COMPUTER SIMULATION OF GROUND BEHAVIOUR AND ROCK BOLT INTERACTION AT EMERALD MINE

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ABSTRACT

A collaborative project between RAG Emerald Mine, NIOSH, and SCT Operations was conducted to investigate ground behaviour, reinforcement performance, and stress redistribution in a coal mine entry subjected to a severe horizontal stress concentration. Field measurements indicated that the stresses applied to the study site nearly doubled during longwall mining, resulting in roof deformations extending to a height of 4.8 m (16 ft) above the entry.

This paper focuses on the computer simulation that was undertaken to provide more insight into the roof behaviour and rock bolt interaction during mining. The model's input rock properties were derived from extensive laboratory testing, and the model itself simulated a broad range of failure mechanisms. The effects of different bolt patterns on roadway behaviour were evaluated. Comparison between the model results and the field measurements indicated that that the model effectively simulated the critical elements of the actual roadway's behaviour. With the confidence gained, the model was used as a baseline for additional simulations that evaluated the expected performance of alternative roof support systems. The study will also provide a benchmark data set for future applications of numerical modelling to U.S. coal underground mining.

INTRODUCTION

The National Institute for Occupational Safety and Health (NIOSH) at PRL together with RAG Pennsylvania and SCT Operations of Australia collaborated to conduct an extensive study of roof bolt strata interaction at Emerald Mine. The goals of the study were to:

- Determine baseline U.S. rock mass and stress properties for input into numerical models;
- Evaluate the performance of U.S. primary supports (roof bolts) in typical U.S. geological conditions;
- Investigate the interaction between supplemental support systems (cable bolts) and primary supports, and;
- Explore the ability of numerical modelling to aid in analyzing complex ground control problems.

The study is part of a broader effort to develop methods to optimize roof bolt designs and prevent roof falls in a range of geologic and stress conditions encountered in U.S. underground coal mines.

The site of the study was the tailgate of the 11 North longwall at the Emerald Mine, located in Greene County, Pennsylvania (figure 1a). The site was chosen because it was anticipated that the extension of 11 North beyond the start line of 10 North would result in a significant horizontal stress concentration (Mark et al., 1998). From past experience at Emerald Mine, a horizontal stress window like the one created by 11 North could be expected to cause severe loading to be applied to the crosscut and tailgate entry. The location thus provided a unique opportunity to study the roof failure process as the applied horizontal stress increased during the progression from development through longwall mining.

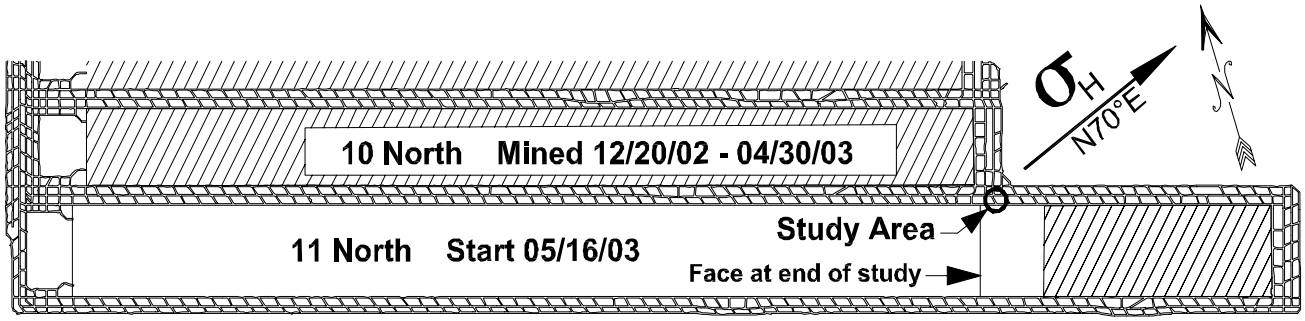

Figure 1a. Emerald Mine and study site.

At the site, two monitoring arrays were installed in a crosscut and a third in the adjacent tailgate entry (figure 1b). The two crosscut sites, labelled Site B and Site C, are the focus of this paper. Conditions in these sites were more severe than in the tailgate site because the crosscut was oriented less favourably relative to the regional maximum horizontal stress.

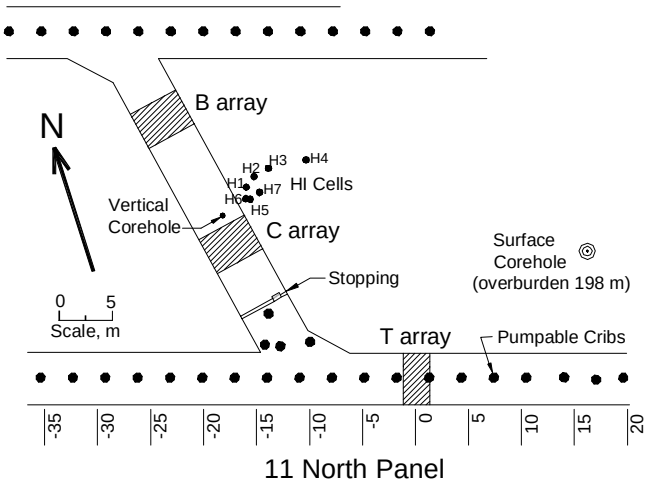

Figure 1b. Detail of study area. Distances shown are meters from the T array.

Instrumentation at the sites included mechanical and sonic extensometers for measuring roof movement, instrumented roof bolts, and three-dimensional roof stress cells (HI cells). Details of the results of the monitoring program have been reported elsewhere (Oyler et al., 2004).

The aim of this paper is to report the results of computer modelling and its relationship to the field site. Computer modelling was undertaken by SCT Operations to simulate the deformation mechanics of the strata and the interaction of bolting patterns with roof control.

DESCRIPTION OF THE FIELD SITE

Emerald Mine operates in the Pittsburgh coalbed in Southwest Pennsylvania, cutting a roadway approximately 2.1-2.4 m (7-8 ft) high and 4.9 m (16 ft) wide. Approximately 0.3m (1 ft) of roof shale is cut in the roadway.

Primary roof support used in the area of this study consisted of three 22 mm (7/8 in) diameter, 2.4 m (8 ft) long combination bolts. They were installed with 1.2 m (4 ft) resin cartridges in a 35 mm (1-3/8 in) borehole. The yield load of the bolts is 19 tonne (21 tons) with an ultimate capacity of 28 tonne (31 tons). At the C-site, supplemental support consisting of rows of three cable bolts were installed between the rows of the primary bolts. The cable bolts were 3.6 m (12 ft) long, 15 mm (0.6-in) diameter, and partially grouted with 1.2 m (4 ft) of resin.

The stress field has been measured in several locations in the Emerald and Cumberland Mines, but not at the specific study site. These measurements were reviewed to assess the range of stresses anticipated at the test site. The major stress was oriented N70°E. The regional stress field appears to be relatively consistent, with a lateral tectonic strain (Dolinar, 2003) of approximately 550 microstrain. This means that the maximum stress is inferred to be approximately 11 MPa (1,600 psi) for a rock having a Young's Modulus of 20 GPa (3 million psi). The horizontal stress within other rock units will be different and dependent on their elastic properties. The minor horizontal stress is estimated to be approximately half of the major stress.

Vertical stress is approximately 5 MPa (700 psi) and related to overburden of approximately 200 m (650 ft).

These have been assumed to be the background field stresses at the site for the purposes of the modelling study, however, past work indicates that significant local stress variation can occur.

The magnitude of horizontal stress affecting roadways will vary depending on the direction of the roadway, and the mining induced stresses redirected about extraction panels. As part of this study, a range of horizontal and vertical stresses were applied to the model to explore the effects of such variation.

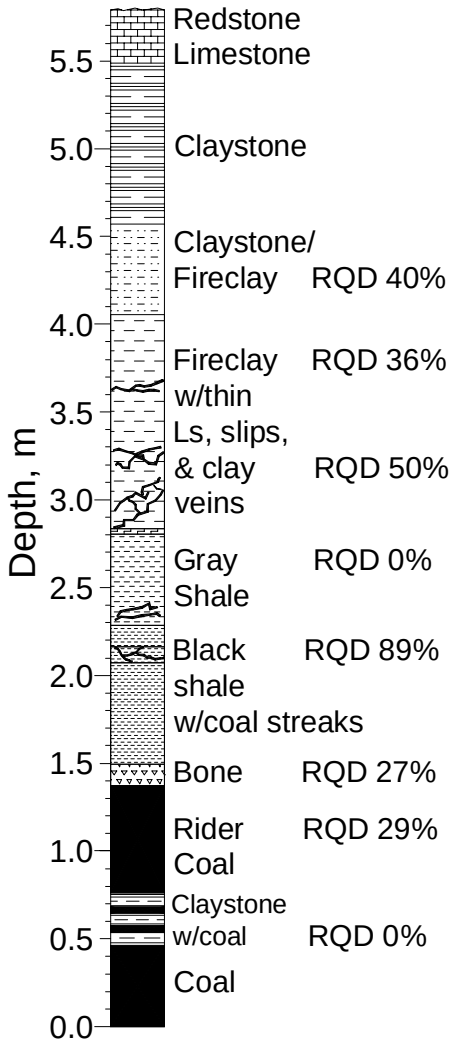

Figure 2. Composite core log from the study site, from the vertical corehole drilled in the study crosscut and from a nearby surface corehole.

A geologic column of the mine roof obtained from a vertical core hole drilled at the site is shown in figure 2. The roof may be roughly divided into three units:

- A sequence of coals and weak, slickensided black shales in the lowest 2.7 m (9 ft);
- A slightly stronger grey claystone sequence from 2.7 to 5.4 m (9 to 18 ft), and;
- A significantly stronger limestone above 5.4 m (18 ft).

The low uniaxial compressive strength and RQD for the bolted horizon results in an estimated Coal Mine Roof Rating (CMRR) of 37 (Mark et al., 2002).

MODELING APPROACH AND MODEL USED

Detailed monitoring studies conducted in coal mines in a number of countries have shown that the mechanisms of failure about excavations can be highly complex, involving fracture of rock, failure of bedding or joints, buckling of parted rock, and slip along weak surfaces (Gale et al., 1992; Gale and Tarrant, 1997; Mark et al., 2000). The use of computer simulation therefore requires a detailed geotechnical characterization of the strata and stressfield, and must incorporate the many potential failure mechanisms.

Beginning more than a decade ago, SCT has undertaken computer simulations at a wide variety of mine sites. Examples of the method have been published (Gale, 1998; Sandford, 1998; Kelly et al., 1998). SCT has found that model results which compare well with field validation measurements can be achieved if sufficient care and detail is employed.

The input rock properties for the computer models are developed from detailed geotechnical testing of strata properties. The rock intact and post failure strengths, stiffness, in situ stresses, permeability and bedding plane characteristics are key factors to be quantified. The aim is to allow the model to simulate a wide range of interacting and complex failure modes in a manner which maximizes its independence from input generalisations. Generalisation of the rock properties or the rock mass section on the basis of averaged properties has been found to limit the capability to reproduce actual rock mass behavior.

The code used in the model is FLAC which has been modified to employ rock failure routines developed by SCT Operations. The constitutive models used by SCT are very similar to the strain-softening, ubiquitous joint model (SU) included with the latest release of FLAC2D (HCItasca, 2000). Rock failure is based on Mohr-Coulomb criteria relevant to the confining conditions within the ground. A broad range of potential failure modes are simulated including:

- Shear fracture of intact rock;
- Tension fracture of the rock;
- Bedding plane shear, and;
- Tension fracture of bedding (bedding separation).

The stability of pre-existing jointing, faults or cleat is also addressed in the simulations where appropriate. The model simulates new or re-activated rock fracture and stores the orientation of the fractures.

In the SCT constitutive model, as well as Itasca's SU, the intact rock matrix exhibits strain-softening post-failure behaviour. A weakness plane of any orientation is also included in the model, and this weakness plane can also exhibit strain-softening behaviour. This constitutive model is most appropriate for coal measure rocks where the intact rock is strain-softening and one dominant weakness plane exists, namely bedding. In both SCT's and Itasca's constitutive models, cohesion, friction angle, dilation angle and tensile strength are specified as functions of the "plastic strain." Depending on the nature of these functions, a variety of complex hardening and softening behaviors can be produced.

Rock properties for the models were obtained from a combination of previous testing at the mine and from tests of underground core samples obtained from the study site. Of particular importance were angled core that were subjected to multi-stage triaxial testing[1] in order to determine bedding plane strength. The bedding plane strength test results are presented in figure 3 for the two shale units.

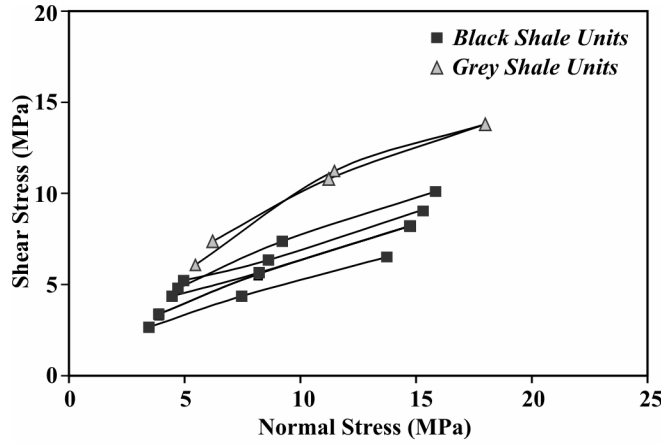

Figure 3. Bedding plane test results from angled core.

The in situ strength of the rock materials is reduced to 0.58 of the laboratory unconfined compressive strength (UCS). This lab-to-field scaling factor was originally suggested by Hoek and Brown (1980), and is routinely used in all SCT model studies.

The model geometry is presented in Figure 4 with the various rock layers characterized by their laboratory UCS. The typical element size in the region of interest is approximately 20 cm by 10 cm (8 in by 4 in). This element size is fine enough to capture geologic variations that may be important at the coal mine entry scale. The UCS profile and bedding cohesion profile used in the model is presented together with the laboratory core test results in figures 5 and 6 respectively. The layer-to-layer variations in the model profiles were derived from both the test results and inspection of the roof core.

The in situ strength of coal within the model was 6.5 MPa (900 psi), which is typical of the bulk strength of coal. Coal cleat was included in the model.

Rock bolts were included in the model. The bolts were bonded in the upper 1.2 m with a free length to the roofline. Yield of bolts was 19 tonne (21 tons) with a pullout force of approximately 15 t/ft. Cable bolts were also modelled as partially bonded with a

[1]The multi stage triaxial test aims to define the rock strength envelope for a number of confining pressures (2, 5, and 10 MPa) using a single sample. A stiff, servo controlled testing machine must be used in the deformation control mode. The sample is loaded progressively until the onset of initial fracture, and then the confining pressure is increased to the next stage and the test continues. At 10 MPa confining pressure the sample is taken to full failure and then the confining pressure is released slowly and the residual strength monitored to determine the post failure strength envelope. When angled core samples are tested, the failure takes place along a bedding plane, and the applied stresses are resolved into the shear and normal stresses as shown in figure 3. An early application of multi-stage triaxial testing is described in Dolinar et al. (1982).

yield capacity of 25 tonne (27 tons). Care was taken to simulate the shear strength and stiffness properties of the resin/rock interfaces of the bolts. All of the bolt properties in the 2-D model were adjusted to account for the row spacing.

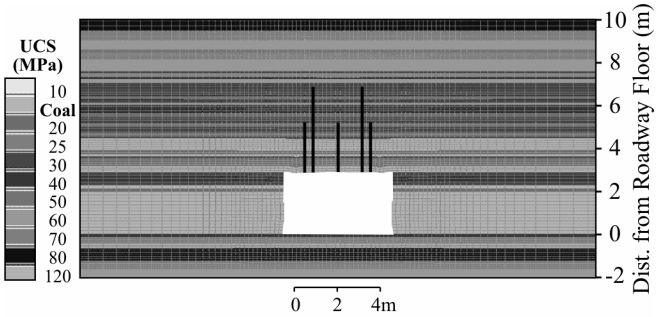

Figure 4. Model geometry and UCS of rock units.

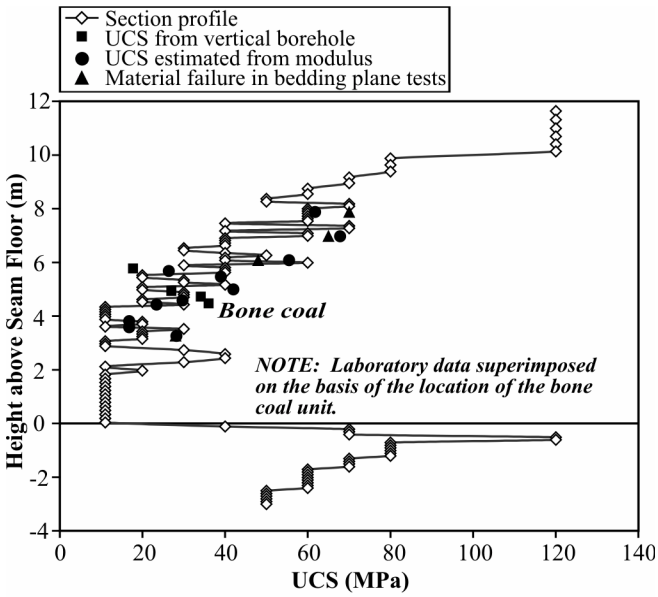

Figure 5. UCS profile used in the model together with rock property data derived from testing.

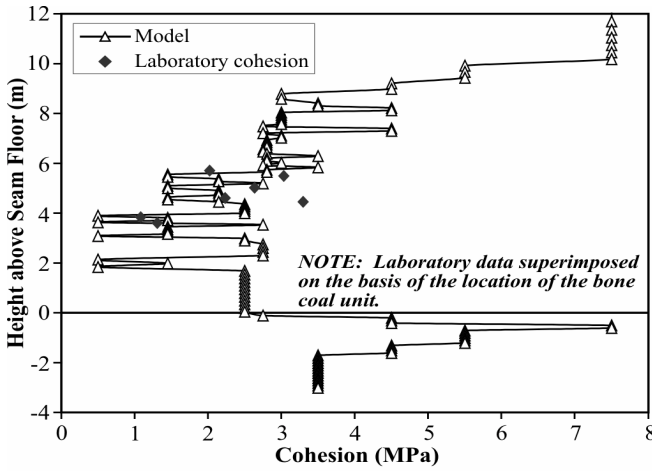

Figure 6. Bedding plane cohesion profile used in the model together with rock property data.

The modelling sequence followed the actual mining process in that the entry was first excavated, then the outside roof bolts were installed, and finally the center bolt was installed. The model was allowed to respond to each of these steps. If cable bolts were used in a model, they were placed last.

The stress path modelled is presented in figure 7 together with the anticipated in situ stresses. The stress path represents the far-field (boundary condition) stress changes (horizontal and vertical) applied to the study site due to the extraction of the two longwall panels. The modelled stress path was estimated from the stress measurements made at the site and measurements made at similar sites in past studies. One indication of the "far field" stress increase associated with longwall mining at this site was the approximately 10 MPa (1,400 psi) of stress relief that was measured following the passage of the longwall face (Oyler et al., 2004).

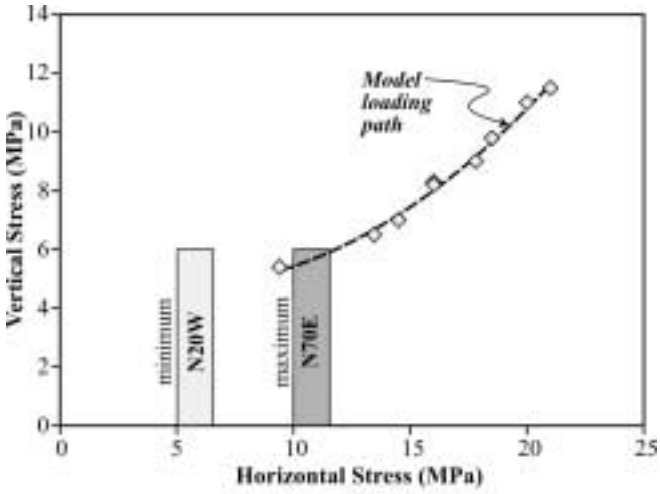

Figure 7. Stress path modeled representing increasing stress during development and longwall extraction operations.

For this model, a plane of symmetry was used at the roadway centre line. The use of symmetry speeds the modelling process particularly in this case where a range of stress conditions or support systems is to be evaluated.

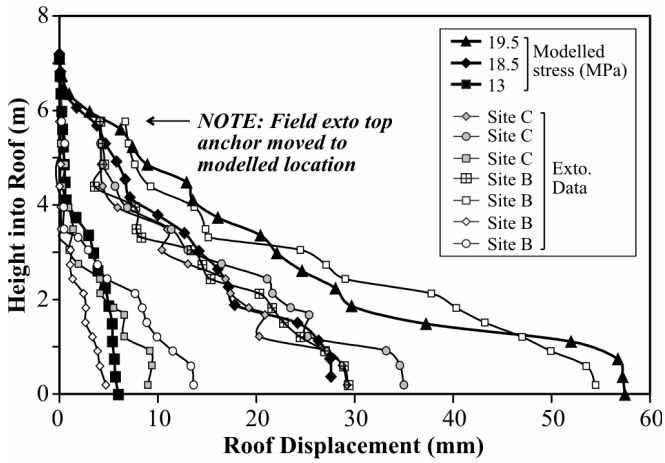

Figure 8. Comparison of modeled and measured roof displacement profiles.

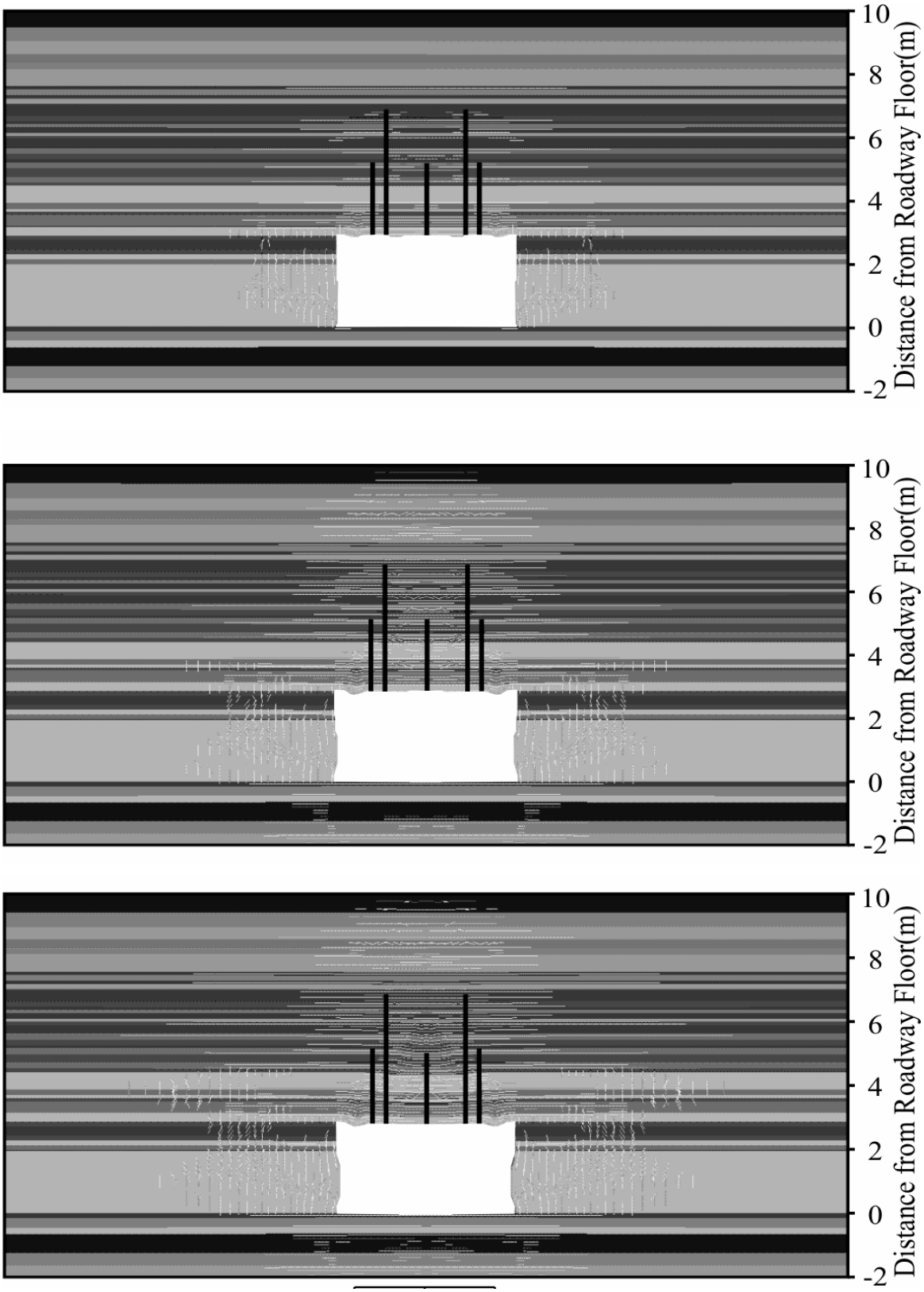

Figure 9. Roof deformation in the model at three stress levels.
(A) 11 to 12 MPa, (B) 16 MPa and (C) 19 MPa.

RESULTS AND COMPARISON WITH SITE DATA

The model is an estimate of the strata response to the incrementally increasing far-field applied stresses that are believed to have occurred at the site. Its purpose is to obtain a greater understanding of the behaviour of the strata. Comparison of the modelled response to that of the actual field site is required to provide confidence in the strata characterization and the computational method applied.

The comparison relies heavily on the roof extensometer data. The approach has been to compare the extensometer results at approximately equivalent total displacements at the roof line. In this way, the nature and style of deformation within the roof which causes the total displacement can be compared. If the comparison is good, then the model is inferred to simulate the rock deformation mode and location in a realistic manner. This allows the performance of different support systems to be evaluated using the same criteria that are employed in the mine—namely, how much roof movement is taking place. Therefore, it is not necessary to employ surrogates such as the maximum stress or a safety factor.

It should be noted that the study is aimed at "normal" unfaulted ground conditions. The effect of faulted or structured ground conditions was beyond the scope of this study. Also, the strata geology may locally vary from that estimated, or the stress conditions may become more complex during mining.

Roof Movements

Figure 8 compares the roof deformations calculated in the model to those measured underground. Model results from three stress levels on the model loading path are shown. Also shown are a number of deformation profiles measured at the two crosscut sites. As Oyler et al., (2004) noted, the sites "differed in the timing of the roof deformation, but it was significant that the deformation process followed a broadly similar pattern in all of them." The figure indicates that the model was able to capture the deformation pattern, showing a very close correlation in both deformation style and height of movement. It should also be noted that the model indicated that some deformation occurred even above the top of the extensometers.

Figure 9 illustrates the location and nature of the rock failure processes that are associated with the roof deformation profiles. Upon initial development (figure 9a) bedding plane shear occurs readily within the section and early in the deformation process. As stress levels increase shear fracture of the weaker shale units occurs. Higher stress levels cause shear of the stronger materials together with additional bedding plane shear. However, total roof deformations are relatively minor until the applied far-field stress reaches approximately 15-16 MPa (2,200 psi; figure 9b). Beyond that stress level, significant roof deformation develops and progresses higher into the roof section (figure 9c).

Roof Bolt Forces

The roof bolt forces developed in the model and roof bolt load data from sites B and C are presented in figure 10. To make the comparison, the average bolt loads were determined for three levels of roof displacement. In general there is a fairly wide range in average bolt load at the monitoring sites, however, the overall forces developed in the model are consistent with the range as monitored. This provides an indication that the bolt-strata interaction is being simulated in a realistic manner consistent with the site response.

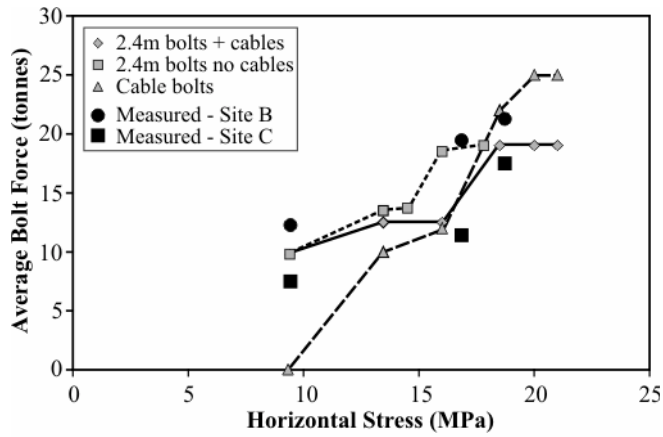

Figure 10. Roof bolt forces developed relative to horizontal stress.

The results indicate that under the in situ development stress state (less than approximately 11-12 MPa (1,600 psi)) roof conditions would be anticipated to be good and well controlled by the bolt pattern placed. The roof bolts continue to be well under yield load up to a stress level of approximately 15-16 MPa (2,200 psi). Once significant roof deformations begin to occur, however, the bolt loads rapidly increase.

The model (figure 10) shows that the addition of cable bolts initially has little effect on bolt loads. However, once major roof movements begin to occur, the cables assume enough load to delay the onset of yield in the roof bolts. The cable bolts appear to develop their full capacity after the roof bolts yield.

Stress Redistribution about the Cross Cut Caused by Roadway Deformation

The measurements made during the study showed that the additional stresses were redirected above the immediate roof of the crosscut even before significant roof deformations had occurred (figure 11). The model indicated that the bedding plane shear that developed early in the deformation process could be sufficient to cause significant stress redirection even though the displacement and visual deformation of the roadway was low. An example is presented in figure 12 for an equivalent displacement of approximately 20 mm (8 in).

The amount of horizontal stress transferred within the initial 2 m (7 ft) of roof at the centre of the roadway is an indication of the stability of the roof section and the requirement for reinforcement of the rock. When the bolted roof section has lost its integrity and become "softened," the horizontal stress it can carry is reduced. Once extensive rock fracturing causes roof softening, the reinforcing action of the reinforcement is the primary design task.

APPLICATION OF THE MODELING RESULTS TO MINING ISSUES

It appears that the model results are consistent with the monitored and observed behaviour of the roadway available at the site. This provides confidence that the model is simulating the rock deformation processes influencing roadway stability and reinforcement interaction. This confidence allows for realistic assessment of various bolt patterns within the stress conditions anticipated at the site.

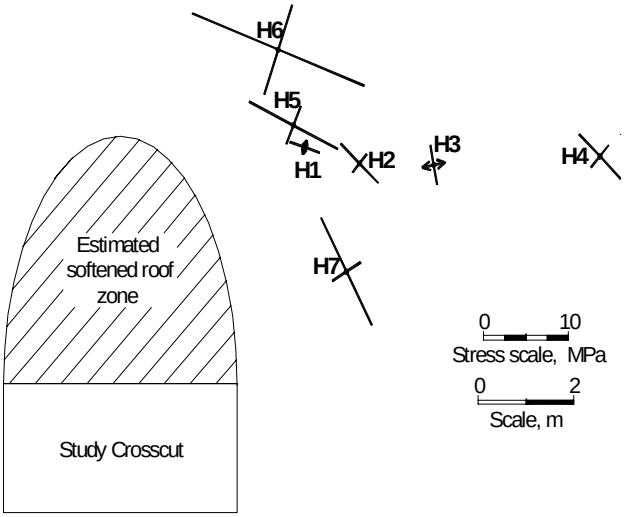

Figure 11. Principal stress changes after the completion of the 10 North longwall and prior to mining the 11 North longwall in the plane perpendicular to the study crosscut, with respect to initial HI cell readings (See figure 1b). Stress changes with arrows are tensile or stress relief, stresses without arrows are compressive.

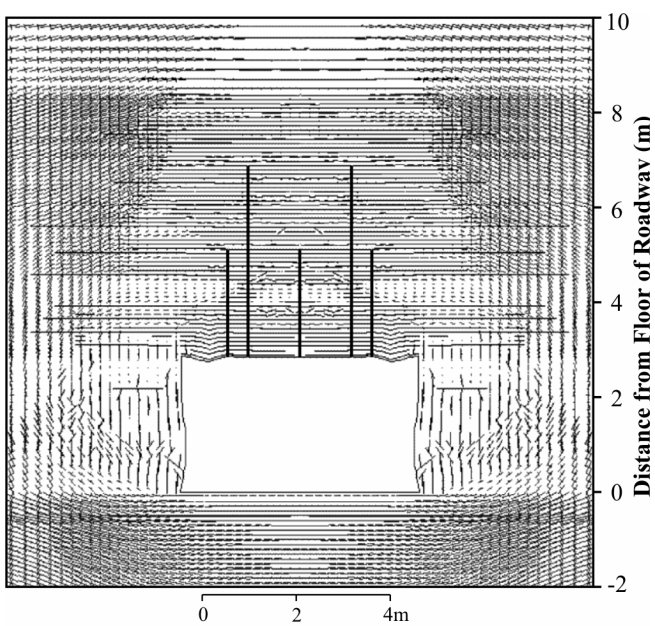

Figure 12. Stress redirection about the roadway caused by localized rock failure and subsequent changes in bulk material properties during roadway development.

In this section, the effect of hypothetical bolt patterns were evaluated to demonstrate the influence of reinforcement patterns on roadway behaviour.

The bolt patterns assessed in this example were:

1. 3, 1.8 m (6 ft), long fully grouted bolts.
2. 3, 2.4 m (8 ft), long combination bolts.
3. 3, 2.4 m (8 ft), long combination bolts with 2, 4 m (13 ft) cables.

Figure 13 shows the roof displacement within the roof section. Each bolt system has a characteristic "limit" at which point the roof deformations begin to rapidly increase. It is significant that the deformation does not follow a smooth curve towards failure, but rather abruptly goes from "controlled" to "uncontrolled" movement. This seems to conform with underground experience, where "good" conditions often seem to "suddenly" go bad.

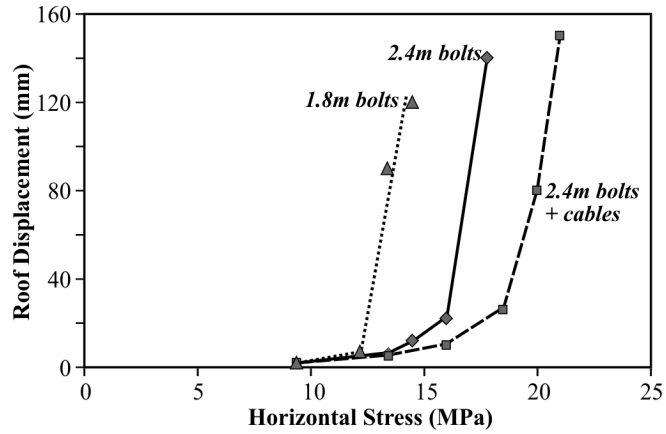

Figure 13. Roof displacement of the roof section for various bolt patterns.

For the standard 2.4 m (8 ft) bolt pattern, the roof maintains integrity up to approximately 15-16 MPa (2,200 psi), which is within the range anticipated during development at high angles to the regional stress field. The addition of supplemental cable bolts would allow the roof to cope with an additional 3-4 MPa (500 psi).

On the other hand, 1.8 m (6 ft) bolts reach their limit at just 12 MPa (1,700 psi), which could change a situation of probable roof control success during development in the cross cut direction to one of potentially difficult roof conditions. These results are consistent with expectations, and indicate that various combinations of reinforcement can significantly modify the deformation limit of the strata section.

CONCLUSIONS

The computer modelling developed for this site has been found to simulate the roof behaviour, rock bolt forces and stress redistribution characteristics about the roadway in a realistic manner. The study has shown that:

- Bedding plane shear occurs early in the deformation process and significantly modifies the stress redirection about the roadway.
- Modification to the bolting pattern has significant effect on roadway stability at the site.
- Cable bolts initially have little effect on either the roof deformation or the roof bolt loads, but they become significant at higher levels of roof stress.

The modelling indicated that the strata section would maintain integrity up to approximately 15-16 MPa (2,200 psi) with 2.4 m (8 ft) bolts. The deformation limit was extended to approximately 19 MPa (2,700 psi) with the addition of cable bolts and elevated vertical stress.

The results of this study demonstrate that sophisticated numerical models can obtain very realistic results, so long as:

- The details of the geology and the rock properties (both pre- and post-failure) are replicated on a very fine scale within the model, and;
- The model can simulate the broad and complex range of failure modes that occur underground.

Modelling to assist with mine planning and support design can be done on a comparative basis to assess the performance of different support options. If ground characterisation is satisfactorily achieved, then the results can be extended to assess ground behaviour in absolute terms. Dedicated geotechnical monitoring and strata characterization is necessary to fully utilize, and extend, the benefits which can be obtained.

REFERENCES

Dolinar, D.R. (2003). Variation of Horizontal Stresses and Strains in Mines in Bedded Deposits in the Eastern and Midwestern United States. Proceedings, 22nd International Conference on Ground Control in Mining, Morgantown, WV, Aug. 5-7, pp. 178-185.

Dolinar, D.R., Horino, F.G. and Hooker, V.E. (1982). Mechanical Properties of Oil Shale and Overlying Strata, Naval Oil Shale Reserve, Anvil Points, CO. U.S. Bureau of Mines RI 8608, 43 pp.

Gale, W.J. (1998). Experience in Computer Simulation of Caving, Rock Fracture and Fluid Flow in Longwall Panels. Proceedings, International Conference on Geomechanics/Ground Control in Mining and Underground Construction, July 14-17, Wollongong NSW Australia, Vol. 2, pp. 997-1007.

Gale, W.J., Fabjanczyk, M.W., Tarrant, G.C. and Guy, R.J. (1992). Optimization of Reinforcement Design of Coal Mine Roadways. Proceedings, 11th International Conference on Ground Control in Mining, Wollongong, NSW, Australia, pp. 272-279.

Gale, W.J. and Tarrant, G.C. (1997). Let The Rocks Tell Us. Proceedings, Symposium on Safety in Mines, The Role of Geology Nov. 24-25, pp. 153-160.

HCItasca (2000). FLAC 4.0 Users Guide.

Kelly, M., Gale, W.J., Luo, X., Hatherly, P., Balusu, R. and LeBlanc, G. (1998). Longwall Caving Process in Different Geological Environments Better Understanding through the Combination of Modern Assessment Methods. Proceedings, International Conference on Geomechanics/Ground Control in Mining and Underground Construction, July 14-17, Wollongong NSW Australia, Vol. 2, pp. 573-589.

Hoek, E and Brown, E.T. (1980). Underground Excavations in Rock. IMM, London, 527 pp.

Mark C., Dolinar, D.R. and Mucho, T.P. (2000). Summary of Field Measurements of Roof Bolt Performance. New Technology for Coal Mine Roof Support, Proceedings, NIOSH Open Industry Briefing, NIOSH IC 9453, pp. 81-98.

Mark, C., Molinda, G.M.. and Barton, T.M. (2002). New Developments with the Coal Mine Roof Rating. Proceedings, 21st International Conference on Ground Control in Mining, Morgantown, WV, Aug. 6-8, pp. 294-301.

Mark, C., Mucho, T.P. and Dolinar, D.R. (1998). Horizontal Stress and Longwall Headgate Ground Control. *Mining Engineering*, pp. 61-68.

Oyler, D.C., Mark, C., Gale, W.J. and Chen, J. (2004). Performance of Roof Support Under High Stress in a U.S. Coal Mine. SME preprint 04-135. Littleton, CO, Society for Mining, Metallurgy, and Exploration, Inc., 7 pp.

Sandford, J. (1998). Review of Longwall Mining Experience at South Bulga Colliery. Proceedings, International Conference on Geomechanics/Ground Control in Mining and Underground Construction, July 14-17, Wollongong NSW Australia, Vol. 2, pp. 591-597.