulb spacing on cable bolts can be used to engineer cable stiffness for specific design requirements. For the upper bound cable stiffness bulbs should be spaced as closely as possible (~25 cm: E_{cable} ~ stiffness of 1.9 cm resin rebar). The lower bound stiffness is simply that of plain strand cable. Cables can be further modified by debonding a length of the cable to allow additional deformation for example under seismic loading conditions. In those cases, bulbs spaced at about 25 cm are normally designed for about a 1.5 m length at the collar to protect the plate with a second ~2 m length of bulb cable at the toe to act as a toe anchor with site specific designed debond length in between for conditions such as seismic loading (Bawden & Jones 2007).

2.4.7 Cable bolt hanger and plating assemblies

Cable bolts have both end anchor and surface plate assemblies. Cable hangers, attached to the toe, are designed to maintain the cable in place during grouting as injuries have occurred with unsupported cables falling out. Cable plate assemblies (Figure 7) are attached at the bore hole collar to assist in the transfer of cable loads to the rock mass and to secure surficial screen support.

Cable plate attachments are particularly critical with plain strand cables to resist stripping. The cable plate attachment design assumes the following:

- Plate installed by applying jacking tension to seat wedges within the barrel.
- A seating load (~10 t) is normally applied resulting in a residual seating load of ~5–6 t following release of the jack.
- As the rock mass displaces toward mine opening some of this deformation transferred to plate.
- As plate displaces into the opening, the wedges are designed to slide deeper into the barrel forcing wedge teeth to sink deeper into the steel cable and therefore maximise cable ultimate capacity.

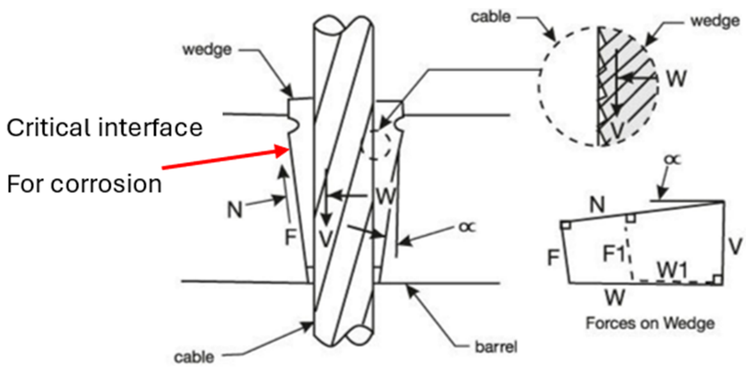
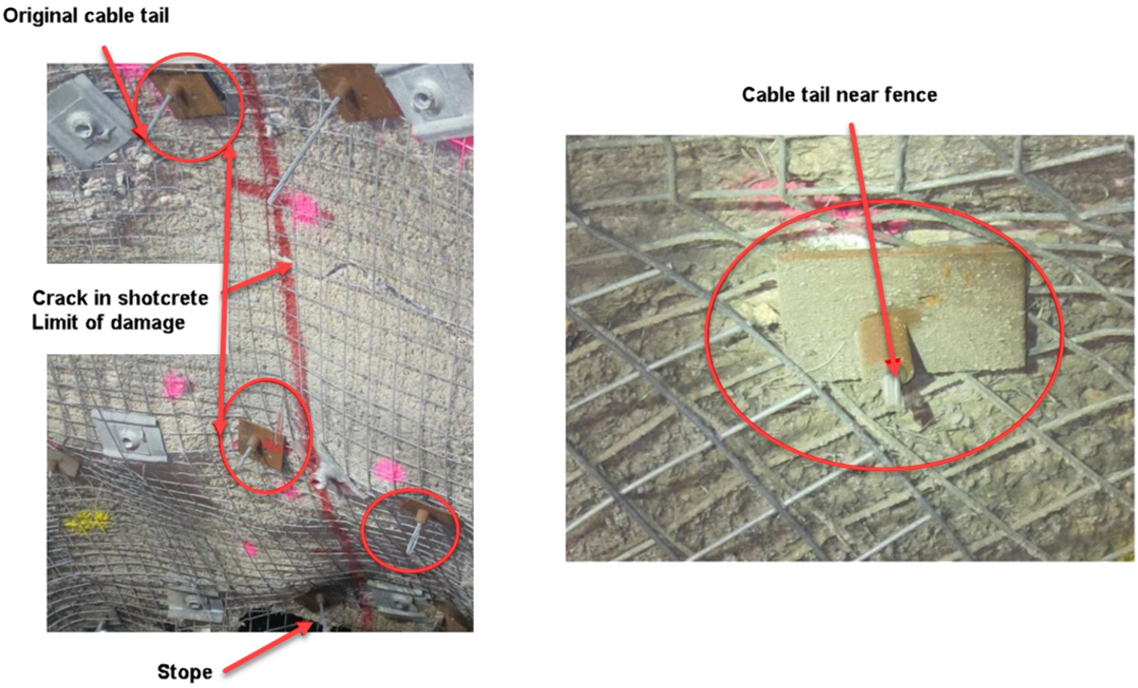


Figure 7 Cable bolt barrel and wedge fixture (after DSI Underground 2024)

However, if minor corrosion occurs between outer surface of wedges and inner surface of barrel, the metal expands and wedges 'lock up', allowing the complete surface plate assembly to slide down the cable at the original residual seating load which is less than the design cable capacity (Bawden 2023). This can be easily stopped by coating the outer surface of the wedges and the inner surface of the barrel with copper coat grease or equivalent to inhibit any corrosion.

Figure 8 shows an example of a cable plate assembly failing by sliding down the cable under rock mass dilation loading. The difference between the original cable tail (Figure 8a) and the cable tail near the face (Figure 8b) is due to the plate and grip assembly sliding down the cable.



(a) (b)

Figure 8 Support surface plate attachment failure example (after Bawden 2023). (a) Original cable tail (red circles); (b) Remaining cable tail after plate slippage

2.5 Cable bolt pattern design

A number of complementary technologies can be utilised to conduct a standard cable bolt pattern design. This may include some or all the following:

- Personal and mine experience.
- Empirical methodologies such as the Stability Graph (Potvin 1988).
- Simple numerical block programs such as Unwedge (Rocscience™).
- Numerous commercial numerical modelling packages.

Each of the above have strengths and limitations. For example, programs such as Unwedge are best suited to simple gravity wedge support analysis. The Stability Graph system is well suited for evaluating the feasibility of cable bolting for a specific site and provides input toward bolt length and spacing considerations. Numerical stress analysis programs are very useful as an assist in selecting cable bolt length requirements but should be used with great caution for modelling of explicit cable bolt behaviour. Used in the proper combination, these techniques provide very effective design tools. They do, however, require an appropriate level of expertise in order to be used effectively.

Today, any initial cable bolt pattern design carries a great deal of uncertainty until explicitly tested in situ. For this reason, instrumentation including SMART Cable and multi-point borehole extensometer (MPBX) instruments (discussed in the following section) provide excellent tools with which to evaluate cable bolt design effectiveness and to minimise risk to both personnel and equipment while at the same time permitting optimisation of the design.

3 Rules and limitations for deployment of instrumentation for cable bolt cable bolt ground support monitoring

In the author's and Mine Design Technologies' experience, considerable confusion is encountered with clients with respect to the design of a cable support instrumentation program and the interpretation of the resulting instrumentation data. This section is an attempt to clarify these issues and to provide guidelines for the successful implementation of such instrumentation programs.

> '*The fundamental issue, often misunderstood, is that embedded support tendons do not respond to changes in mine induced stress. Rather they respond to what changing mine induced stresses cause, 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, etc.), 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*.' (Bawden 2023).

Figure 9 shows a schematic view of a fully encapsulated solid bar support element. The same mechanism applies to fully encapsulated cable bolts. 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. As discussed in Section 2.1, 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 9). 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 9, the bolt strain is local to the dilating joint/s and is given by d/l (%). In the case of bulb cable, the length 'l' is constrained by the selected bulb spacing that then dictates cable stiffness (after Bawden 2023).

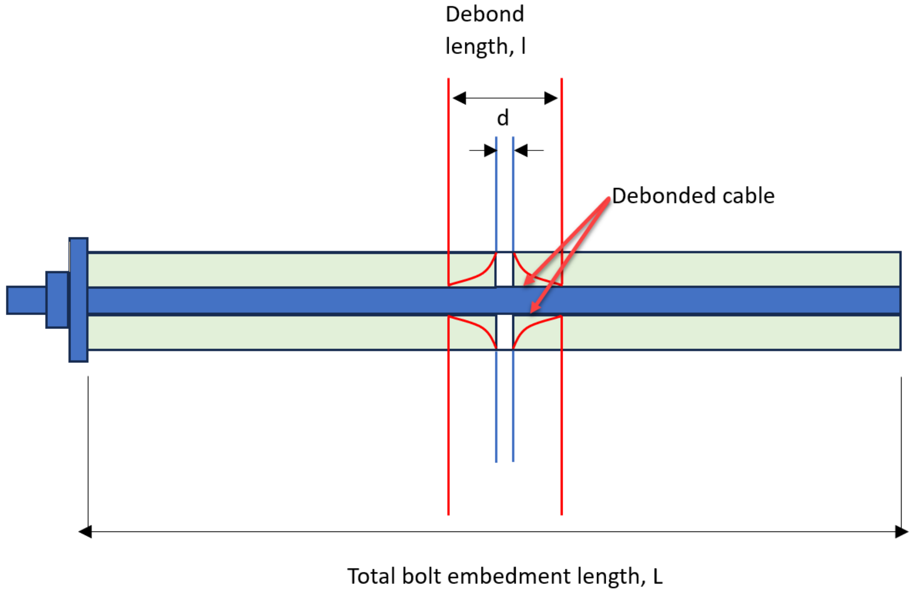


Figure 9 Loading mechanism for a fully bonded sold bar support element (L = full bolt length; l = debond length; d = local ground dilation)

3.1 Definition of a SMART Cable

A SMART Cable is an instrumented cable bolt support element that:

- measures the deformation (stretch) of the steel cable between set anchor points from which the cable strain is calculated
- provides the same support capacity as a normal cable bolt in the elastic range with a slight reduction at ultimate plastic strain.

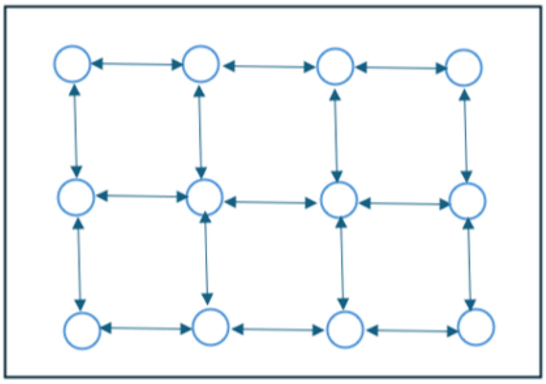
3.1.1 Installation guidelines

The following instrumentation guidelines should be followed for any cable bolt instrumentation program:

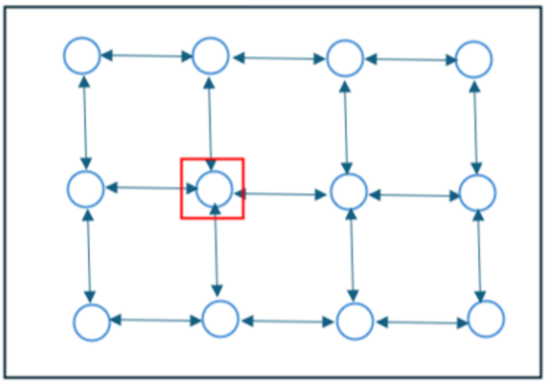
- SMART Cables should be installed as part of the design cable bolt pattern and definitely not outside of the pattern (Figure 10).
- For twin strand applications, only one of the cables needs to be a SMART Cable.
- SMART Cables must use the same cable configuration (i.e. bulb or plain strand) as the rest of the design.

These instruments can then be used to:

- optimise cable bolt pattern design (length and spacing)
- evaluate rehabilitation need and timing
- control access to potentially unstable areas.



(a) Uniform cable bolt pattern – no Smartcable



(b) Uniform cable bolt pattern – with Smartcable

Figure 10 SMART Cable location in pattern

3.1.2 Interpretation of SMART Cable readings

Figure 11a shows cable deformation data from three SMART Cables from a mine in Northwestern Ontario. The measured deformations, interpreted as 'stretch' of the steel cables, is then used to calculate cable strain which, based on laboratory cable stress–strain curves, is used to determine cable load in tonnes (Figure 11b).

> '*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 cause, 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 dictate 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.*' (Bawden 2023).

Displaying the cable load in tonnes is done strictly for operator convenience. The actual behaviour is governed strictly by the steel cable strain (yield at 0.9%; rupture at ~3.5%).

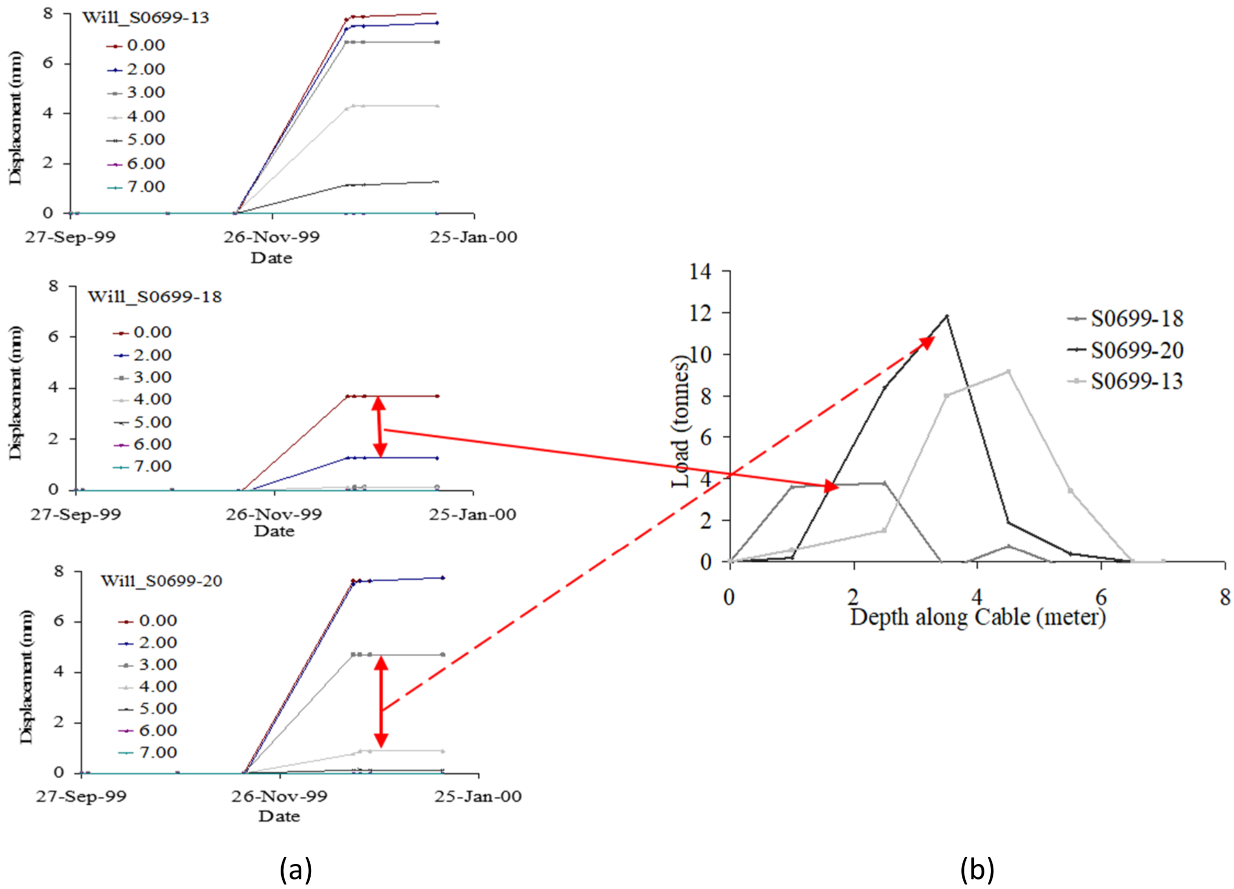


Figure 11 (a) Measuring cable displacement (mm); (b) Interpretation of load (t)

3.2 Definition of a multi-point borehole extensometer

An MPBX is a passive instrument installed in a bore hole to measure differential ground movement between set anchor points. It provides no ground support. It is designed to be placed in direct tension (i.e. limited shear capacity and shear is difficult to interpret).

These instruments are used to determine areas undergoing ground deformation, including the absolute amount and rate of deformation.

MPBX instruments can also provide warning of areas of potential support overload and/or collapse. Interpretation of ground support load from an MPBX reading must be done with great caution as discussed in the following subsection. They are interpreted in the same manner as a SMART Cable and the measured ground deformations can be used to calculate ground strain. Ground strains should not be interpreted as equal to the local ground support strain unless 100% bond efficiency can be guaranteed.

3.3 Are multi-point borehole extensometer and SMART Cable readings the same?

MPBX and SMART Cable readings are the same under two limiting boundary conditions:

1. There is no ground movement.
2. The cable bolts are perfectly bonded to the rock mass.

As discussed in Section 2, cable bolt BS depends on a number of factors including:

- stiffness of the fractured rock mass
- grout quality (strength and stiffness)
- cable type (bulb vs plain strand)
- cable surface condition.

If the cable BS is insufficient, cables when loaded will pull through the grout without mobilising the full cable capacity (stripping failure [Figure 3]). Alternately, cable plate and grip assemblies can slide if minor corrosion has occurred between the barrel and wedge surfaces.

3.4 How to determine if cables are stripping

It is strongly recommended that some MPBX instruments be included with the SMART Cable instrumentation (Figure 12). If the SMART Cable deformations are less than the MPBX passive measure of the rock mass displacement, then the cables are pulling through the grout and a stripping failure is occurring. Absent suitable instrumentation, such failures can occur apparently 'without warning'.

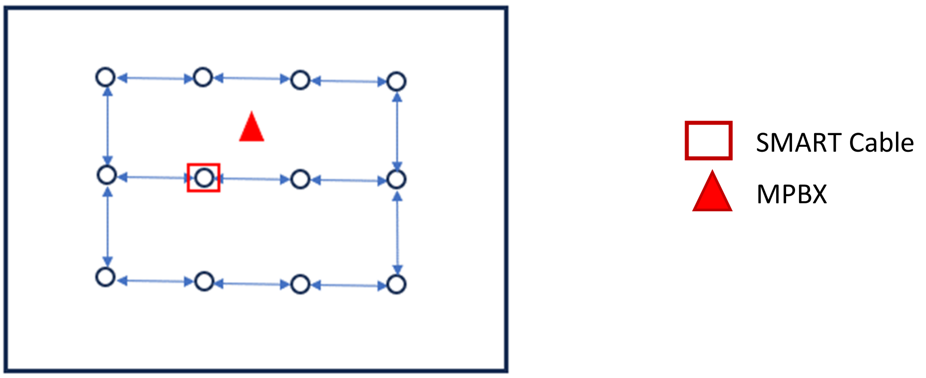


Figure 12 Positioning of multi-point borehole extensometer (MPBX) and SMART Cable in cable bolt pattern

3.5 SMART Cable installation options

Mine rock mass closure deformations, particularly if driven primarily by excessive mine induced compressive stress, are commonly highest in the near field to the mine opening surface (i.e. the inner shell). In such cases, if SMART Cables are installed in the normal fashion with the instrument head at the borehole collar (head at collar), the large rock mass movements can pull the instrument head off the cable at which point, the SMART Cable no longer functions as an instrument, although it still functions as a support element. In such situations, the SMART Cable installation should be reversed with the instrument head being installed at the borehole toe (head at the toe). In such cases, the lead wire from the head must be protected from the grout displacements and the instruments lead wire is passed through a sectioned steel pipe that debonds the lead wire from the grout deformation. The instrument can then continue to function through large surface deformations.

4 Conclusion

Critical factors that must be assessed and incorporated in a cable bolt program design include:

- rock mass strength and stiffness
- grout strength and stiffness
- cable type (bulb versus plain strand)
- bulb cable stiffness (bulb spacing)
- cable installation procedure
- quality and capacity of grouting equipment
- grout QA/QC procedures.

These factors must be evaluated individually but then be incorporated together to create the optimal cable bolt support system.

The best ground support design can be flawed due to insufficient or inaccurate input data, poor installation QA/QC or unforeseen field conditions. Instrumentation is therefore critical to successful ground support design to:

- validate/calibrate design assumptions
- optimise the design
- provide early warning of flawed design
- monitor support consumption to optimise rehabilitation requirements.

References

ASTM International 1980, *Standard Specification for Uncoated Seven-wire stress-relieved steel strand for prestressed concrete. Standard # A 416 -80*, West Conshohocken.

Bawden, WF & Jones, S 2007, 'Ground support design and performance under strong rockburst Conditions', in Y Potvin, J Hadjigeorgou & D Stacey (eds), *Challenges in Deep and High Stress Mining*, Australian Centre for Geomechanics, Perth, pp. 327–326.

Bawden, WF 2023, 'The ground support life cycle considering real time ground consumption monitoring', in J Wesseloo (ed*.), Ground Support 2023: Proceedings of the 10th International Conference on Ground Support in Mining*, Australian Centre for Geomechanics, Perth, pp. 3–22, https://doi.org/10.36487/ACG_repo/2325_0.01

DSI Underground 2024, *Cable Bolts: The Wedge Anchorage of the Cable Bolt*, https://www.dsiunderground.ca/products/mining/cable-bolts/wedge-anchorage

Hutchinson, DJ & Diederichs, MS 1996, *Cablebolting in Underground Mines*, Bitech Pub Ltd, Richmond.

Hyett, AJ, Bawden, WF, Lausch, P, Ruest, M, Henning, J & Baillargeon, M 1997, 'The S.M.A.R.T. cable bolt: an instrument for the determination of tension in 7-wire stand cable bolts', *1st Asian Rock Mechanics Symposium: Arms '97 A Regional Conference of ISRM*, International Society for Rock Mechanics and Rock Engineering, Lisbon.

Potvin, Y 1988*, Empirical Open Stope Design in Canada*, PhD thesis, The University of British Columbia, Vancouver.