Validation of Cable Bolt Support Design in Weak Rock Using SMART Instruments and Phase²

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Introduction

A shallow underground mining operation in weak rock has been experiencing problems with deteriorating ground conditions in their development headings, leading to extensive rehabilitation. Localized ground support, consisting of swelllex/super swelllex and fibre-reinforced shotcrete, was effective in retaining the materials close to the face. However, the plastic zone surrounding the opening extended beyond the extent of the rock bolts used, and the size of the openings prevented use of longer rock bolts to tie into the un-yielded rock behind this plastic zone.

To overcome this problem, it was proposed that cable bolts be used to develop a high-capacity deep anchorage system. To prove the concept and evaluate the cable design, a program involving instrumentation and numerical modeling was proposed. Instrumentation consisted of SMART cables and multi-point borehole extensometers (MPBX’s) from Mine Design Technologies (MDT); numerical modeling was performed using Rocscience Inc.’s Phase². This paper will describe the instrumentation and the model used, present the instrumentation data and modeling results, and show the correlation between the modeling and the instrumentation program.

Overview of SMART Instruments

The instrumentation for this program consisted of SMART cable bolts and MPBX’s. The SMART (Stretch Measurement to Assess Reinforcement Tension) cable bolt permits accurate assessment of the deformations, and calculation of the loads, to which long cable bolt elements are subjected during the excavation process (Hyett et al, 1997). To achieve this, the SMART cable makes use of a miniature six-wire extensometer incorporated within the cable, thereby avoiding interference with the cable:grout bond that occurs with externally mounted gauges (Bawden et al, 2002).

The six wires in the extensometer are attached at six discrete user-specified locations along the length of the cable. The other end of each wire is attached to a spring-loaded wiper that passes across a linear potentiometer in the readout head. As the cable stretches, the displacements at the anchor points are determined through the movement of the wiper across the potentiometer. By measuring the extension \( d_i - d_{i+1} \) between two known locations \( L_i \) and \( L_{i+1} \) along the cable, the strain may be calculated via:

\[
\varepsilon = \frac{d_i - d_{i+1}}{L_{i+1} - L_i}
\]

(1)

The corresponding tension in the cable may be calculated from the load-deformation response of the cable using the following equation:

\[
F = E_b A_b \varepsilon, \quad \text{or}
\]

(2)

\[
F = k \varepsilon
\]

(3)

where

\[
F = \text{average tensile load (kN)},
\]

\[
E_b = \text{elastic modulus of the cable},
\]

\[
A_b = \text{cross section area of the cable}
\]

\[
k = \text{constant otherwise known as the cable stiffness}
\]

For the elastic response in 15.8 mm (0.6 in) diameter low relaxation 7-wire strand (ASTM A416-80),

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

(4)
and for the strain hardening response after yield,

\[ k = 600 \text{ kN/m/m} \ (F > 225 \text{ kN} \text{ and } \varepsilon < 0.008 \text{ m/m or 0.8\%}). \] 

Thus, the average load in the cable can be calculated from the strain between adjacent anchor points, as shown in Figure 1. By using multiple anchor points, the load along the entire length of the cable bolt can be determined (Bawden et al., 2002).

SMART cables can be manufactured from any cable type (bulge, plain, etc.) up to lengths of 30 m. Cables can also be plated, if required.

SMART Multi-Point Borehole Extensometers (MPBX’s) make use of the same principles as the SMART cables, and are used to measure the dilation of the rock mass. These can be used on their own, or in combination with SMART cables. When used together, it is possible to determine both the displacement of the rock mass, and the displacements and loads on the cables.

**Geomechanical Data**

The ground conditions at the site in question are not unlike those encountered in many civil applications. The site is located at shallow depths (<300 m), with soil-like ground conditions in some areas.

Unconfined compressive strengths for the rock types encountered at the mine range from less than 20 kPa in the worst rocks up to 800 kPa for some of the moderately altered rock types. The best quality rocks have a UCS ranging from 40 to 150 MPa. Ore UCS ranges from 10 to 50 MPa.

No far-field stress measurements have been taken, either at the mine, or in the surrounding area.

**Instrumentation Program**

Instrumentation was installed in two areas of the mine. The first area consisted of good quality rock that had experienced no deterioration. This was considered the control area, and was used to get baseline data for the rock mass and the instruments. The second area consisted of poor quality rock where significant deterioration had occurred.

In each area, a series of cable bolt rings were installed. Plain strand cables were used in one length of the drift, and bulge cables were installed in the remainder. All of the cables were plated. One ring of each cable type was instrumented in each of the areas. The instrumentation configuration and the geology at the second test area are shown in Figure 2. The remainder of the discussion will focus on this area.

The geology at the test area consists of three
rock types of varying strengths. The yellow in Figure 2 represents the host rock mass; turquoise represents the ore, which is the highest strength material in the study area. Between these two rock types is an altered zone (grey) of low strength material. This zone experiences significant movement under loading.

**Instrumentation Data and Analyses**

After the instruments had been installed and the data collected for a period of about 3 months, plots were generated showing the displacements measured on the SMART cables and MPBX’s, and the corresponding loads developed on the SMART cables. The displacements in mm are shown along the lengths of the instruments in Figure 3.

As can be seen from Figure 3, the displacements measured on the MPBX’s are similar in range for both the plain strand and the bulge cable layouts. In both cases, the movement occurs within the first 4 m of the face, with the majority of the movement occurring at the drift wall.

For the plain strand cables, while the movement zones are similar to those observed in the MPBX, the amount of displacement is significantly less.

Loads on the cables between the anchor nodes were calculated using Equation 3. Calculated loads for the two types of cable bolts also show some differences, as shown in Figure 4. For the plain strand cable, the maximum observed loads are on the order of 10 tonnes, whereas the bulge cables show loads up to 25 tonnes. The ultimate capacity of a 15 mm cable bolt is on the order of 26 tonnes.

These data indicate that the plain strand cables are not developing peak loads in the weak
ground at the site. Rather, they are pulling through the rock at loads well below their peak capacity. The bulge cables appear to be effective under the same ground conditions. However, because the bulge cables are loading to capacity an alternate cable layout will be required.

**Numerical Modeling**

Modeling of the instrumented area was performed using *Phase*², a two-dimensional plastic finite element program created by Rocscience. This program was selected for its plastic modeling capabilities, multiple materials, and automatic mesh generation. This final feature greatly enhanced the speed at which analyses could be performed, allowing parametric studies of the many unknown properties of the system to be conducted, and a good estimate of the site properties to be determined.

One of the results that came out of the cable bolt research program conducted at Queen’s University during the 1990’s was the development of constitutive models for all of the cable bolt geometries available (Moosavi, 1997). The model for plain strand cables has been incorporated into *Phase*² already, allowing modeling of the plain cable geometry to be performed.

As mentioned above, little information about the far-field stresses or rock strengths was known. Estimates of these parameters were made based on field observations, and used in the model. Figure 5 shows the model geometry used in the analyses; the estimated rock mass input properties are summarized in Table 1.

<table>
<thead>
<tr>
<th>Rock Property</th>
<th>Rock Type</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Orange</td>
</tr>
<tr>
<td>UCS (MPa)</td>
<td>25</td>
</tr>
<tr>
<td>Young’s Modulus (MPa)</td>
<td>3000</td>
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<td>Poisson’s Ratio</td>
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<tr>
<td>m (intact/residual)</td>
<td>1.36/0.8</td>
</tr>
<tr>
<td>s (intact/residual)</td>
<td>0/0</td>
</tr>
</tbody>
</table>

Figure 5. *Phase*² model geometry, with plain strand cable bolts shown in blue.

The *Phase*² model was run using the parameters in Table 1. For in-situ stresses, Sigma 1 was assumed vertical, and equal to the superincumbent load. Sigma 2 and Sigma 3 were assumed equal and horizontal. The ratio of Sigma 1:Sigma 3 was assumed to be 2:1.

Figure 6. Major principal stresses (Sigma 1) acting on opening. Deformed opening shown by grey line.

A plot of the major principal stress (Sigma 1) acting around the supported opening is shown in Figure 6. This figure also shows the

Table 1. Geomechanical properties at test area.
deformation profile of the drift due to the stress conditions and rock strengths at the site. Note the prominent sidewall buckling and resulting roof closure at the hangingwall side of the drift. This profile is consistent with observations at the site in the vicinity of the plain strand installation.

Phase\textsuperscript{2} also permits the plotting of various parameters related to the ground support elements included in the models. The ability to plot the axial loads on the individual cables, as well as both the cable and the rock displacements at the element locations allows comparison of the modeling results with the data obtained from the SMART instruments.

Plots of modeled cable load versus length are overlain on the cable geometry in Figure 7. From this figure, it can be seen that the loads are comparable to those observed by the models. Discrepancies are observed, however, due to the difference between the continuum nature of the model and the combination of blocky ground and nodal nature of the SMART instruments. What is most interesting is the zones where the model predicts cable loading coincide quite well with what was observed in the SMART instruments.

Figure 7. Loads on plain strand cables (in tonnes) calculated using Phase\textsuperscript{2}.

Another parameter that can be calculated in Phase\textsuperscript{2} is the displacement at the cable locations, both in the cable and in the adjacent

Figure 8. Displacement versus distance plots from Phase\textsuperscript{2} modeling for a) cable 1, b) cable 2, c) cable 3, and d) cable 4.
rock mass. Plots of the displacement versus distance for each of the 4 cables are shown in Figure 8. For each plot, both the rock and cable displacements are shown. Cable slip is indicated by a gap between the rock and cable displacements.

Because each cable bolt is plated, there is good agreement between displacement predicted in the rock and the cable bolt at the excavation surface. The exception of this result is cable 2 (Fig. 8b), where the displacement near the face exceeds the strain capacity of the cable, resulting in rupture about 0.5 m behind the face.

Behind the face, most of the cables show a gap between the rock and the cable displacements, with the displacement in the rock being higher. This indicates that the plain strand cables are slipping in the model, as well.

As was observed for the cable loading predicted by the model (Fig. 7), the majority of the displacement observed occurs within about the first 4 m of the face. This again is consistent with the data from the SMART instruments. It can also be seen from the plots in Figure 8 that most of the cables are pulling through the rock after loading to between 8 and 15 tonnes. None of the cables reach the ultimate capacity of 26 tonnes.

**Conclusions**

This project has shown a unique way for using SMART instrumentation and numerical modeling to understand the interaction between cable bolts and the rock mass in soft ground conditions in a low stress environment. The instrumentation suggests the plain strand cables are not effective and tend to pull out of the rock well before peak load. However, the data for the bulge cables indicates they are capable of achieving their full capacity under the same ground conditions.

Due to the limited geomechanics data available, the numerical modeling performed to date has been preliminary at best. However, the results from the Phase² modeling mirror the trends observed in the instrumented cables.

**Future Work**

At the field level, better geomechanics information is required. This includes a better estimate of the far field stresses. Once this data is available, it will be possible to calibrate the numerical model based on the data from the SMART instruments.

From the modeling side, incorporation of the constitutive model for bulge cables into Phase² will be a definite asset, allowing simulation of the bulge cable behaviour. A well-calibrated model will permit forward modeling of support design under known or anticipated ground conditions.

From the instrumentation standpoint, data collection is the bottleneck. At present MDT is working towards alleviating this bottleneck and allowing automatic data collection and transmission to a desktop on surface. This will allow ground control engineers to focus their attentions on looking at problem areas rather than data collection and interpretation.

**References**

