Hudson Bay Mining and Smelting Co.'s Field Trials Using 'SMART' Technology - Successful Ground Support Design Through *In Situ* Cable Bolt Performance Evaluation

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ABSTRACT

Cable bolts are widely used as a principal means of support. The monitoring of the performance of reinforcement is critical in improving and optimising reinforcement designs. This paper presents case studies where Stretch Measurement to Assess Reinforcement Technology (SMART) instrumentation was used in conjunction with other observational, analytical, and numerical techniques to evaluate cable design performance and determine the nature of the failure mechanisms. These case studies also provide an excellent comparative study of the *in situ* bond stiffness of plain strand and Garford bulb cable, as well as in evaluating the influence of faceplates on Garford cable's performance. Cable bolt design was optimised through a multifaceted design methodology and verified through field instrumentation. The changes in stope support design and cable bolting practice have resulted in significant cost savings.

INTRODUCTION

The benefits of cable bolt support in stabilising surface and underground excavations are well established and this support system is extensively used in the mining and civil engineering industries as a principal means of support. The monitoring of the performance of reinforcement around excavations is critical in assessing overall stability as well as in improving and optimising reinforcement designs. Hutchinson & Diederichs (1996), emphasise this in the verification portion of their cable bolting cycle. The verification process should involve an evaluation of the effect of cable bolts on rock mass stability, based on a combination of observation and instrumentation.

One of the major problems associated with the use of fully grouted cable bolts is the lack of a reliable method to monitor cable tension. In this paper, an innovative instrument will be described, that can determine the load distribution along fully grouted cable bolts. This instrument, the SMART (Stretch Measurement to Assess Reinforcement Tension) cable, allows strains along cables to be quantified; hence enabling loads to be calculated. The instrument incorporates a miniature MPBX (Multiple Point Borehole Extensometer) within the cable, thereby avoiding interference with the cable:grout bond, as is the case with externally mounted gauges. The SMART cable has been progressively improved upon, since the initial prototype described Hyett *et al* (1997) and Ruest (1998). Field trials were undertaken in stopes at Hudson Bay Mining and Smelting Co.'s (HBM&S) Callinan and Trout Lake mines. Due to limitations on the length of the proceedings, only the Callinan experiment is presented in detail and the Trout Lake trial is heavily précised.

SMART CABLE

The SMART cable measures the displacement of up to six anchor points as the cable stretches when subjected to tensile loading. Since the relative displacements between anchor points are known, through movement of the wiper across a linear potentiometer in the readout head, the amount of cable stretch may be calculated. By measuring the extension or stretch between two known locations along the cable, the strain may be calculated. Since the load-deformation relationship of the cable is known (from laboratory testing), the average tensile load between the two anchor points may be calculated from the measured cable strain. The instrument has a potentiometric readout head small enough to be grouted into an NX (54mm) sized borehole. Since the head may be grouted into the borehole, this offers protection from mechanical damage in the harsh mining environment, and facilitates the tensioning of cables when the head is positioned at the toe of the hole (head-up configuration). This instrument has been validated through both laboratory and field trials, and has proven to be an accurate means of assessing loads in cable bolts. Successful field trials have been carried out at six North American mine sites in over 10 different experiments, and most recently in a tie-back wall application for a large civil engineering project in Toronto. The laboratory trials indicate that the instrument has an accuracy better than 1.4% FS and has a very high level of repeatability (de Graaf, 1998).

CALLINAN FIELD TRIAL

An intensive ground instrumentation program was undertaken at the Hudson Bay Mining and Smelting Co.'s Ltd. (HBMS) Callinan mine. This 600 000t/yr base metal mine is located in western Manitoba. Sublevel open stoping, by longitudinal retreat, is the most commonly used stoping method. The instrumentation included; two Multiple Point Borehole Extensometers (MPBX's) and nine instrumented cables, using the SMART technology (See Figure 1). The field trial was designed to allow *in situ* performance of different cable types and configurations to be compared and quantified. The experiment also aimed to provide a better understanding into cable-rock mass interaction, which in turn would allow cable support design to be optimised.

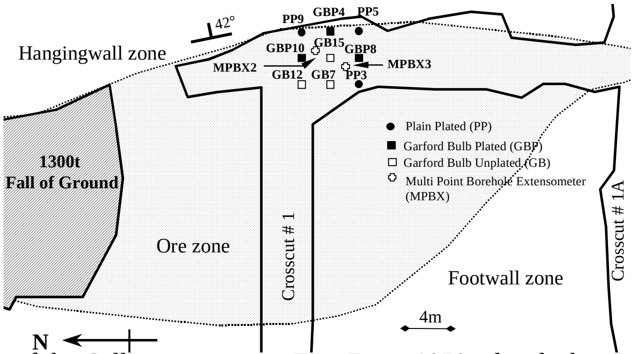
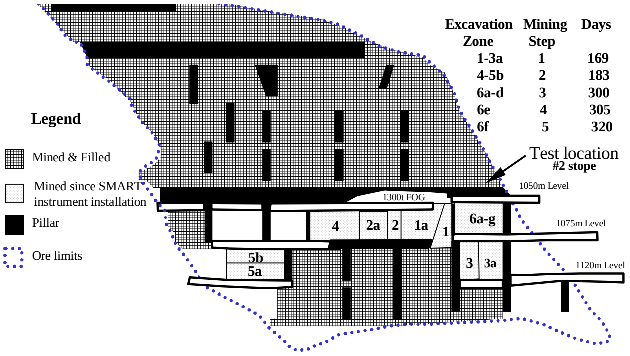


Figure1. Schematic plan view of the Callinan test stope, East Zone, 1050m level, showing the geotechnical zones and the SMART instrumentation locations.

The ground conditions in the test stope at Callinan may be simplified into three geotechnical zones; hangingwall, ore and footwall zones. Rock mass properties of the footwall, hangingwall and ore zones were assessed to be '*good rock*' according to both the RMR'$_{76}$ (GSI) and Q' classification systems. A dual stress driven and structurally controlled deformation mechanism was recognised. The stress driven component was evident since rebar faceplates were observed to have failed and some sidewall slabbing was apparent. Structurally controlled failure had been identified in adjacent stope backs, and was confirmed visually when the #2 stope back failed.

The Callinan stope represents a late stage, sill pillar or remnant stage of mining. The excavation sequence of mining in the East Zone, since installation of the SMART instrumentation, is illustrated in Figure 2. The excavation stages 1 though to 6g have been subdivided into 5 mining steps as indicated.



Excavation Zone	Mining Step	Days
1-3a	1	169
4-5b	2	183
6a-d	3	300
6e	4	305
6f	5	320

Figure 2. Longitudinal section of the Callinan East Zone showing the excavation zones in the mining sequence.

The instruments were installed in the #2 stope on the 1050m level. Conventional cables within the existing support design were replaced with SMART cables. The instrument array comprises two different cable configurations (plated and unplated) and two cable types (Garford and standard) which were combined to make up three SMART cable instrument types; plated plain strand (PP), plated Garford (GBP), and unplated Garford (GB) cables. This allowed load distributions along conventional and modified geometry cables to be quantified and compared, as the rock mass responded to mining induced stress changes. Standard ground support comprised of single 7.5m long plain plated cables on a 1.8 by 1.8m pattern, and 2.25m (22mm) resin rebar on a 1.25 by 1.25m spacing. Figure 3 shows the detailed mining sequence of the development of the slot and excavation of the test stope.

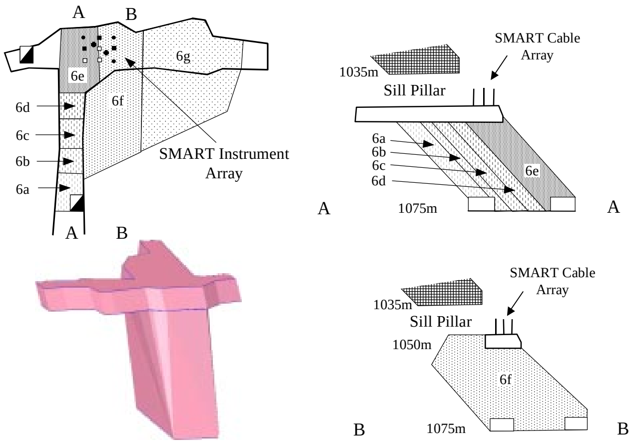


Figure 3. Views showing the sequence of mining (6a-g) within the test stope. Clockwise: Plan, cross-sections, and perspective view of the test stope at the completion of the 6f excavation zone (mining step 5).

The test stope is one of the last stopes in the #2 lens to be blasted. SMART MPBX's indicate how the rock mass is moving, while the SMART cables measure how much the cable is stretching in response to these deformations. Fully grouted cable bolts behave as passive reinforcement. Tension develops in response to the rock mass displacements.

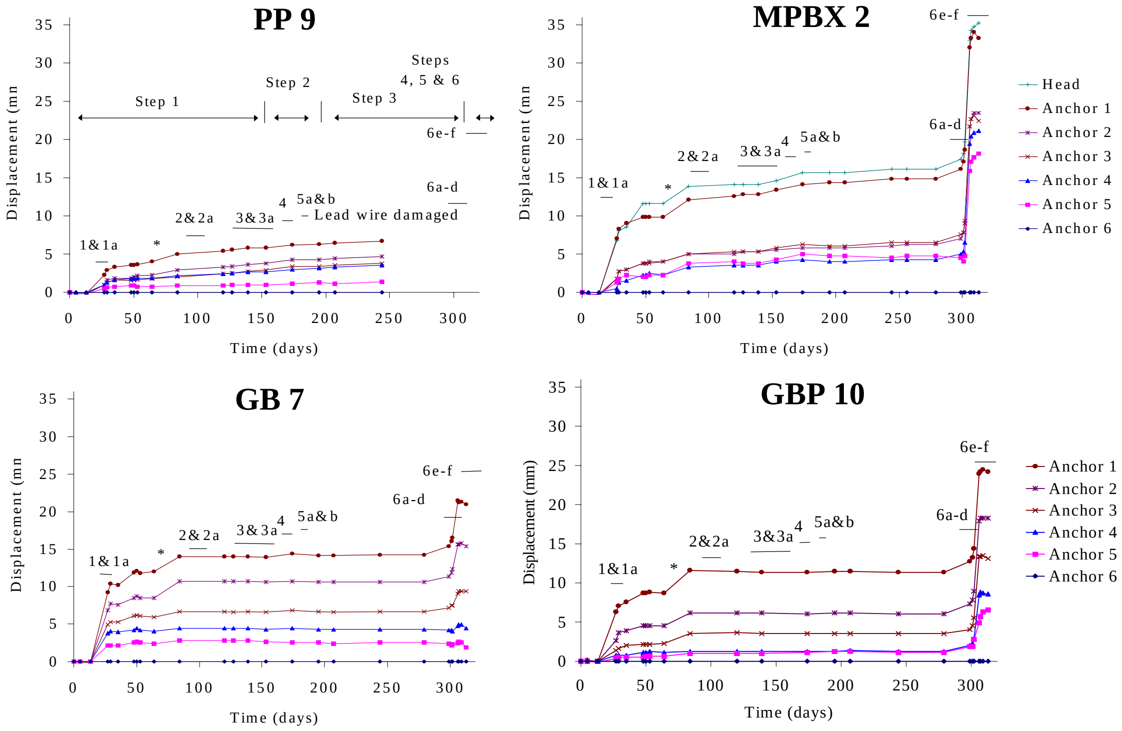


Figure 4. Time vs displacement graphs for the different types of SMART instrument, in relation to the blasting sequence (and mining steps PP 9). (* 70 days non-production blast)

Graphs of time versus displacement for each of the SMART instrument types correlate very well to the timing of the production blasts, as well as with one another (see Figures 4 and 5). Typically a time dependent rock mass displacement relationship was observed following the blasts, this comprises an initial large movement, followed by successively smaller displacements with time. This is a function of the rock mass readjusting to the stress redistribution associated with the excavation. Clearly only excavations in the immediate vicinity of the test stope have an influence on the instrumentation. A non-production blast (to scale down unstable material in the back) was undertaken 70 days after installation in the crosscut #1, approximately 6m from the test location. Displacements up to 4mm were recorded following this blast. GB 12's lead wire was severed during this blast.

For both the plated and unplated Garford bulb cables the displacements are similar in magnitude to those measured by the MPBX's. The high bond stiffness of the Garford bulb cables approximates displacements of the MPBX anchor points, since there is very little relative slip between the cable, grout and rock interfaces. Obviously sufficient bond strength is mobilised at the cable-grout interface to stretch the cable along with the rock. The differences between the displacements measured in the SMART cables and those measured in the MPBX's represent bond slip at the cable-grout interface. There are no significant differences between the plated and unplated Garford bulb cables. The standard cables (PP) showed significantly less displacement than the MPBXs and Garford Bulb cables. This implies that significant slip is occurring at the cable-grout interface. The corresponding loads developed in the plain cables are typically more than 50% lower than those of the Garford bulb cables. PP5 indicates an even greater difference, but it may have been poorly grouted. GBP 8 also appears to have been poorly grouted, but still mobilised loads well in excess of those in PP5. The bond strength of the standard cables is insufficient to mobilise high loads along the standard cables. Load profiles along the SMART cables are plotted for mining steps 3 and 4 in Figure 5.

At an early stage in the experiment it was recognised that many of the cables were carrying loads very close to their ultimate tensile strengths, and that significant falls of ground were anticipated. The mine operator re-engineered the blasting sequence of the stope accordingly, and attempted to blast the stope in as few stages as possible.

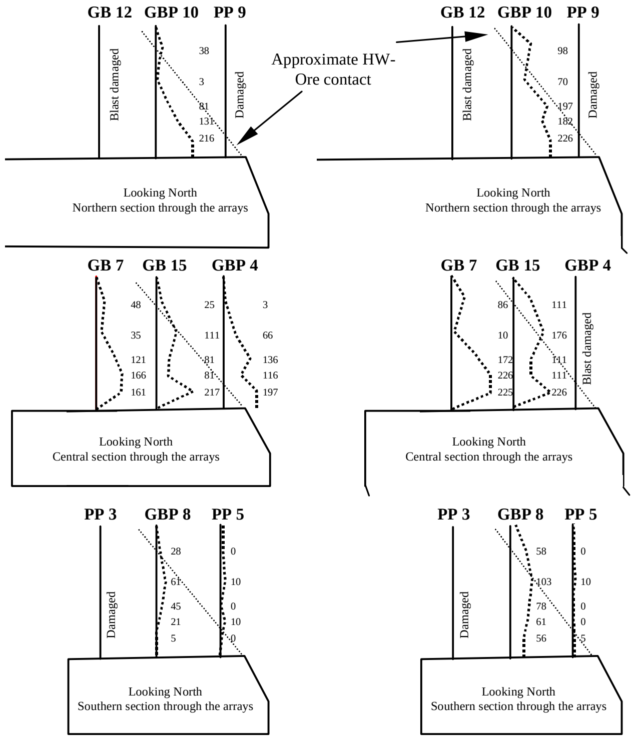


Figure 5. Sections through the instrument array, showing load (kN) along the SMART cable's length. Left: 300 days (step 3), Right: 306 days (step4).

The structural control on rock mass deformation is clear from the load profiles. Many cables show one or more peaks, indicating that deformation is localised at more than one zone along the cable's length. In all cases, at least one of these zones of deformation corresponds with the hangingwall-ore contact. Also, the total zone of deformation in the stope back is observed to increase or become more deep seated with time.

This case study provides an excellent comparison of the relative bond stiffnesses of Garford bulb and standard cable *in situ*. Each mm of rock mass displacement results in the mobilisation of more than double the load in the bulb cables over that in the standard cable. The plain cable allows significant rock mass displacement before reaching its tensile capacity, potentially allowing the rock mass to completely lose its inherent strength, leaving the cables to support a dead weight. This is particularly important for the support of gravity driven wedges in stope backs. Even quite small amounts of movement (dilation) may be enough to begin to release the wedge, reducing the clamping stresses and resulting in dead weight loading of the cables. The stiffer Garford cables result in more immediate development of reinforcement tension, so preventing loss of the rock masses inherent strength.

The performance of each type of SMART cable is graphically shown in Figure 6, where excavation boundary displacement (measured from the MPBX's) is compared to the peak load developed along each SMART cable. This plot of raw data spans the entire duration of the experiment (312 days) and includes over 20 readings per instrument. The significantly higher bond stiffness of the GB cables is obvious, since this cable type attracts more than double the load of the PP cable per mm of excavation boundary deformation. Interestingly, the influence of faceplates on the Garford cable is negligible since there is no noticeable difference between the GB and GBP instrument responses. Also, the sensitivity of the plain strand cable to grout quality control is evident from the dismal response of PP5. GBP8 (also poorly grouted) only performed similarly to the adequately grouted plain cable (PP9).

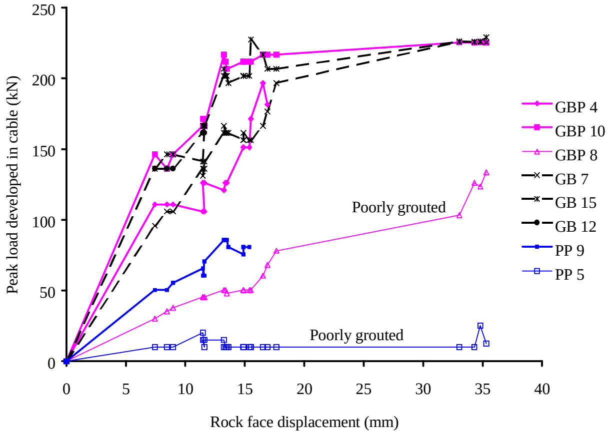


Figure 6. Cable performance evaluation - Peak cable load (SMART cable) versus rock mass displacement (MPBX).

The stress driven component of the dual (structural-stress failure mechanism) was investigated using the boundary element programme ***Examine***^{3D}. From the initial (mining step 0, at instrument installation) through to mining step 4, mine induced stresses increase in the stope back (See Figure 7).

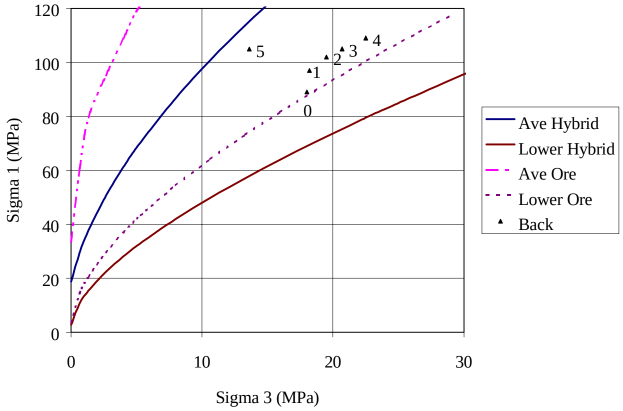


Figure 7. Changes in σ_1 and σ_3 with respect to H-B failure criterion in the sill pillar during mining (initial stage is step 0; blasts 6g and 6f are steps 4 and 5).

However, once the test stope is excavated along strike (step 5), both σ_1 and σ_3 decrease, as shown in Figures 7 & 8. This reduction in confining stresses effectively lowered the clamping stresses action on potentially unstable wedges thereby lowering their factor of safety against failure, along with negatively influencing cable bolt performance. The associated reduction of bond strength with decreasing confinement is well documented in the literature, and the plain strand cable is more sensitive to this than the Garford cables. Remembering that the majority of the stope was supported with single plain strand cable, it is not surprising that two significant falls of ground occurred. An initial 200t failure, in the vicinity of the instrument array, after the first blast along strike, and another larger failure associated with the final blast. These plain plated cables were ineffective in controlling dilation and have allowed this progressive failure to occur.

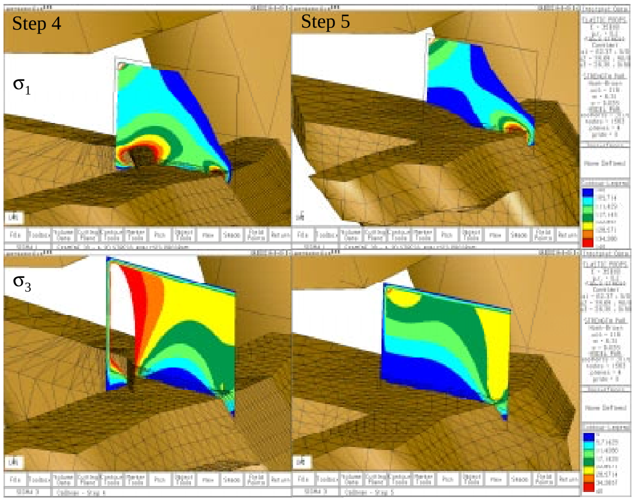


Figure 8. ***Examine***^{3D} results showing the decrease in σ_1 and σ_3 between mining steps 4 and 5.

The structural control on the failures that occurred was supported through visual evaluations of the fallen ground as well as through a cavity monitoring survey (CMS) (See Figures 9 & 10). The inadequacies of the current single PP cable design are clear in Figure 9. The lack of sufficient bond strength is evident since many cables have been stripped. For those cables that did attract significant load, the single cable design did not possess adequate capacity to carry the dead load of the wedge.

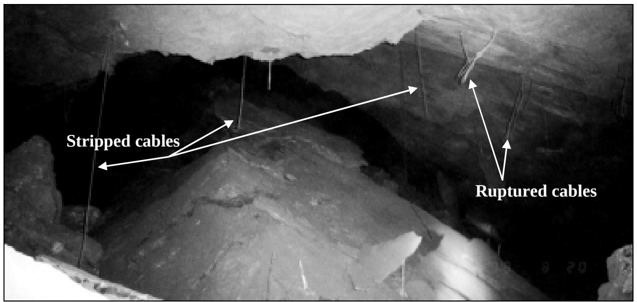


Figure 9. Photograph looking northwards in the test stope, showing the clear structural control on the back failure, as well as cable failures.

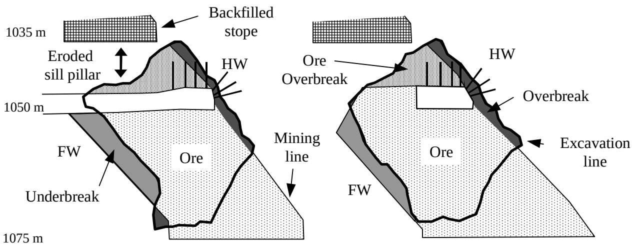


Figure 10. CMS results from the test stope. Left: northern end of the instrument array, Right: southern end of the array.

Based upon the geomechanical characteristics of the rock mass, the SMART cable results and the ***Unwedge*** analyses, an immediate change from plain plated cables on a 1.8 by 1.8m pattern to twined unplated Garford bulb cables on a 2.0m by 2.0m pattern was recommended. Cable spacing may realistically be increased to 2.2 by 2.2m once the 2.0 by 2.0m pattern has been validated through instrumented trials. Since wedge failures are of primary concern, the stiffer support offered by the Garford bulb will help reduce any loosening of wedges, retaining the inherent stiffness and frictional properties of the rock mass, thus helping it support itself more effectively. Furthermore, the Garford cables are less sensitive to destressing (reduction in confinement) and grout quality control. The twinned cables will further increase the dead load capacity of the support system. The reduced drilling requirements and absence of face-plating cycle translate into significant cost savings. In material and drilling costs alone these translate to savings of 9.5% and 31% per stope for the 2.0m and 2.2m square patterns respectively. The cost savings are secondary to the significantly improved stope stability of the GB cable designs.

TROUT LAKE FIELD TRIAL

In a similar experiment, carried out at HBM&S' Trout Lake mine, significant improvements in cable bolt design were also achieved. 27 SMART cables and 5 SMART MPBX's were installed in instrument arrays in the hangingwall, back and brow of a stope on the 1010m level in the West Zone (See Figure 11). Ground conditions are similar to those encountered during the Callinan trial, however the test stope lies in a lens that is at an early stage in the mining sequence. Here too, a combined structurally controlled (dominant) and stress driven failure mechanism was identified. The results from Mathews' analysis, the SMART instrumentation, and ***Unwedge*** indicate that the existing backsupport design is overly conservative and that the hangingwall and brow designs may also be improved. During the mining sequence to date, ***Examine***^{3D} analysis shows that stress induced damage in the back is minimal, while notable destressing occurs in the hangingwall and brow locations (particularly with future mining steps). This mumerical modelling was validated through field measurements. A high degree of correlation was observed between the measured rock mass displacements (SMART MPBX's) and those predicted by the elastic numerical modelling. Measured cable loads were not particularly high since only elastic rock mass deformations occurred during the experimant.

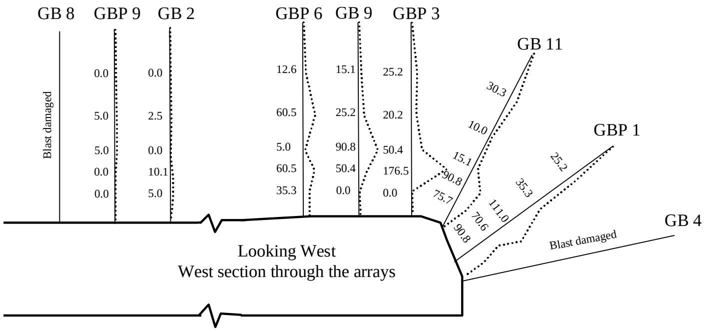


Figure 11. Schematic illustration of the distribution of load (kN) along some of th SMART cables in the brow, back, and hangingwall arrays at 352 days from installation (The test stope was mined out from 127 to 186 days from instrument installation).

An immediate change from the existing design (twin 7.5m long plain plated cables on a 2.4 by 1.83m pattern) to twin unplated GB cables on a 2.0 by 2.4m pattern was recommended. Realsitically the cable pattern could increase to 2.4 by 2.4m. The drilling and material cost savings of these designs are 7% and 25% respectively. The use of twin GB cables at lower cable densities reduce support costs without affecting stope stability.

CONCLUSION

The SMART cable has been validated through both laboratory and field trails. The field results confirm the extensive laboratory investigations into the load distributions along fully grouted cables carried out by; Reichert (1990), Goris (1990), and Hyett *et al* (1995). The data compares very well with previous field trials of the SMART technology at the Bousquet, Trout Lake and Golden Giant mines Ruest (1998), de Graaf (1998) and Hyett *et al* (1997).

The Callinan study has provided an excellent comparison of the relative stiffness of Garford bulb and standard cable *in situ*. The Garford cables offer a far stiffer support than the plain cables, and thus attract higher loads. The influence of faceplates, on Garford cables, is negligible since the performance of the plated cables was indistinguishable from that of the unplated cables.

The proposed improved cable bolt designs for the Callinan and Trout Lake mines, comprising of twin Garford bulge cables is a stiff, high capacity support system, which is significantly less sensitive to changes in confining stresses and installation quality control. These designs have been shown to out perform the existing plain plated cable design.

When comparing the Callinan and Trout Lake trials an important note in the differences in measured cable response and the nature of the rock mass deformations should be made. At Callinan the numerical model predicted extensive failure and rock mass deformations were beyond the elastic range. This was observed physically in the rock mass. The cables were exposed to significant deformations and excessive loads developed in response to these strains. At Trout Lake the predicted elastic behaviour was validated through observation, since the MPBX deformations matched those forecast by the numerical model. In addition, the cables were not subjected to excessive loads. Therefore it can be deduced that cables are subjected to significant loading as the rock mass moves towards, and beyond, its failure envelope. Non-linear models are therefore necessary to predict rock mass failure, and to characterise the associated rock mass deformations. The modelling of cable element-rock mass interaction requires a non-linear approach in order to adequately characterise the rock mass behaviour that is known to place the highest demand on the individual cable elements, as well as on the entire cable design.

Cable bolt support design has been optimised through a simple multifaceted design methodology. This methodology comprises; detailed geotechnical mapping, empirical design, numerical modelling of support elements and design verification through field instrumentation. The final stage in support design should entail design verification. The SMART cable, in quantifying the loads developed in cables, allows the cable bolt’s performance to be assessed individually and collectively. This ‘closure’ of the design loop enables support design to be improved. These changes in stope support design and cable bolting practice have resulted in significant cost savings.

ACKNOWLEDGEMENTS

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