THE *S.M.A.R. T.* CABLE BOLT: AN INSTRUMENT FOR THE DETERMINATION OF TENSION IN 7-WIRE STRAND CABLE BOLTS

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ABSRACT: One of the major problems associated with the use of fully grouted cable bolts is the lack of a reliable method to monitor the tension that develops in response to rock mass displacements. Existing gauges are mounted external to the cable itself and therefore potentially interfere with the bond strength in the measurement area. This can make the results extremely difficult to interpret.

This paper describes a novel instrumented cable bolt. The technology is applicable to conventional and modified geometry cables. Twin strand cable bolts can also be instrumented. Since the device is internal to the cable, it does not interfere with the bond strength. Results from two initial underground trials are presented.

BACKGROUND

In their comprehensive handbook on cable bolting Hutchinson and Diederichs (1996) introduce the cable bolting cycle (Figure 1), "a cyclical, iterative process which should be worked through a number of times as mining progresses to ensure that the cable bolting process is well tuned". It involves three principal components: Design, Implementation and Verification. Whereas approximately 70% of the handbook is concerned with design and 25% with implementation, less than 5% is devoted to verification. They suggest that 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.

For rock bolts, strain gauges adhered to the bolt surface have been used quite effectively (Freeman, 1978: Xueyi, 1983) to measure the strain and hence load developed along the length. However, the complex helical geometry of a cable and the tendency for debonding to involve an untwisting mechanism, complicate the load determination problem for a 7-wire cable. Nonetheless, a number of tension measuring devices, all of which attach to the outside of the cable, have been developed. In Canada the Tensmeg (Choquet and Miller, 1988) comprises a spiral resistance wire wound into the flutes of the cable. Based on tensmeg results from Winston Lake mine, Maloney et al. (1992) commented that "cable strains and, hence, loads developed in a somewhat random fashion". Both Hutchinson (1992) at Ansil Mine and Goris et al.(1991) at Homestake mine have reported mixed experience with Tensmeg cables. In Australia, a number of instruments designed to measure cable bolt load have been developed (Windsor & Thompson, 1992). The Resistance Wire Cable Strain Cell (RWCSC) was used successfully to determine the load distribution that developed in cable bolts at Mount Isa Mine and indicated that the cables were attaining significant loads (up to 250kN). However, these instruments were never made commercially available. As pointed out by the authors, an inherent problem with these instruments is that load (or more accurately strain) is measured over a finite base length and inclusion of multiple instruments on the same cable to determine the load distribution becomes expensive. In addition, since the vast majority of cable bolts are fully grouted, strain measurement devices attached to the outside of the cable combined with associated lead wires, will affect the bonding process and hence the overall behavior of the cable bolt.

Overall, the number of documented cases for which instrumentation has been successfully used to verify cable bolt design are limited.

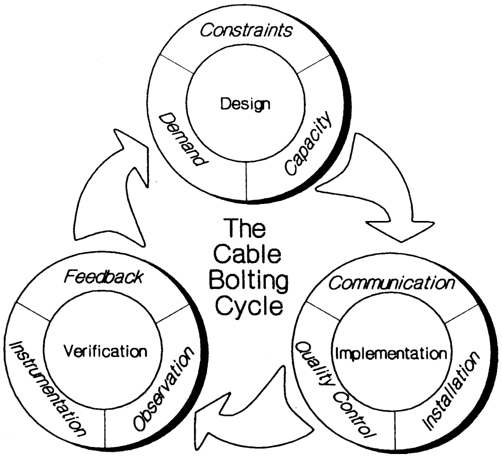


Figure 1: The cable bolting cycle (after Hutchinson and Deiderichs, 1996)

SMART CABLE CONCEPT

If the extension or stretch ($d^i - d^{i+1}$) between two known locations (L^i and L^{i+1}) along a 7-wire strand cable can be measured, the strain (often referred to as elongation) may be written:

$$\varepsilon = \frac{d^i - d^{i+1}}{L^i - L^{i+1}} (m/m)$$

For 0.6" low relaxation 7-wire strand (ASTM A416) the corresponding tension is

$$F=k\varepsilon(kN).$$

where for the elastic response:

$$k= 25000 \text{ kN/m/m } (0<F<225kN)$$

and for the strain hardening response after yield:

k= 600 kN/m/m ($F>115kN$ $\varepsilon <0.035m/m$ or 3.5%).

Thus the average load in the cable can be calculated from the strain between adjacent anchor points, and by using multiple anchor points the load along the whole cable bolt is determined. The instrumented cable described in this paper employs this basic principle. It will be referred to as **S**tretch **M**easurement to **A**ssess **R**einforcement **T**ension or ***SMART*** technology.

SMART CABLE DESIGN

In the manufacture of a SMART cable a miniature multi-point borehole extensometer (MPBX) is constructed within the kingwire of a 7-wire strand cable. To minimize size, spring loaded stainless steel wires rather than rigid rods are used. In the current SMART cable design, 6 wires are secured to the kingwire at specified distances from the instrumentation head where they are spring loaded. The displacement of these as the cable stretches is measured using potentiometers in much the same way as for a regular MPBX readout head. For a regular MPBX, the cost of a readout head is approximately $2000. Since cable bolts are often installed in locations where safe access cannot be guaranteed during mining, a disposable electrical readout head is required. Hence a major breakthrough in this research has been the development of a low-cost potentiometric readout head. As a further benefit, since the size of the readout head is dramatically reduced it is possible to fully encapsulate (i.e. protect) it within the cement grout, either at the collar or the toe of the borehole. The latter configuration facilitates pretensioning of the cable.

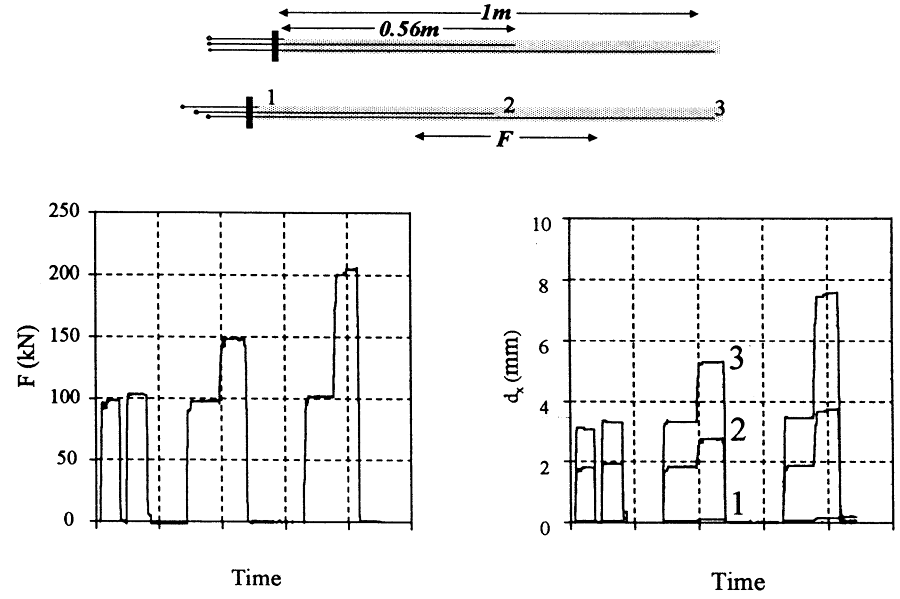


Figure 2: The response of the three anchor points located at $x_1 = 0.05$ m, $x_2 = 0.56$ m and $x_3 = 1.0$ m, when the cable was subjected to loads up to 200 kN. As expected the anchor point furthest away from the readout ($x_{readout} = 0$) exhibits the highest displacement (d_x).

Numerous tests were conducted to validate the SMART cable. The simplest of these involved a tension test in which an instrumented cable with three anchor points, the locations of which are indicated in Figure 2, was loaded in tension. The applied force (F) and the corresponding response of the SMART cable are shown.

The magnitudes of displacement, even for a 1m length of cable (i.e. 0.5m base length), are easily measured to high resolution using potentiometers.

CASE STUDY 1 9-1-15 Hanging wall at Bousquet # 2 mine.

SMART cables were installed in the H/W of the 9-1-15 slope at Barrick Gold Corporation's Bousquet #2. Prior to the experiment, doubt was expressed as to whether the cable bolts used in such situations were being significantly loaded.

Cable bolt layout

9-1-15 is a primary stope in a relatively new mining block. The H/W cable bolt design specified 8 cable bolt rings (designated 151-158) recessed from the 9-1 H/W access, each comprising a fan configuration of 9 cables ranging from 18m to 27m in length. The spacing between rings was 2m (Figure 3). A single Garford bulb cable with a 12" bulb spacing was placed in each 2.5" (63mm) hole, and was grouted from toe to collar using a 0.35 w:c ratio grout.

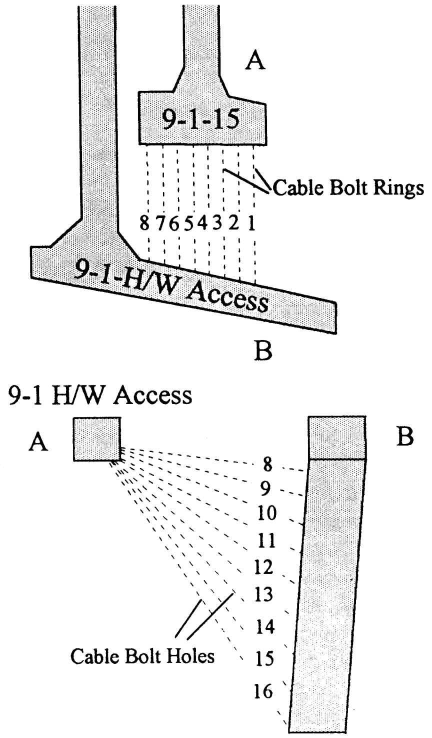


Figure # 3: The cable bolt layout for the 9-1-15 stopein plan (Top) and section (Bottom).

A combination of eight SMART cables and two MPBXs were installed. The SMART cables were simply substituted for regular cables (Figure 4). Four of the readout heads were completely immersed within the grout for protection. During the experiment both performed successfully.

The 9-1-15 stope was mined in essentially three stages (Figure 5) between November 28th (Day 13) and December 11th (Day 26). An MPBX located between rings 154 and 155 and coaxial with hole 10 measured relatively insignificant displacements during blasts 1 and 2. However following the main production blast, 231mm of displacement was measured at the furthest anchor point, with over 100mm of this being concentrated between 4m and 1m from the hanging wall. Similar results were obtained from the MPBX located in hole 155-12.

SMART cable results

Since fully grouted cable bolts behave as a passive reinforcement system, tension develops in response to the rock mass displacements. Therefore, based on the MPBX results, high loads were expected in the cable bolts.

Figure 4: Installing a SMART cable.

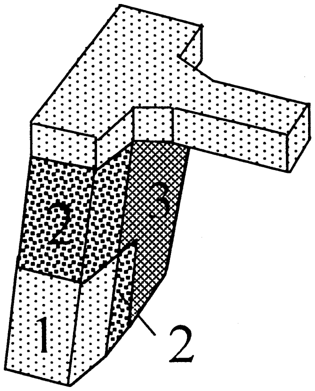


Figure # 5: The mining sequence for the 9-1-15 stope

Figure 7 shows the displacement of each of the six anchor points relative to the readout head over the duration of the experiment for three of the SMART cables (153-10, 153-12 and 154-10). For the readout head used, the stroke of the potentiometers was limited to 63mm. Due to the length of the cables and the high rock mass displacements, when the production blast was taken, this limit was exceeded for the anchor points closest to the stope. (To solve this problem potentiometers are now being used with a stroke length of 125mm). During each blast the electronic readout heads allowed the SMART cables to be monitored at 10 second intervals for a lhr period using a data acquisition system. The detailed response of cable 153-12 to blast 2 is shown in Figure 6. Immediately after the blast the anchor points moved significantly, indicating an increase in load in the cable. During the following 60 mins the anchor points continued to move as the rock mass readjusted to the stress redistribution associated with the excavation. These time-dependent movements (which should not be confused with the measurement resolution which is 0.01mm) sometimes affected the whole length of the cable (event A), and sometimes just a particular segment (events B and C). It is evident that the rate at which the anchor points were moving gradually decreased over the monitoring period.

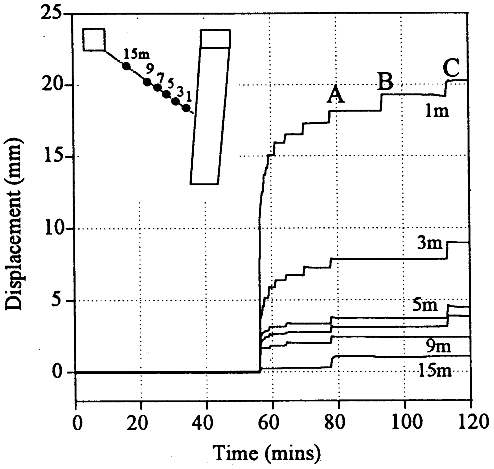


Figure # 6: The detailed response of cable 153-12 to Blast 2. Data was recorded at 10 sec intervals.

The distribution of anchor point displacement along the length of the cable is shown in Figure 8. As for the MPBX data, the highest displacements occur for those anchor points closest to the stope. However whereas the MPBX indicates how the rock is moving, the SMART cable measures how the cable is stretching. If the cable were perfectly bonded to the rock then both would give identical results. However slip occurs at the cable-grout interface as tension is mobilized in the cable. Consequently, the displacements recorded by the SMART cable should be less than those for the MPBX, with the difference between the two representing the bond slip at the cable grout interface.

The corresponding average load at the midpoint between anchor points was calculated as described in Section 2 (Figure 9). Since the range of the potentiometers was exceeded during the production blast, the detailed load distribution in the immediate hanging wall (based on anchor points 1 and 2) could not be determined (dashed line drawn to known boundary condition F=0 at distance zero).

The response of the three SMART cables to blasts 1 and 2 was dependent on their proximity to the excavation. Thus, when the hanging wall adjacent to 153-12 was exposed by blast 2, an increase in cable bolt load was recorded in the first few meters of the cable. After the production blast, when the stope was fully mined out, the load appeared to increase further back along this cable, possibly as the zone of significant rock mass deformation became increasingly "deep seated" due to the wider span. In comparison, cable 154-10 which was more remote from the initial blasts, shows virtually no response until the production blast, when it became significantly loaded at a depth of 6m from the toe. In fact the response from all three cables (and the MPBX) at this stage appeared to indicate significant opening across a geological structure that was mapped at 5-6m from the hanging wall contact.

Figure # 6:

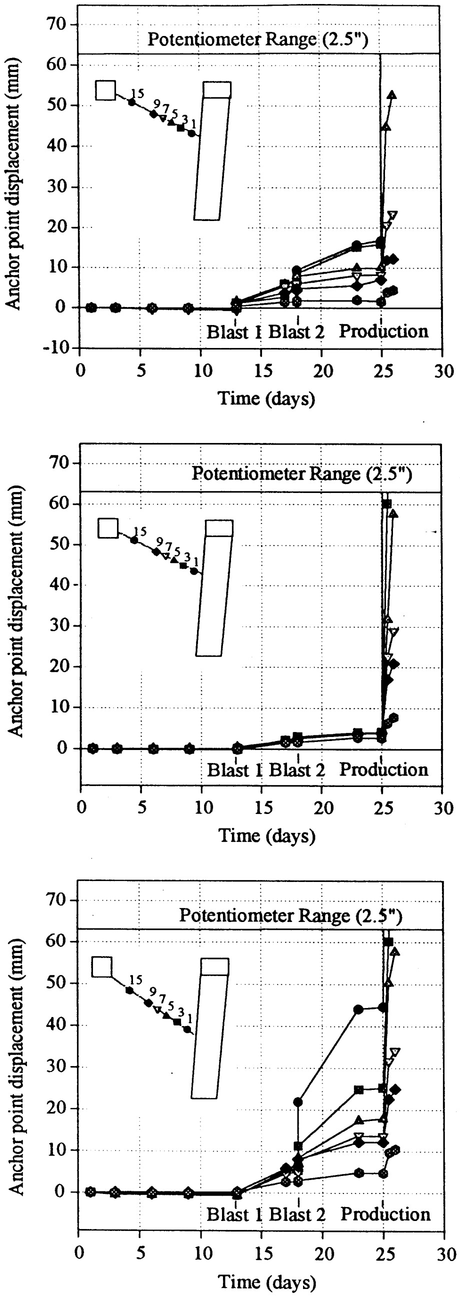


Figure 7: Response with time of the SMART cables 153-10 (top), 153-12 (middle) and 154-10

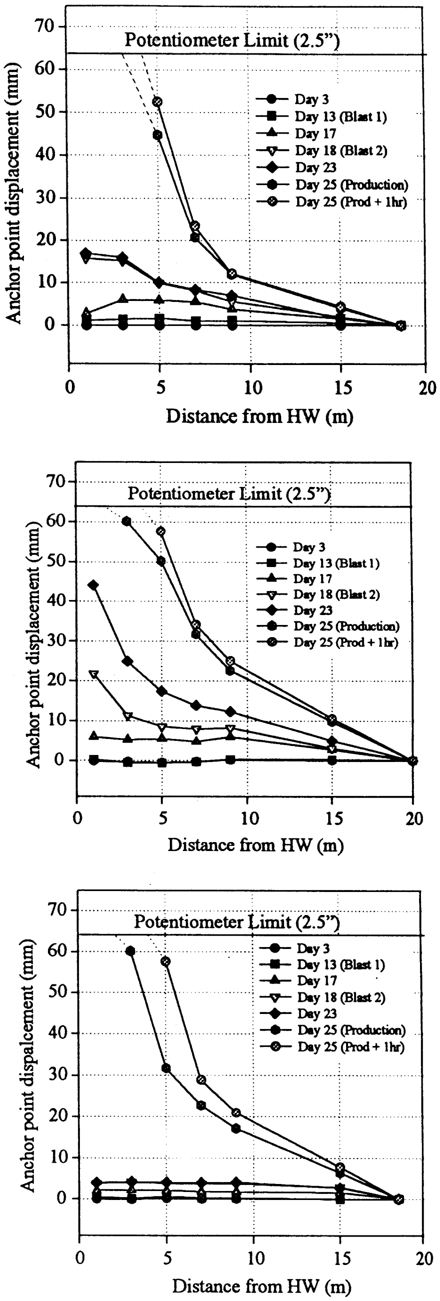


Figure 8: Displacement of anchor points located at 1, 3, 5, 7, 9, and 15 m along the cable during the experiment (153-10, 153-12 and 154-10).

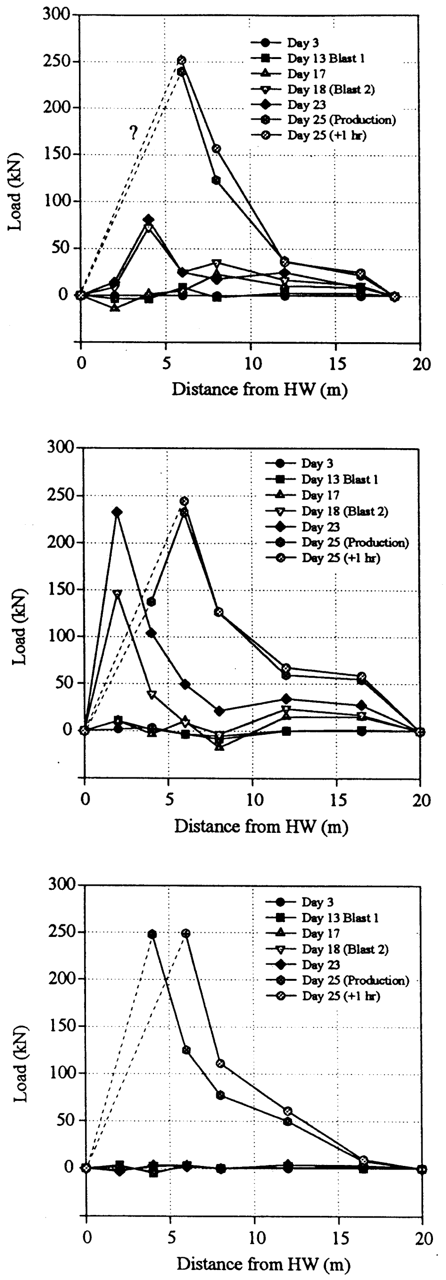


Figure 9: Load distribution along the SMART cables.

CASE STUDY 2

The Q15 back at the Golden Giant Mine

Twelve SMART cables were installed in the back of the 4600 Q15 and Q14 stopes at Battle Mountain Canada's Golden Giant Mine (Figure 10). The objective was to monitor the loads in the cable bolts, first when the neighboring 4600 2E stope was mined, and then when the 4600 Q15 stope itself was mined.

A plan of the area is shown in Figure 11. 10m long twin Garford bulb cables with a 300mm (12") bulb spacing were fully grouted in each hole. Faceplates were not used. SMART cables were simply substituted for regular cables during the installation procedure. The electronic readout heads were grouted just inside the collar of the holes. The Q15 cross-cut was fully shotcreted after the cable bolts were installed. The location of the instrumentation is shown in Figure 11. The 2E production blast occurred 17 days after the installation of the SMART cables. A significant increase in load was measured by all of the SMART cables in the Q15 back. As the 2E stope was mucked out over the subsequent 20 days the load measured continued to increase, probably in response to the reduction in lateral confinement on the end wall of 2E.

Results from three of the SMART cables are shown in Figure 12. For cable El (upper two plots) the load in the cable increased to 248kN at which point three anchor points indicated spurious readings. It is conceivable that this may correspond to rupture of the cable. For cable Fl, up until Day 26 the load distribution in the cable indicated that the rock displacement was occurring on a number of fractures. Thereafter, the load increase was almost totally confined to a specific point of the cable between the anchors at 3m and 5m, indicating a localization in the crack opening. For cable G2 a peak load of 250kN was measured at 1m from the back. This result indicates that the driving force was not solely due to the dead weight of the 1m slab of rock through which the cable bolt passes (i.e. for the 2m by 2m cable spacing - 4m^2 or 120kN), but instead to the larger block that the cable bolt array was supporting.

Over the corresponding period the bolts in Q14 showed almost no change.

The corresponding anchor point displacements indicated 15 – 20 mm of total extension over the 10m length of the cables. The principle difference between them is the location at which the maximum stretch was measured. As the experiment proceeded, data collated from a number of instruments indicated that a sizeable block was cantilevering from the Q15 back into the open 2E stope. The extent (and hence weight) of the wedge was determined by a combination of the SMART cables, Multi Point Borehole Extensometers, Ground Movement Monitors (GMMs) and fracture mapping of the core from two diamond drill holes that were drilled down from 4633. Its geometry is partly controlled by the location of an old vent raise which broke through into the Q15 cross-cut. The interception of this with each ring of the cable bolt array and its effect on the location of maximum load in the SMART cables is shown in Figure 13. The implications of these results for future mining in this area are currently being reviewed by the Golden Giant engineering personnel.

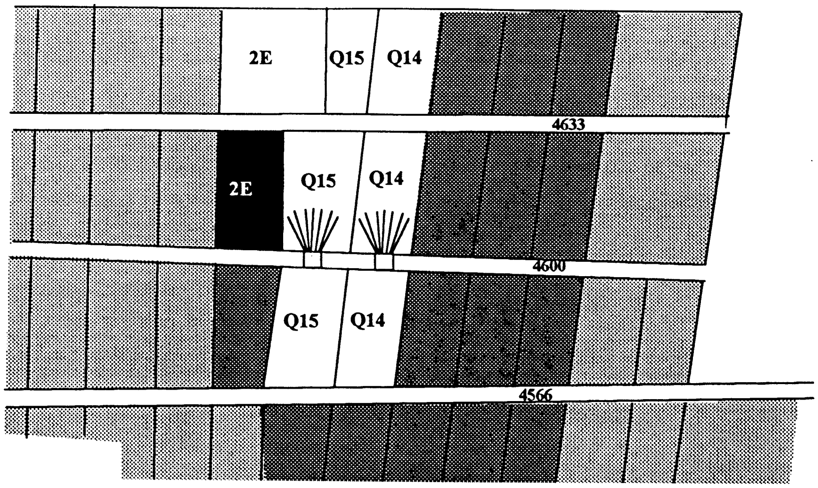


Figure 10: Longitudinal section indicating the location of the cable bolts in the backs of the Q15 and Q14. The shaded stopes have been mined and filled. 4600 2E was mined over the first 17 days with the final production blast on Day 17.Over the remainder of the experiment the stope was mucked out.

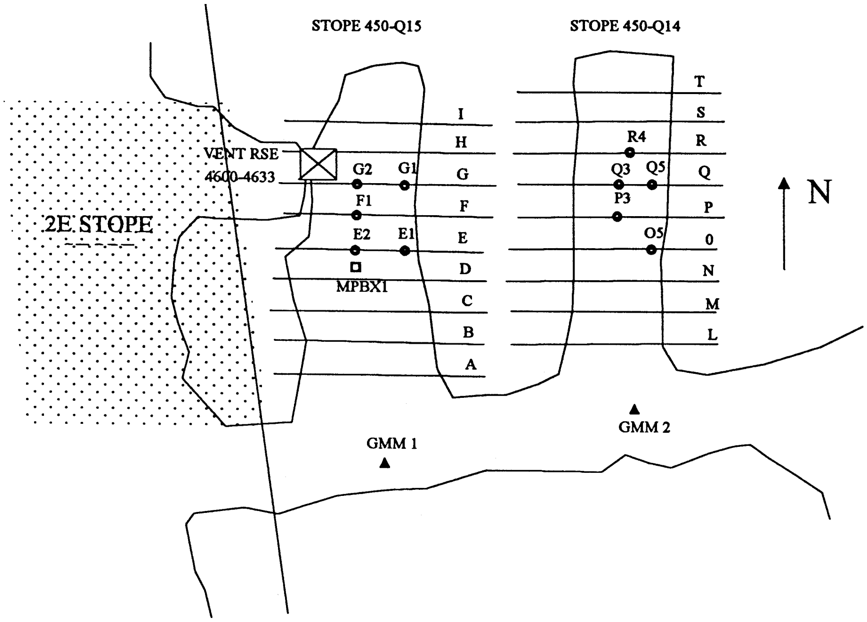
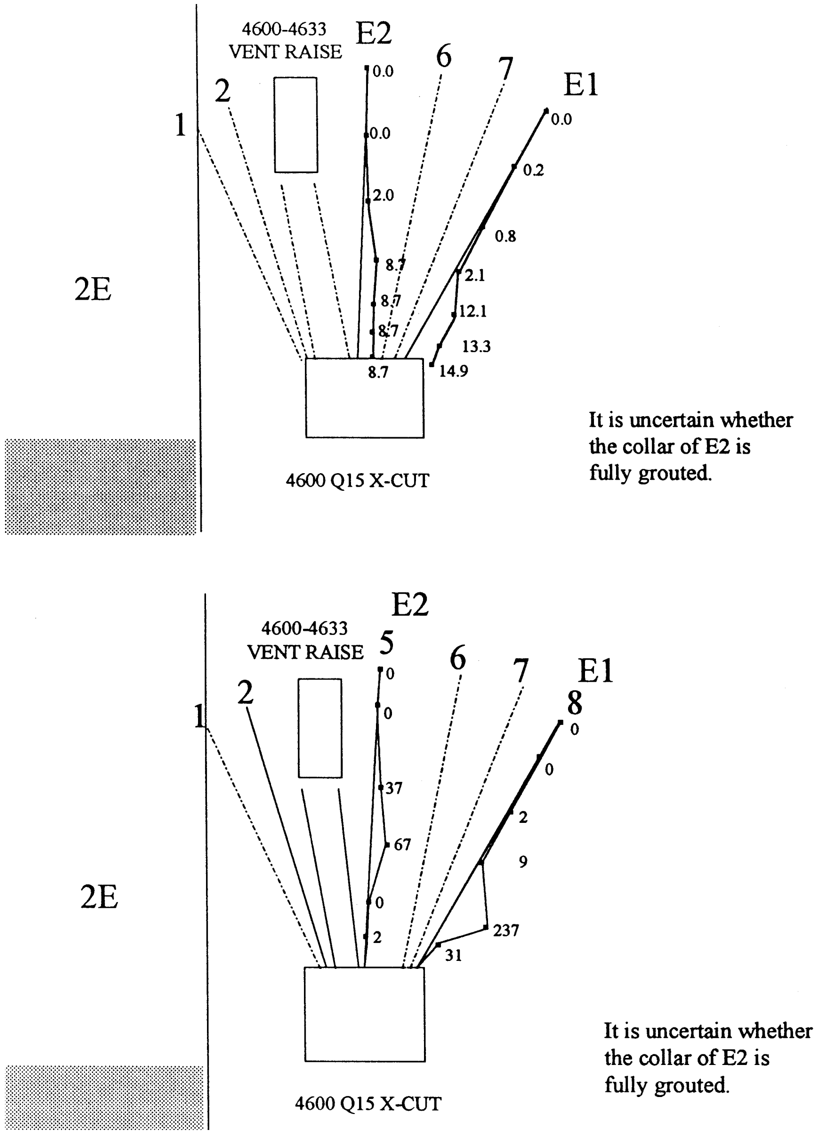


Figure 11: Plan view of the 4600 level showing the location of the instruments installed to monitor the Q14 and Q15 backs. The letters identify different cable bolt rings. In each ring a 'fanned' pattern of 8 cable bolts is placed. The vent raise plunges 75° to the north. Arrow is 5m long.



It is uncertain whether the collar of E2 is fully grouted.

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Figure 13a: SMART cable results for ring E. (Top) The profile of anchor displacement (in mm) along the SMART cable. (Bottom) The corresponding distribution of axial load (in kN). During installation of E2 the grout hose repeatedly burst and the hole was eventually abandoned. The results indicate that the lowermost 2-3m may not be fully grouted.

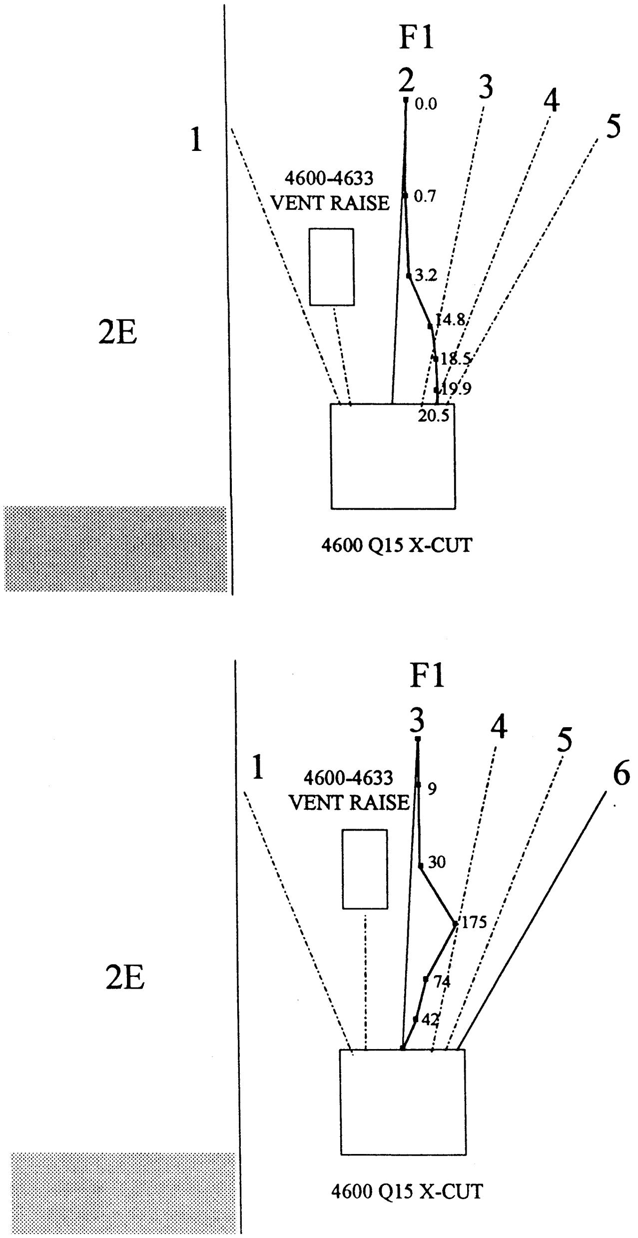

Figure 13b: SMART cable results for ring F. (Top) The profile of anchor point displacement (in mm) along the SMART cable. (Bottom) The corresponding distribution of axial load (in kN).

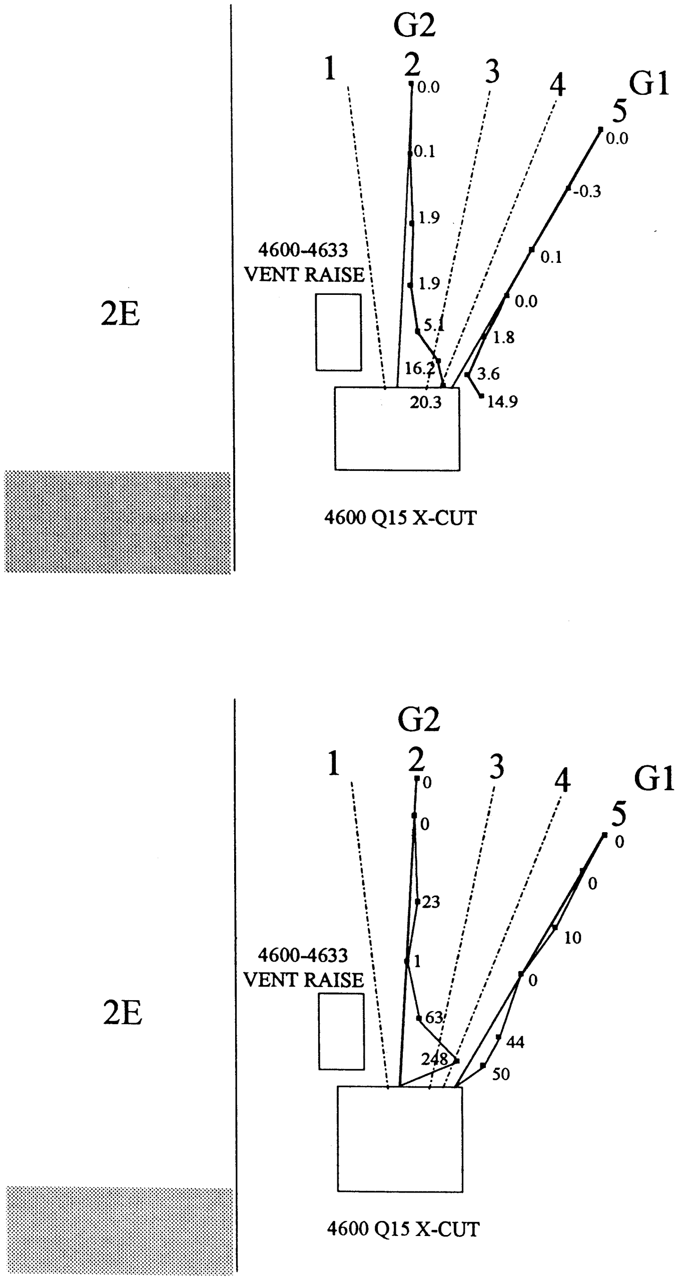

Figure 13c: SMART cable results for ring G. (Top) The profile of anchor point displacement (in mm) along the SMART cable. (Bottom) The corresponding distribution of axial load (in kN).

CONCLUSIONS

An instrument that measures elongation and the corresponding load distribution that develops along a cable bolt has been developed. It is incorporated internally inside the cable so that the bond performance of the cable is not inhibited. A low cost (i.e. disposable) electronic readout head allows readout using a hand-held unit and data collection using a data acquisition system.

Based on initial underground experiments the following conclusions can be drawn.

From a technical perspective:

1. The instruments performed equally well when the electrical head was immersed in the grout as when it was left exposed.
2. The response of the cables was successfully monitored using both a hand-held unit and a data acquisition system. The advantage of a continuous electronic readout was demonstrated in that the response of the cables immediately following a blast was recorded.

From an operational perspective:

1. The cables were quickly and efficiently installed using the routine procedure.
2. The response to mining was predictable: cable bolts closer to the excavations exhibited higher loads.
3. The load in the the cables increase in a very well-order and predictable manner. Maximum loads were observed where MPBX data indicated crack opening.
4. The results indicated that in general the cables were fully grouted during installation (sometimes a concern) and that very high loads (in excess of the yield point of the steel) were mobilized.
5. For CASE STUDY 1, the detailed response to the blast indicated sporadic loading of the cables in the hour following the blast. The rate of these events decreased with time as stability was progressively attained.
6. For CASE STUDY 2, the instrumentation data was able to determine that the full capacity of the cables were being mobilised to support a potentially unstable wedge of rock. The benefit of installing a significant number of SMART cables in combination with different instruments was demonstrated.

ACKNOWLEDGEMENTS

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