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PERFORMANCE OF ROOF SUPPORT UNDER HIGH STRESS IN A U.S. COAL MINE

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ABSTRACT

The National Institute for Occupational Safety and Health's (NIOSH) Pittsburgh Research Laboratory (PRL), RAG Pennsylvania and Strata Control Technologies of Australia have collaborated to conduct an extensive study of roof bolt strata interaction at the Emerald mine in Southwestern Pennsylvania. The primary goal of the project was to obtain detailed data on the interaction between the mine roof and the support elements for use in modeling studies. The study site was a longwall tailgate subjected to high horizontal stress. Three arrays of instruments were installed at the site, one in the tailgate entry and two in an adjacent crosscut. Pumpable concrete cribs were present in the tailgate array, and cable bolts were installed in one of the crosscut arrays. The instruments included mechanical and sonic extensometers for measuring roof movement, instrumented roof bolts, and three-dimensional roof stress cells. The study was ultimately successful in determining the magnitude of the horizontal stress concentration, the height of roof failure and the roof failure sequence, and the loading history of the primary roof supports.

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INTRODUCTION

Nearly 1,500 roof falls occur each year in U.S. underground coal mines, creating serious safety hazards and operational impacts. The cost of the support installed to prevent roof falls approaches $1 billion annually. Improving the effectiveness of roof support is a major goal of the NIOSH mine safety research program.

Although field studies have provided important insights into the performance of roof supports and their interaction with the mine roof (Mark et al., 2000; Signer, 2000), few U.S. studies have combined detailed extensometer and bolt load data with systematic measurements of roof stress. This complete suite of data is essential for validation of numerical models (Gale and Tarrant, 1997).

In late 2002 the NIOSH Pittsburgh Research Lab entered into a research partnership with RAG Pennsylvania and Strata Control Technologies of Australia to conduct a baseline study of roof support performance and roof behavior in a U.S. coal mine. The site was the tailgate of the 11 North longwall at the Emerald mine, located in Greene County, Pennsylvania (figure 1). 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 the collapse of the crosscut and severe damage to the tailgate, providing a unique opportunity to gather data from the complete progression of the roof failure from initial development through final collapse of the entry.

In addition to providing baseline data for validation of numerical models, the study had the following specific objectives:

- To quantify the magnitude of the stress increase associated with the horizontal stress concentration;
- To determine the height of roof failure and the sequence of the roof failure process;

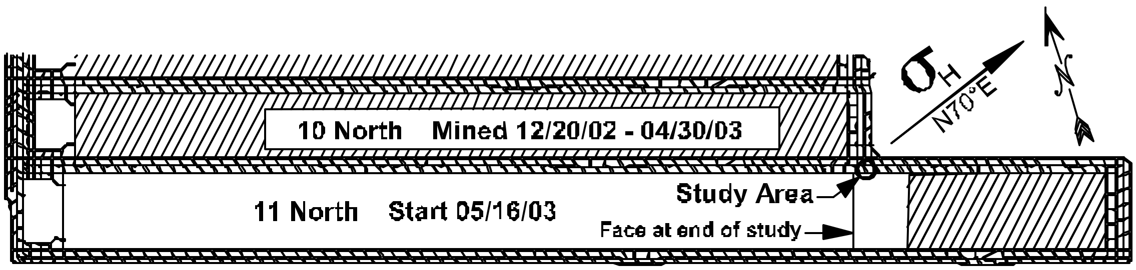

Figure 1. Emerald mine and study site.

- To evaluate the effectiveness of the roof bolts installed as primary supports, in particular with regard to their length, load bearing capacity and failure modes, and;
- To investigate the interaction between the primary support and two types of secondary support.

The purpose of this paper is to present the most significant results from the field study. The numerical modeling program is currently underway, and its findings will be reported in future publications.

STUDY SITE

The Emerald mine operates in the Pittsburgh coalbed, mining the main bench and about 0.3 m (1 ft) of roof shale. Typical mined heights range from 2.1 to 2.4 m (7 to 8 ft), with entry widths of 4.9 m (16 ft).

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 shales in the lowest 2.7 m (9 ft);
- A slightly stronger 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 in-mine coreholes barely reached the limestone, so its thickness and strength were estimated from a nearby surface corehole. 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).

No pre-mining in situ stress measurements were made as part of this study. However, nearby measurements indicate that the maximum horizontal stress conforms to the regional orientation of approximately N70E. The magnitude of the maximum stress varies with the stiffness of the rock, but is typically on the order of 11 MPa (1,600 psi) for rock with a Young's modulus of 20 GPa ($3x10^6$ psi), (Dolinar, 2003). The depth of cover above the site is 200 m (650 ft).

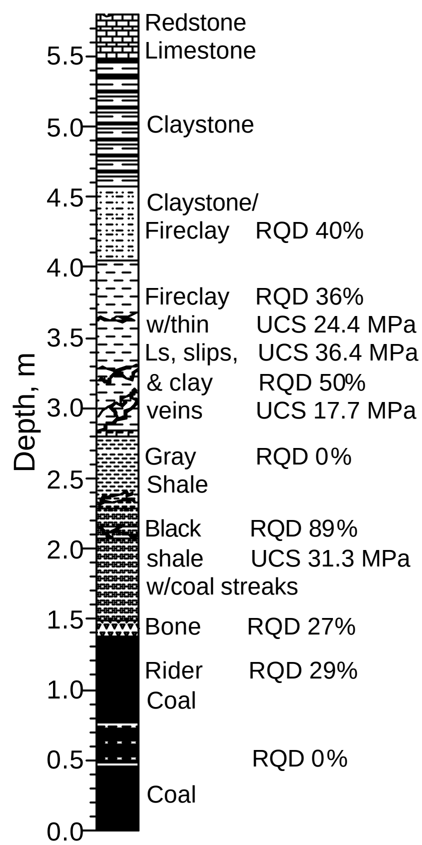

Figure 2. Composite core log from the study site with rock physical properties. Data from the vertical corehole drilled in the study crosscut and from a surface corehole.

The primary roof supports used throughout the study area were 22 mm (7/8 in) diameter, 2.4 m (8 ft) long, grade 75, two-piece combination bolts installed with 1.2 m (4 ft) of resin grout in a 35 mm (1-3/8-in) hole. The yield load for these bolts is about 19 tonnes, and their ultimate load tested in the lab at 28 tonnes. The bolts were installed three per row, with rows on 1.2 m (4 ft) centers. The two outside bolts in each row were installed from the continuous miner, together with a roof channel, and the middle bolts were installed later by the center bolter.

Three arrays of instruments were installed at the site (figure 3). Array T was located in the tailgate entry and arrays B and C in an adjacent crosscut. Crosscuts at Emerald Mine typically suffer more damage on development because they are oriented less favorably than the gate entries relative to the maximum in situ horizontal stress.

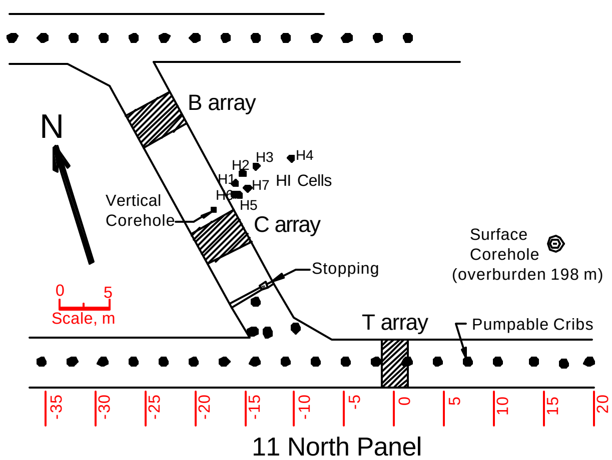

Figure 3. Site map. Distances shown are meters from the T array.

Supplemental supports were installed at two of the arrays. At crosscut array C, nine rows of three cable bolts each were installed between the rows of combination bolts. Cable bolts are not typically required in the Emerald mine gateroads, but were installed at this location to obtain data on their behavior. The cable bolts were 3.6 m (12 ft) long, 15 mm (0.6-in) diameter, partially grouted with 1.2 m (4 ft) of resin. In the tailgate, a single row of 0.76 m (30 in) diameter pumpable concrete cribs were set prior to the start of the 10 North longwall.

INSTRUMENTATION

Instruments were deployed to measure roof movements, support loads, and roof stress changes. The most detailed roof movement data were provided by multi-point sonic extensometers, with magnetic anchors located approximately every 0.3 m (1 ft) to a height of 5.8 m (19 ft) above the roof line. However, the sonic extensometers could only be read manually, and it was anticipated that deteriorating roof conditions would eventually make it unsafe to continue reading them. Therefore, they were supplemented by mechanical, three point extensometers that were monitored remotely. The anchors of the mechanical extensometers were located at 2.1 m (7 ft), 3.6 m (12 ft) and 5.8 m (19 ft). Since the data from the mechanical extensometers generally agreed with the sonic probes, they will not be reported here.

Loads on the lower, 1.2 m (4 ft) long, ungrouted portions of the combination roof bolts were measured using three types of devices:

- Strain gauges installed inside the bolts using the technique developed by Dr. Hani Mitri at McGill University (Mitri et al., 2001);
- Hydraulic U-cells with a strain gauge pressure transducer calibrated to convert cell pressure to load in tonnes, and;
- Commercially available strain gauge load cells.

The strain gauged combination bolts were prepared at McGill using roof bolts originally obtained from Emerald mine. Holes were drilled into the head of each bolt to accept a single strain gauge, near the bolt head, and electrical connectors. The bolts were individually calibrated to 13 tonnes by NIOSH and found to have a highly linear load-to-strain-gauge-signal response in the elastic range. NIOSH also tested combination bolts to determine the post-yield load-deformation relationship, so that estimates could be made of the bolt loads beyond yield. During the study the strain gauged bolts performed well, with no failures. All the bolt loads reported in this paper are from the strain gauged bolts.

Although U-cells have been used successfully in past studies (Mark et al., 1998), they had a high rate of failure in this study. Of the nine U-cells deployed, two failed due to bursting or leaks during installation, and at least two others had poor performance due to leaks induced during the installation process. Moreover, recent laboratory studies have shown that the U-cell stiffness is approximately the same as that of the bolts, producing a bolt-cell system with about one-half the stiffness of a normal bolt. This reduced system stiffness caused the six bolts installed with U-cells to reach significantly lower loads than the strain gauged bolts. For these reasons the U-cell data obtained from the combination roof bolts will not be presented here.

U-cells were also used to monitor the loads on three of the cable bolts, but only one provided useful measurements. Loads on two pumped-in-place cement cribs were measured using hydraulic flatjacks, but instrument failures again resulted in the loss of useful data. Fortunately, detailed data on the behavior of pumped-in-place cement cribs at the Emerald mine are available in a report by Barczak et al. (2003).

Horizontal stress changes were measured by seven CSIRO Hollow Inclusion (HI) cells that were installed in the roof above the gateroad pillar inby and adjacent to the crosscut site. Each HI cell consisted of an array of 12 strain gauges arranged to allow three dimensional determination of stress changes. The cells were grouted in place using an epoxy designed specifically for HI cells to provide coupling between the rock and the gauges in the cell. Seven cells were installed with a 100% success rate using procedures developed by Dr. Jan Nemcik of SCT. Before installation, the holes were undercored to identify appropriate setting zones and to obtain samples for physical property testing.

The strain data obtained from the HI cells were reduced using software developed by the U.S. Bureau of Mines (Larson, 1992). For presentation purposes, the stress changes have been transformed into principal stresses perpendicular to the crosscut. The absolute principal stresses are not presented in this report.

SCT has observed that it can require up to several months for the glue of HI cells to fully cure, and during this time glue creep and water uptake can affect the readings. While glue creep may have been a factor in the early readings, fortunately the 11 North mine by took place more than six months after the cells were installed.

Figure 4 is a cross section showing the instrumentation in each array. During initial entry development by the miner-bolter, two strain-gauged and two U-celled bolts were installed on adjacent channels at each array. The center bolter then installed the third strain-gauged bolt and a commercial load cell. The center bolter also drilled holes for one sonic and two mechanical extensometers, at each array, and these were installed later. At the C array, the center-bolter installed 9 rows of three cable bolts each. U-cells were installed on the row closest to the C array. When the pumped-in-place cement cribs were installed in the tailgate, approximately one month after entry development, the two T array flatjacks were deployed.

The stress cells were installed in a fan pattern as shown in figure 5. Cell H7 was installed towards the top of the lower shale unit, while cell H6 was placed in the bottom of the limestone. The other five cells were installed to provide information on the stress distribution within the upper claystone unit.

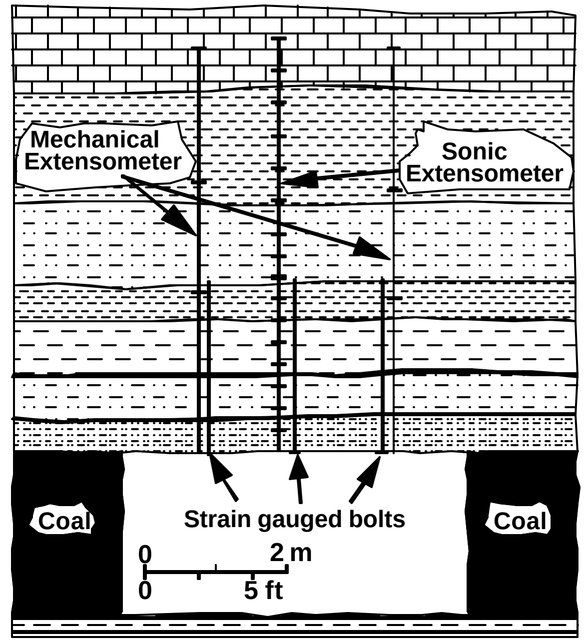

Figure 4. Typical instrument array. The C site included 9 rows of three cable bolts, and one row instrumented with U-cells in addition to the instruments shown.

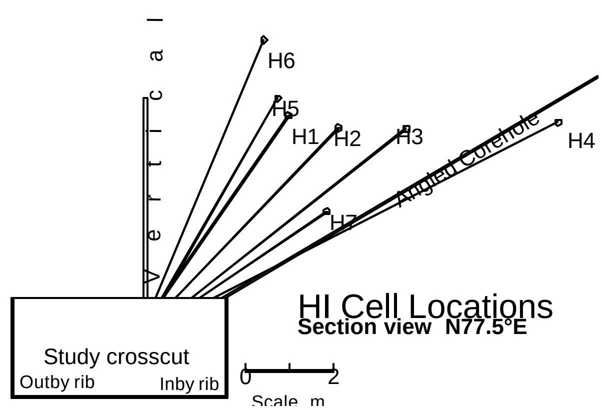

Figure 5. Section view of HI cell locations.

RESULTS

The study was conducted in three phases. The first was development, which took place early in October of 2002. The sonic extensometers and instrumented roof bolts were installed at this time. Two HI cells and half of the mechanical extensometers were installed in late-November, and the remaining instruments were installed in early-December. Roof conditions in the gateroad entries during development were generally good, although roof cutters developed in crosscuts outby the study crosscut, near the 10 North start-up room.

The second phase commenced with the start up of the 10 North longwall in mid-December. Although the 10 North set-up room was approximately 100 m (300 ft) from the study site, conditions noticeably deteriorated in the crosscut as the longwall moved away. This was attributed to development of the horizontal stress concentration at the corner of the 10 North gob. More severe changes occurred closer to the 10 North start-up room, including the collapse of a crosscut adjacent to the start-up room. Unfortunately, the instruments could not be connected to the continuous data loggers until mid-January, so complete data (particularly from the stress cells) are not available for this period.

The third phase was the mine-by of the 11 North longwall, which started up in mid-May from a set-up room approximately 950 m (3100 ft) inby the study site. The 11 North longwall passed the study site on July 20 and 21. Monitoring of some instruments continued for a few more days, until the longwall face was approximately 60 m (200 ft) outby.

Development: The roof bolt loads at installation were typically 3 to 8 tonnes. The loads slowly increased before stabilizing about a month later (figure 6). Bolts in the B arry, the array nearest the middle (track) entry of the three entry gateroad systems, saw the highest loads, between 10 and 15 tonnes, and the C and T array bolt loads were in the range of 5 to 11 tonnes. Initial extensometer readings were made several days after development, so the data do not include the initial roof sag, but by mid-November the roof at all three sites had stabilized with less than 5 mm (0.2 in) total deformation (figure 7). However, the maximum height of roof movement was about 3.3 m (11 ft), well above the top of the bolting horizon at 2.4 m (8 ft). Two HI cells (H5 and H7) were installed on November 21, with initial readings on November 24. Despite the "glue creep" effect, the stress changes between November 24 and December 10 appear to be less than 2 MPa (300 psi). Prior to the start up of the 10 North longwall the roof appeared to have stabilized, with no significant rock failure, although the T array sonic extensometer indicated strain levels close to 1% in the first 0.3 m (1 ft) of the roof skin.

10 North Longwall Start-Up: The first readings after the start of 10 North were made on January 7, 2003, after the longwall had advanced approximately 300 m (1,000 ft). During that time the two HI cells showed that roof stress increases on the order of 3.5 MPa (500 psi) had occurred, and there were increases in bolt load and roof movement at the B and C arrays. At the T array bolt loads were unchanged and there was only a slight increase in roof sag, primarily within the bolted horizon. These observations are consistent with the development of a horizontal stress concentration around the 10 North gob.

The maximum height of roof deformation at the B and C arrays increased during this 10 North start-up period, to 3.9-4.2 m (13-14 ft.), with total deformations of 16 and 10 mm (0.6 and 0.4 in), respectively (figure 7). Bolt loads at the B array increased by 3-5 tonnes to 12-22 tonnes, with the highest readings indicating that bolts were reaching yield (figure 6). At the C array bolt load increases were somewhat less, to 8-15 tonnes.

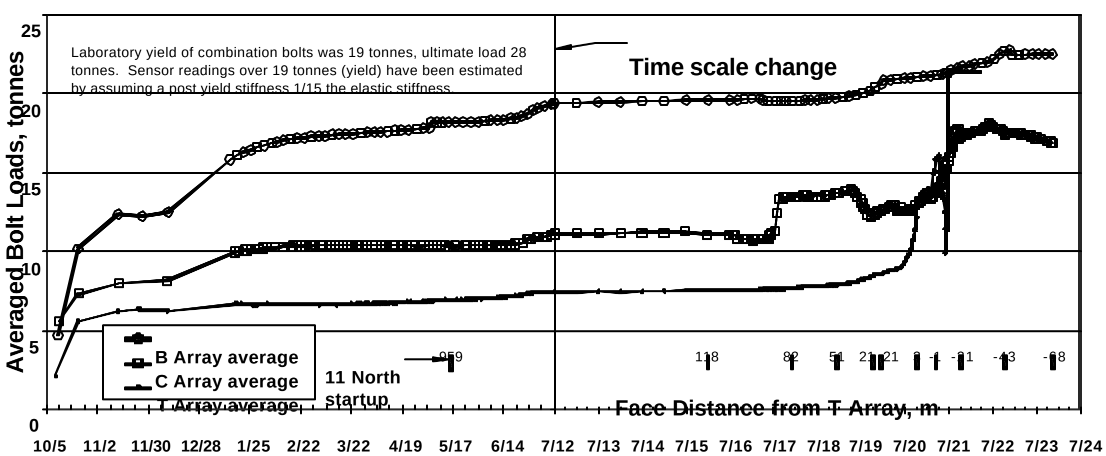

Figure 6. Bolt loads. Strain gauged bolts only, from the B, C and T arrays. Each curve is averaged from three bolts.

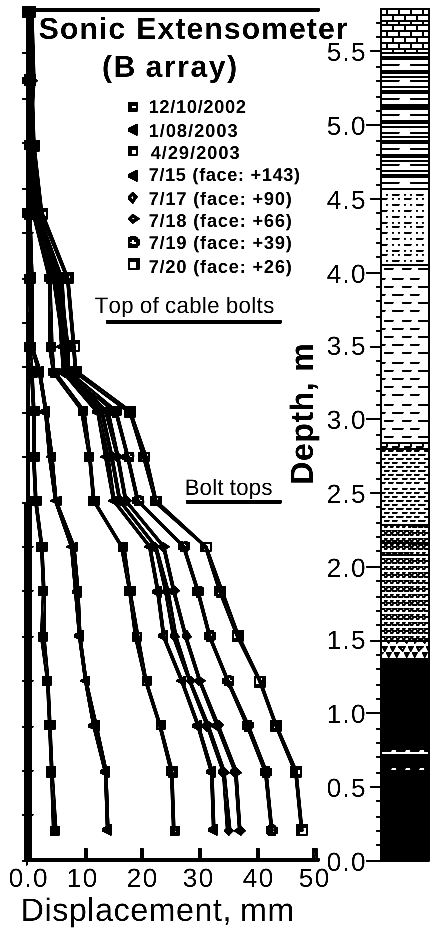

Figure 7. Profile of roof movement in the study crosscut at the B array sonic extensometer, from December 2002 through the last reading on July 20, 2003, with roof lithology. Face distances shown are in meters, with the face inby the extensometer. Depths are referenced to the roof lines

There was no nearby mining activity between mid-January and early-April, but the HI cells (now all 7) continued to indicate increases in stress. The rate of increase gradually decreased through April, but never completely stabilized (figure 8), implying that the breakup of the roof near the start up room of the 10 North panel may have caused a gradual transfer of stress to the vicinity of the study site. Figure 9 shows the stress changes that had been measured by the end of April. The major principal stresses are all compressive, and range in magnitude up to 20 MPa (2,900 psi). The orientations of the principal stress increases imply that the crosscut roof yielded or "softened," forcing the stress higher above the crosscut.

Further evidence of roof softening during this period is apparent in the measurements of bolt loads and roof movements. By the end of April the maximum height of deformation at both the B and C arrays was 4.2 m (14 ft), and the maximum deformations at the B and C extensometers were 25 and 12 mm (1 and 0.5 in), respectively. Maximum roof strains in excess of 1.5% were measured at two points in the B extensometer, while the C extensometer had one location where the strain exceeded 1%. The T array continued to be nearly stable during this period, except at the roof skin.

Mine-by of the 11 North Panel: Definitive changes in roof stress resulting from the 11 North longwall began to be observed in all HI cells by late-June, when the face was approximately 180 m (600 ft) inby the T array. After the face reached 15 to 20 m (50 to 70 ft) inby the cells the rate of stress change greatly accelerated. In most cases the stresses increased as the face approached, typically by about 7 MPa (1000 psi). The direction of the maximum principal stress increases continued to be in a generally sub-horizontal orientation, directed around the softened roof of the crosscut (figure 10). In the last HI cell readings (figure 11), large stress changes continued to take place, with increases in the vertical stress components and relief (reduction) of the horizontal components.

Both of the sonic extensometers in the crosscut recorded significant roof movement as the face approached. Total deformations in each increased by about 20 mm (0.8 in) and the height of roof movement reached 4.9 m (16 ft). Most of this deformation occurred during the last 23 m (75 ft) of advance before the face reached the crosscut, which is when the extensometers were abandoned due to safety considerations. In contrast, the T array remained fairly stable until the face was 7 m (23 ft) from the array. Then total movements of more than 60 mm (2.5 in) were measured before the instrument was destroyed as the face moved past it. The final deformation profile looked very similar to the two crosscut profiles, including a sharp "knee" just below the top of the bolts and another high-strain zone at about 3.5 m (13 ft).

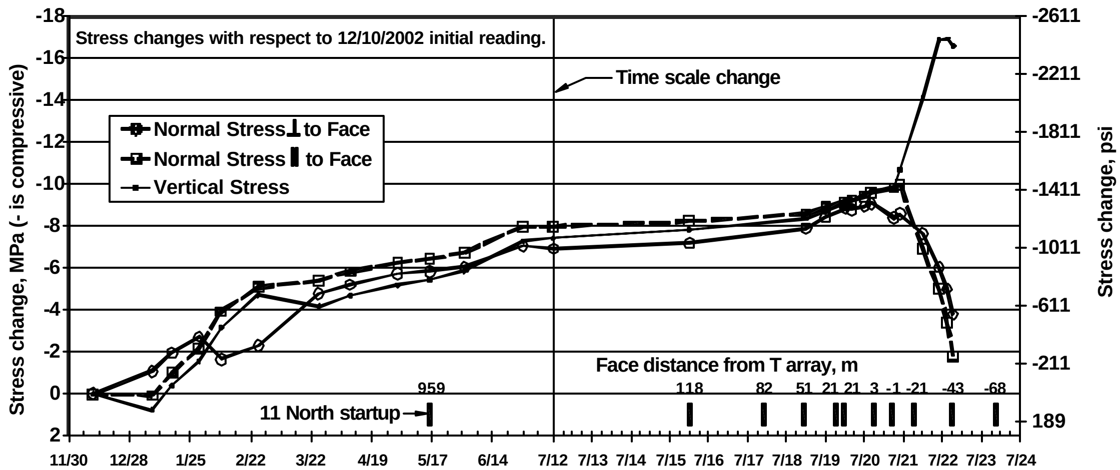

Figure 8. HI cell stress changes from cell H4 located 4.0 m above the roof and 7.6 m into the gateroad pillar. Vertical and normal stresses parallel and perpendicular to the face are shown. The shear stresses are not shown. Negative values are compressive changes.

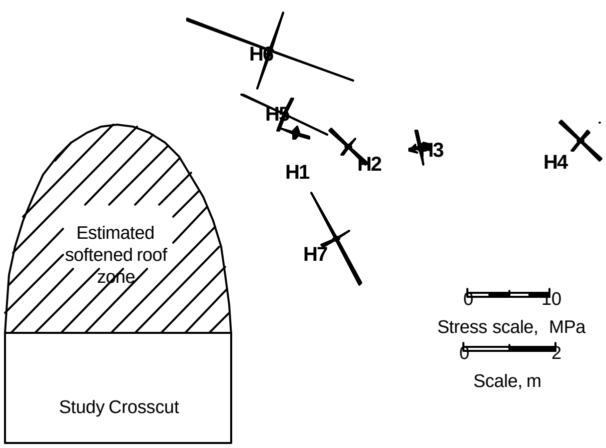

Figure 9. Principal stress changes on April 9, 2003 in the plane perpendicular to the study crosscut, with respect to initial HI cell readings. Stress changes with arrows are tensile or stress relief, stresses without arrows are compressive.

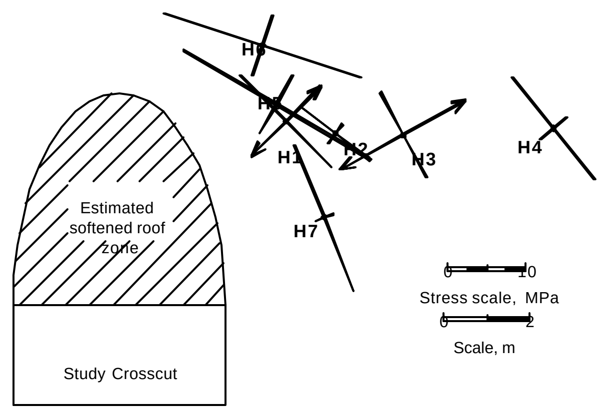

Figure 10. Principal stress changes at 0330 on July 21 in the plane perpendicular to the study crosscut, with respect to initial HI cell readings. The face is 14 m (47 ft) outby the T array (See figure 3). Stress changes with arrows are tensile or stress relief, stresses without arrows are compressive.

The largest bolt loads were measured at the B array where all the bolts were in yield by the time the face was 40 m (130 ft) inby the array. At the C array bolt loads were considerably less. One C array bolt went into yield suddenly when the face was 105 m (340 ft) inby, and the center bolt yielded almost as the face passed. The cable bolts reached their maximum recorded loads at this time, apparently below yield. After the face passed the study crosscut the mechanical extensometers indicated that roof deformations large enough to load a cable bolt well into yield (more than 50 mm) took place below the tops of the cable bolts.

Bolt loads at the T array remained low, between 10 and 18 tonnes, until the face was within 3 m (10 ft) of the array. Only the middle bolt ever went into yield before data from the bolts were lost as they went behind the shields.

As the face passed by the site, nearly every HI cell measured an immediate horizontal stress reduction of about 10 MPa (1,500 psi), indicating that caving of the immediate roof panel resulted in stress relief. In general, the horizontal stress parallel with the longwall face decreased somewhat more than that perpendicular to the face. The exception was H6, which was set at the bottom of the limestone member. In H6 the horizontal component parallel with the face continued to increase until the face was 15 m (50 ft) past the cell, probably due to delayed caving of the limestone member. Even then, only the stress parallel with the face was relieved, while a high level of horizontal stress continued to be carried above the crosscut. The delayed stress relief parallel with the face at H6 indicated that the limestone remained intact above the gateroads for some time after the lower rock units caved.

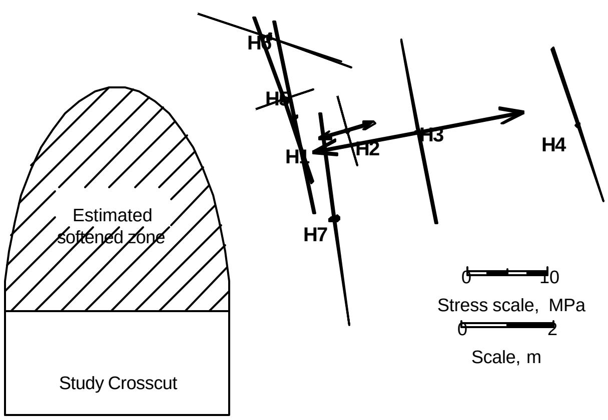

Figure 11. Principal stress changes at 0000 on July 23 (except H4 and H5, for which data were available only through July 22) in the plane perpendicular to the study crosscut, with respect to initial HI cell readings. The face is 58 m (190 ft) outby the T array (See figure 3). Stress changes with arrows are tensile or stress relief, stresses without arrows are compressive.

In contrast, the vertical stresses continued to increase until measurements ceased. On average, the vertical stress increase due to the mining of 11 North was about 13 MPa (1800 psi).

Bolt loads at the crosscut arrays reached a maximum shortly after the face had passed, and then began to decrease. Of the 17 instrumented combination bolts, only 2 maintained their load, while 12 shed load gradually, and 3 lost load suddenly. The reduced loads may have been associated with the horizontal stress relief that occurred when the face passed, or to failure of the grouted portion of the bolts.

CONCLUSIONS

The most surprising result of the study was that the roof conditions at the study site were not as severe as experienced in past “stress windows” at the Emerald Mine. Instead, at the time the data loggers were removed, with the face 58 m (189 ft) outby the study site, the crosscut, though observably damaged, was still standing. Even the tailgate entry generally stayed open for some distance into the gob. During a subsequent visit to the 11 North tailgate well outby the study site, it appeared that the typical vertical abutment stress caused more gateroad damage than had the horizontal stress window.

Despite the moderate ground conditions, significant stress changes were measured. The total horizontal stress increase, confirmed by the stress relief that occurred as the longwall passed, indicates that the mining-induced stress concentration approximately doubled the original in situ stress. The orientation of the stress increases indicates that the stresses predominantly passed over, and not through, the softened (yielded) roof immediately above the crosscut.

The sonic extensometers clearly showed that from initial development the conditions in the crosscut were more severe than in the tailgate entry. This was expected because the crosscut was oriented nearly perpendicular to the regional maximum horizontal stress. The greatest deformations were measured at the B array. This could be due to the B array’s proximity to the 10 North gob and the track entry, or because of the additional support provided by the cable bolts at the C array, or because the stopping near the C array provided some support (Oyler et al., 2001), or to a combination of these effects.

While the three arrays differed in the timing and magnitude of the roof deformation, it was significant that the deformation process followed a broadly similar pattern at all three locations. In all three instances maximum height of movement was approximately 5 m (16 ft), and significant roof strains occurred both near the top of the combination bolts (at 2.4 m) and approximately 1.0 m (3 ft) above them.

The roof bolt loading pattern was consistent with the extensometer data, with the greatest loads at the B array and the least at the T array. The measurements indicated that the roof supports in use at the mine, that is the combination bolts and pumpable cribs, appear to be sufficient to maintain roof control under the observed conditions. Following development, the loads appeared to normally be below the yield capacity of most of the bolts, and roof movements were largely limited to the bolted horizon. During longwall mining, some of the bolts in the tailgate reached yield loads as the face approached, implying that the secondary supports (pumpable cribs) could have been necessary to provide adequate roof support.

Unfortunately, little reliable load data were collected from the pumpable cribs and the cable bolts. However, data from a pressure gauge on one pumpable crib and the limited cable bolt load data combined with extensometer data give some indications of the loads on both of these types of supports. The limited data available suggest that neither the cribs nor the cable bolts developed significant loads before the face passed. However, with nearly 50 mm (2 in) of roof movement, it seems hardly likely that some load did not develop on the cables or the cribs. Indeed, one explanation for the lower bolt loads at the C array is that the cables assumed some of the load. Recent field and numerical model studies (Tadolini and Barczak, 2003; Barczak et al., 2003) both indicate that supplemental supports probably reduced the loads that would have otherwise have been applied to the roof bolts.

In summary, the study was successful in providing a substantial set of baseline data from a U.S. coal mine, incorporating stress change, roof deformation, and support loads. Although different results would be expected under different geological conditions, this data set will provide a solid foundation for calibrating international state-of-the-art numerical models for U.S. conditions. Ultimately, it will help make these sophisticated design tools available to U.S. mine planners.

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