ROCK MECHANICS STUDY OF LATERAL DESTRESSING FOR THE ADVANCE-AND-RELIEVE MINING METHOD

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ABSTRACT

The advance-and-relieve method benefits from lateral destressing associated with mining in laminated rocks and a high horizontal stress regime. This stress control method is based on measurements showing that occurrence of rock failure in the roof and floor of an entry (or caving of roof strata in a panel gob) results in redistribution of stresses in adjacent entries. By locating other entries within the shadow zone of the first entry (or gob), improvements in stability can be achieved.

Numerical modeling proved useful in studying the basic mechanics of lateral relief while investigating the sensitivity of results to different geologic and mining parameters using controlled experiments. It was shown that failure of rocks near an entry results in redistribution of horizontal stress and shifting of the stress to higher horizons. Measurements from two mines are consistent in showing significant horizontal stress reductions in comparison with the far-field stress regime within the destressed zone. Although the far-field stress regime is very anisotropic, these measurements show near-equal secondary principal horizontal stresses, or perhaps a switch in orientation, as a result of destressing. Stress relief is achieved through lateral movement and relaxation of rocks along weak bedding planes toward adjacent caved zones (or softened zone).

Because of cave geometry in the advancing panel, horizontal stress concentrations occur near the cave line both in front of the face and to the sides. The horizontal stress concentration reaches 1.7 times the far-field stress ahead of the face. This stress increase is significant and may cause structural damage in this zone benefiting from additional support. In the next advancing panel located within the shadow zone of the gob, horizontal stresses are significantly reduced in the roof (by 50%). Thus, the stability of future advancing panel can be improved through prudent layout designs and sequencing. The width of the relief zone is significantly influenced by the height of the softened (or cave zone) and rock mass properties.

INTRODUCTION

As the most favorable coal reserves are depleted, modern mines are being developed under more extreme conditions, such as deep cover, multiple seams, and/or high horizontal stresses. The trend toward mining reserves under more difficult conditions has accelerated dramatically in the past year with the increased demand for coal. Room-and-pillar mines, in particular, are facing severe ground control problems and are actively searching for solutions.

National Institute for Occupational Safety and Health (NIOSH) researchers have been studying the mechanics of stress redistribution associated with retreat mining for more than a decade. A particular approach of interest is a new stress control method called “advance-and-relieve” mining. This method involves the extraction of a pillar row and part of the barrier on one side of a panel as the panel is developed. A cave is then created along the side of the panel as the pillars are extracted that advances with, but, just behind the panel face development. The width of the cave zone does not encompass the width of the panel but is limited to the extracted pillar and barrier. Both zones of stress relief and concentration are developed in the panel adjacent to the cave. Maximizing stress relief while simultaneously minimizing unwanted stress concentrations is the key to the technique. During the past 3 years, researchers from NIOSH have completed two field studies aimed at developing the advance-and-relieve stress-control method (1). These field studies have provided much needed information, but are expensive and time consuming and results are difficult to generalize to other studies. Numerical modeling offers an alternative approach to studying the basic mechanics of lateral destressing for better utilization of the advance-and-relieve method.

The advance-and-relieve method benefits from lateral destressing associated with mining in laminated rocks and under a high horizontal stress regime. This concept is based on the premise that rock failure in the roof and floor of one entry (or caving of roof strata in a panel gob) results in a redistribution of stresses in adjacent entries. By locating other entries within the horizontal shadow zone of the first “sacrificial” entry (or gob), improvements in stability are achieved. Republic Steel utilized this concept and realized improvements in the stability of adjacent entries 30 to 50 ft from the first entry. Practical implementation of this concept involved using a Dosco miner to mine an arched entry in the middle entry ahead of other entries and installing external support while allowing the rocks above the steel sets to fail (estimated cave height 25 to 30 ft). This sacrificial entry then shielded side entries against lateral stresses. Researchers using numerical modeling to study the results found that failure or movements along bedding planes was possibly required to develop the extent of stress relief (2, 3).

The U.S. Bureau of Mines (USBM) researchers used numerical modeling to investigate the effectiveness of lateral destressing and pillar softening due to the transfer of loads to the sides and improving cutter roof problems (2). Slotting the pillar at the roof and at mid-height proved ineffective, while lateral softening in conjunction with a reduction in pillar width resulted in significant stress reductions. Pillar width was reduced from 30 to 12 ft before significant reductions in horizontal stresses were calculated in adjacent entries. For an elastic rock mass, the shadow zone surrounding an entry is very narrow and thus requires very narrow pillars to achieve lateral destressing (4). Because narrow pillars are less stiff than coal on the sides (side block), they will always provide some lateral destressing by transferring loads to the sides through the action of a "pressure arch." This results in lower horizontal and vertical stress concentrations on the inside entries.

In this paper, the authors review the results of field measurements in two mines to study stress distribution in laminated rocks. Numerical modeling is then used to evaluate the failure mechanism and to determine the effect of panel width, geology, and other factors on the stress distribution and the extent of stress relief. It is also demonstrated that destressing can have a significant impact on the interpretation of stress measurements taken to obtain the far-field stress while the identifying characteristics of measurements in destressed zones is given.

REVIEW OF FIELD DATA

Three recent stress measurement sites provide evidence of lateral destressing. The first set of data was collected at the Deserado Mine (Mine 1) through cooperative work among Spokane Research Laboratory (SRL) NIOSH, Maleki Technologies, Inc. (MTI), and Blue Mountain Energy, Inc. The last two sets were obtained by the Pittsburgh Research Laboratory (PRL) NIOSH at the Tanoma Mine. One of PRL measurements was intended to measure the far-field stress regime while the last set was designed to quantify stress changes associated with the advance-and-relieve method. Measurements at both mines are consistent in showing significant horizontal stress reductions in comparison with the far-field stress regime within the destressed zone. Although the far-field stress regime is very anisotropic, these measurements show near-equal secondary principal horizontal stresses, or perhaps a switch in orientation, as a result of destressing. Both measurements were obtained using the overcoring method with the USBM deformation gauge. The measurements were assumed to be at sufficient distance (10 to 19-ft) from the excavation so that far-field horizontal stress could be determined. However, because of significant lateral destressing, the measurements were actually obtained within the destressed zone. In both field studies, measured horizontal stresses were significantly lower than the far-field stress regime.

Measurements at Mine 1

The Deserado mine is located near Rangely, Colorado, extracting B and D seams from the base of the Lower Williams Fork Formation, Cretaceous in age. During the extraction of the D Seam, far-field horizontal stress was measured at four locations over a distance of several miles (figure 1) (5, 6). These measurements were taken with the USBM borehole deformation gage and analyzed using site-specific measurements of rock deformation modulus (5). The measurements indicated a maximum principal stress of approximately 2,000 psi. Minimum principal stress was approximately 1,400 psi at a depth of 600 ft. Subsequent measurements at greater depths indicated a slight increase in horizontal stress caused by gravity effects. The orientation of maximum principal horizontal stress was consistent (N 73 °E to N 88 °W, approximately east-west). The higher stress of 6,100 psi at site 1 was measured in a very stiff limestone that was locally present. Because of its high stiffness, the limestone absorbed very high stresses (4).

Three stress measurements were recently taken in the mine roof in the B Seam some 40 ft below the D Seam. These measurements were obtained from a vertical drillhole at 10.0, 11.5, and 12.3 ft above the roof in crosscut 7 along the B Mains. The B Mains are oriented approximately north-south (N 25 °E) at a distance of a mile from other workings in the D Seam. Because of the uniformity of geology and lack of faulting in the area, the far-field stress regime in the B seam could be assumed to be similar to that measured in the D Seam (figure 1).

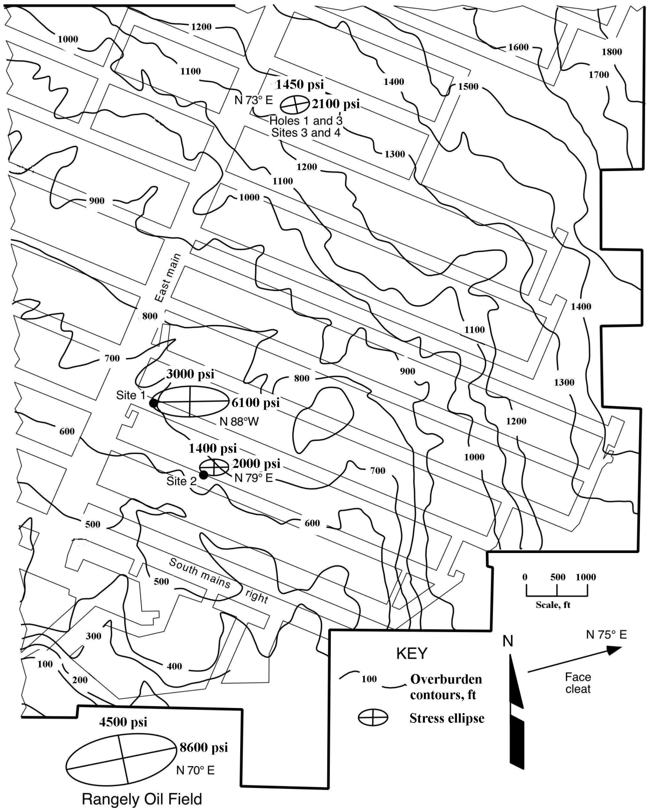

Figure 1. Horizontal stresses measured in Mine A D Seam (After Maleki and others 1997).

Table 1 presents the calculated maximum horizontal stress at the measurement sites in the B Seam. These measurements are significantly lower than previous measurements of far-field stresses in the D Seam. Considering the accuracy of the overcoring method, the measured stresses are nearly equal. The measured maximum stress is oriented approximately north-south, and minimum stress is oriented east-west. These data give the appearance that the principal stresses have switched orientations. The north-south orientation of maximum stress is not consistent with the observed failure pattern along the rooms in these mains, and thus it is believed that recent measurements are not a measure of far-field stress. Had additional measurements been taken deeper into the roof, far-field stresses may have been measured that were consistent with regional measurements in the D Seam.

Table 1. Calculated secondary principal horizontal stress and orientation of maximum stress, B Seam.

Overcore distance above roof, ft	Maximum stress, psi	Minimum stress, psi	Bearing
10.0	540	420	N 0 °E
11.3	470	400	N 9 °E
12.3	560	440	N 17 °W
Average 11.3 to 12.3	515	420	N 4 °W

Recent measurements in the B Seam are influenced by the height of failure, or "softened" zones, about the entries. Since most of the stress-induced failures occurred along the rooms, the authors believe that the maximum far-field horizontal stress is oriented near-perpendicular to the entries (approximately east-west). Failure of laminated rocks along the entries shifts horizontal stresses to higher horizons. This failure process appears to relieve horizontal stress within the crosscuts at some distance behind the face, particularly in rocks that contain layers having low shear strength values. This results in a reduction in horizontal stresses particularly the maximum horizontal stress within the immediate roof rocks in the crosscuts. Because of roof damage in the northeast orientated entries, the stresses measured in the crosscuts have been significantly altered from the expected regional stress field as measured in the D-seam. Essentially, the regional maximum horizontal stress (east-west) has been reduced by stress relief with this reduction also affecting the measured minimum stress. In the lower roof, with less damage in the crosscuts, stress can be transferred more efficiently in the roof in the north-south direction than in the east-west direction where damage occurred to the entries. Therefore, a higher stress can be sustained in the north-south direction than in the east-west direction. This assertion is in agreement with numerical modeling results and detailed stress mapping within the entire mine. Modeling results from this mine are not included in this paper. Results are, however, similar to that presented later in this paper for Mine 2, East Mains.

Stress Measurements at Mine 2, East Mains

One successful stress measurement was obtained at a distance of 17 ft above the roof in the East Mains just outby the entrance to panel E15 at the Tanoma Mine (figure 2, stress site, SS). This mine is located 10 miles northeast of Indiana, PA, and extracted coal reserves from the 4-ft-thick Lower Kittanning Seam. The East Mains are oriented N 60 °W. Roof lithology and mechanical properties are summarized in table 2.

Table 2. Roof lithology and average mechanical properties at the measurement location.

Distance above roof, ft	Lithology	Young's modulus, 10^6 psi	Uniaxial compressive strength, psi
0-14	Shale	2.5	10,800
14-23	Sandy shale	3.3	14,850
23-26	Sandstone	4.5	29,300
23-30	Shale	NA	NA

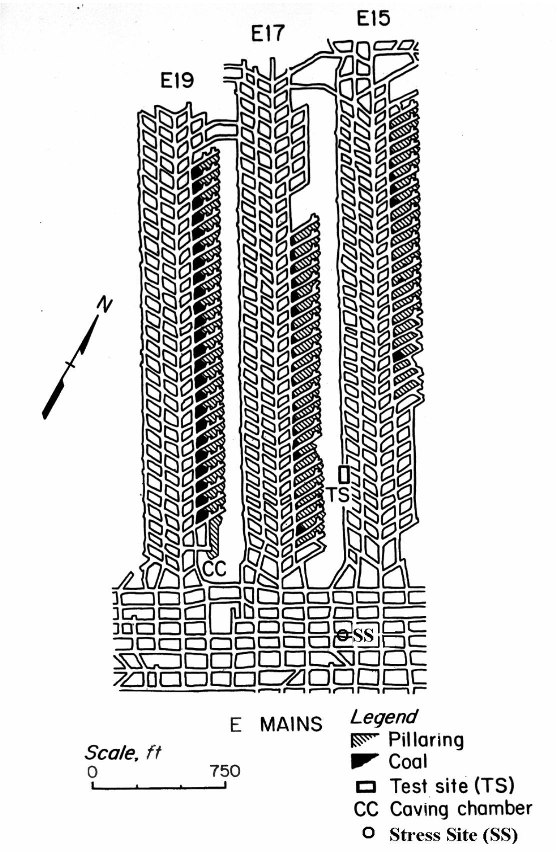

Figure 2. Location of test site (TS) in the L2 entry, stress site (SS).

To estimate the far-field stress regime, the authors reviewed available measurements in the Kittanning (1) and Freeport coal seams. Considering geologic conditions, the authors expect the following pre-mining horizontal stress range for the Tanoma Mine:

maximum stress (P) = 2, 400 to 2,800 psi,
minimum stress (Q) = 1,750 to 2,100 psi, and
maximum stress direction = N 70 °E.

The measured secondary principal horizontal stress regime is summarized below. Considering the accuracy of the overcoring method, secondary principal stresses are near-equal, and the maximum measured stress is significantly below the assumed far-field stress. The stresses are

maximum measured stress = 1,975 psi,
minimum measured stress = 1,710 psi, and
maximum stress direction = N 78 °W.

Stress Measurements at Mine 2, E15-E17 Panels

The last set of measurements was obtained in the L2 entry of E15 panel (figure 2). At this site, six multi-component deformation gauges were installed in the roof at a distance of 2 to 20 ft above the seam. The intent of these measurements was to quantify lateral destressing that occurred in the L2 entry as a result of caving in the E17 panel as the panel was advanced. In this case the cave was produced by the advance and relieve mining method. The instruments were at a distance of 120-ft from the cave line. E15 and E17 panels are oriented N 30 °W, or near- perpendicular to the maximum far-field stress (P).

Figure 3 presents the history of horizontal stress changes for four advancing positions of the cave in panel E17. In spite of variability in the data, there is a consistent trend for horizontal stress changes in the roof.

- The horizontal stress acting perpendicular to the panel (P or maximum far-field stress) is reduced by 700 to 1,200 psi.
- The horizontal stress acting parallel to the panel (Q, or minimum far-field stress) is slightly increased at the face position followed by a slight decrease behind the face position. This stress change is generally within the accuracy of the measurement technique (about 200 to 400 psi).

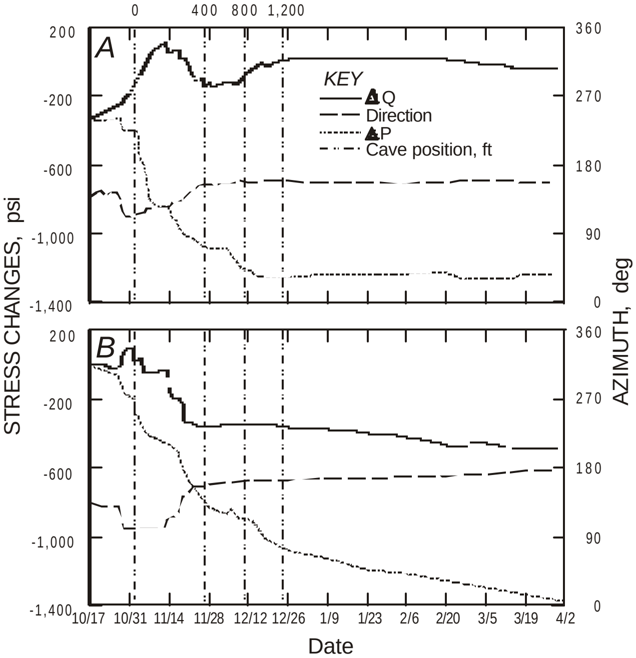

Figure 3. Measured stress changes from advance and relieve mining at the Tanoma mine. (A) 2-ft depth and (B) 10-ft depth. Delta P and Q are the maximum and minimum stress changes. The azimuth direction is to delta Q.

Considering the limitations in this field program, the authors expect these measurements to be accurate within a 25% margin in the magnitude of stress changes. Nevertheless, the trends indicate significant reduction in maximum horizontal stress (P), in particular at large distances from the gob that cannot be readily accounted for using elastic solutions.

BACK-ANALYSES OF STRESSES AT THE TANOMA MINE

Numerical modeling is used as a tool for back analyses of stresses and for examining the mechanics of lateral stress relief in laminated, inelastic rocks. In this section, the authors provide analyses of stress distribution along the measurement locations using both elastic and inelastic constitutive models and a comparison of results with available field data. The intent is to enhance the understanding of the mechanics of lateral destressing. For this purpose, the authors used both two - and three-dimensional finite-difference codes (8) with multi-material elastic and inelastic constitutive laws.

Modeling Methodology

The authors started the modeling exercise by using elastic material models and then incorporating inelastic models. Elastic models are advantageous because they require the least amount of input data while incorporating basic lithology and material properties. In selecting the material models for inelastic runs, the authors examined the laminated nature of the rocks that have been always associated with significant lateral destressing. The authors chose several constitutive models that can simulate the effects of bedding planes with low shear-strength properties, as well as crushing the rock mass layers to a residual strength. These models were:

- Ubiquitous joint model.
- Mohr-Coulomb model.
- Strain-softening rock mass model with ability to crush and soften under increased strain.
- Strain-softening model for the rock mass with interfaces located at the boundary of laminated rock units. The horizontal interfaces with low shear-strength properties “soft interfaces” are suitable for simulating lateral movements and the associated stress relief.

Two approaches were investigated to simulate the compressive failure of the rock mass about the entries. First, a strain-softening model was used for laminated rocks. With this model, one can simulate crushing and unloading of material by reducing cohesion and/or the angle of internal friction from peak values to residual values after failure. Alternatively, failed elements in the roof were removed because failed material can be considered to have insignificant load-carrying capacity (9). By removing the failed rocks for an elastic rock mass bounded with soft interfaces, the authors simulated horizontal stress relief that was in agreement with field measurements.

Initially, the authors used two-dimensional models to develop modeling procedures and to select material models and suitable ranges for the material properties (table 3). A three-dimensional, finite-difference code (FLAC3D) was used for complementing the two-dimensional stress analyses so that the three-dimensional nature of the stress field and mine excavations could be modeled realistically. FLAC3D (Fast Lagrangian Analyses of Continua in Three Dimensions) simulates the behavior of rock and soil structures that behave elastically or undergo plastic flow when yield limits are reached.

Table 3. Range of material properties used in models.

Property	Roof and floor	Coal seam	Bedding planes (soft to stiff)
Young’s modulus, mpsi	1 to 4.5	0.30	
Poisson’s ratio	0.25	0.25	
Cohesion, psi	NA	NA	40 to 70
Angle of internal friction (degrees)	NA	NA	15 to 45
Normal stiffness (psi/in)	NA	NA	40,000
Shear stiffness (psi/in)	NA	NA	40 to 400

NA = Not applicable.

Stress Analyses of East Mains, Mine 2

East mains are a set of 18-ft wide entries oriented near parallel to the maximum horizontal stress direction of N 70 °E (Figure 2). The entries are separated by crosscuts on 100-ft centers. Because of unfavorable orientation of crosscuts with respect to the maximum horizontal stress, there was higher structural damage in the crosscuts than the rooms. The only successful stress measurement was obtained in a room at a distance of 60 ft from the center of the crosscut.

Figure 4 presents mesh geometry, material layers, and the coordinate system. The mesh includes one of the East Mains' entries, three crosscuts, and two pillars. Because of symmetry conditions applied on the model boundaries, the functional modeled area is many times larger than shown in figure 4. The model is loaded with far-field minimum horizontal stress (Q) in the X-direction and maximum stress (P) along the Y-direction. Geologic conditions are analyzed using four material models. Instead of removing the failed roof rocks within the crosscuts, the authors utilized the strain-softening model. Peak cohesion varied from a maximum of 150 to 50 psi for the sandy shale and shale layers, respectively. The residual cohesion for softened rock was reduced to a minimum of 25 psi in some analyses. The peak and residual angle of internal friction were 38 to 20 degrees.

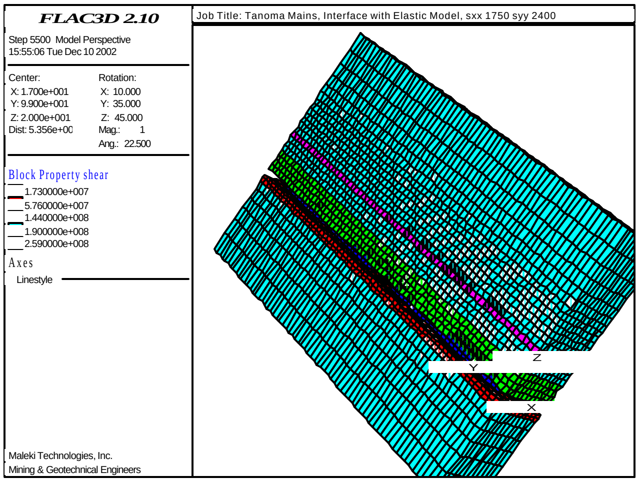

Figure 4. Mesh geometry and model properties, Tanoma Mine, East Mains, 3D analysis.

Selective results are summarized in table 4 and figure 5. There is a good agreement between the calculated and measured stresses particularly when using the lower bound for the far-field stress condition. Note that the calculated stresses are near-equal, and maximum stress is now oriented in the X-direction.

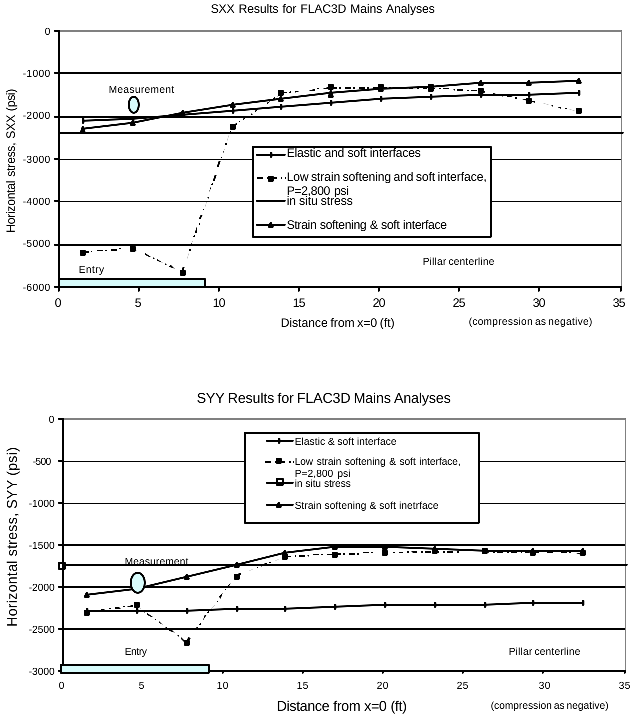

Figure 5. Comparison of the model results versus measured horizontal stresses, Tanoma mine, east mains, 17 ft in roof.

Top is Sxx-direction and bottom is Syy-direction.

Based on the results pertaining to modeling procedures, the authors believe that an elastic model with soft interfaces and inclusion of cave geometry is the best approach for simulating lateral destressing. Because the plastic strain is mesh-dependent in FLAC formulation, the predicted results for the strain-softening model may not be adequate for the relatively coarse mesh resolution. The authors have, therefore, used elastic models for roof rocks while simulating the failure/softening of roof rocks by removing the material for the remaining part of this study.

Table 4. Calculated horizontal stress at point A instrument location. Measured range varies from 1,700 to 2,000 psi.

Model	Syy, psi	Sxx, psi	Comment
Elastic	2,750	2,200	Very limited lateral relief
Mohr-Coulomb plasticity for roof rocks with cohesion = 50 psi	2,200	2,300	Near equal stresses
Strain softening and soft interfaces	2,350	2,350	Using peak cohesion of 150 to 90 psi for sandy shales and shales
Strain softening and soft interfaces	2,050	2,350	Using peak cohesion of 50 psi for both sandy shales and shales
*Strain softening and soft interfaces and lower bound for far-field stress**	*2,000*	*2,070*	Using peak cohesion of 50 psi for both sandy shales and shales

*Using the lower limit for far-field stress SYY =2,400 and SXX= 1,750 psi

Stress Analyses of Panel E15 and E17, Mine 2

As illustrated in figures 2 and 3, changes in horizontal stress were measured in the mine roof at a test site located in the L2 entry, panel 15. This five-entry panel was isolated by a 100-ft barrier from the cave developed from the advance and relieve method in panel 17. The width of the caved zone in panel 17 was approximately 120 ft. A significant reduction (700 to 1,200 psi) in maximum stress (P) was measured in the mine roof and attributed to the formation of the cave in panel 17. Assuming that the sandy shale-sandstone roof rocks remained elastic during the development of panel 15, the change in horizontal stress is related to formation of the cave and lateral displacement of laminated roof toward the cave zone. The following three-dimensional analysis addresses some of the mechanisms involved using a cave height of 20 ft. The sensitivity of results to different parameters is examined later in this paper.

Figure 6 presents the mesh geometry. The mesh includes half of the gob zone in panel 17 and half of the entry development in panel 15. Because of the planes of symmetry on the model boundaries, the actual modeled area is many times larger than shown in figure 6. The model is loaded with far-field maximum horizontal stress (2,400 psi) in the X-direction and minimum stress (1,750 psi) along the Y-direction. Geologic conditions are analyzed using four material model properties.

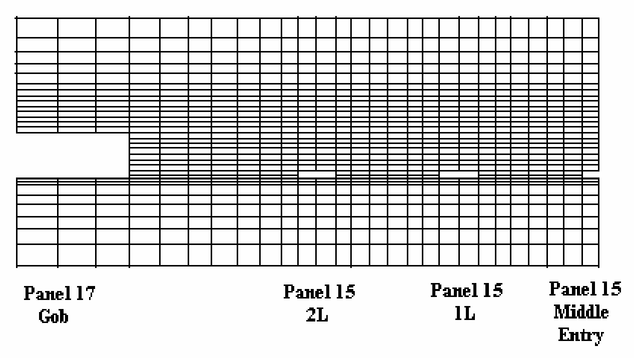

Figure 6. Mesh geometry for cross section of panels 15 and 17, Tanoma Mine, 3D analysis.

Below are five face positions (or modeling steps). Comparison of model results versus measured stress changes at 5 different face positions from advance and relieve mining at the Tanoma Mine corresponding to retreat distances as shown in figure 3.

1. Panel 15 development with no pillaring or cave in panel 17.
2. The pillar/cave line is near the instrument location.
3. The pillar/cave line passes the instruments by 400 ft.
4. The pillar/cave line passes the instruments by 800 ft.
5. The pillar/cave line passes the instruments by 1,200 ft.

Figure 7 compares the measured and model stress changes at five face positions and two instrument locations. There is a good agreement between measured and calculated results, particularly in the main roof. The model does not show any significant change in the horizontal stress pattern after a retreat of 400 ft from the instrument location.

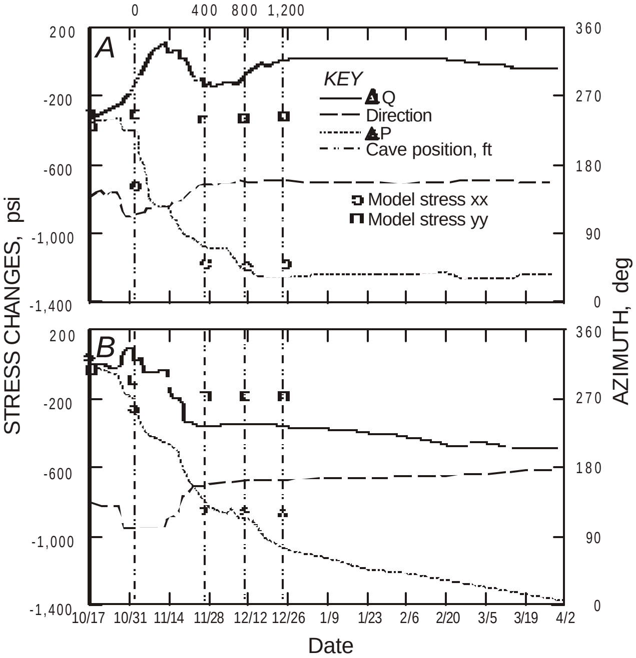

Figure 7. Comparison of model results versus measured stress changes at 5 different face positions from advance and relieve mining at the Tanoma Mine. (A) 2-ft depth and (B) 10-ft depth. Delta P and Q are the maximum and minimum stress changes. The azimuth direction is to delta Q.

Figures 8 and 9 present the horizontal stress distribution (Sxx) during the retreat at the measurement horizon for steps 2 and 3. The direction of retreat in panel 17 is from the bottom of the page to the top.

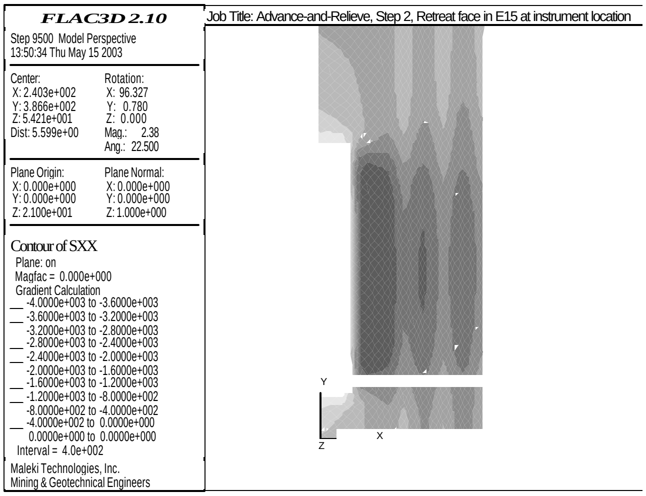

Figure 8. Horizontal stress contours (Sxx) at 17 ft into roof, modeling step 2. (Lighter shades indicate stress concentration and darker shades indicate stress relief.

- In panel 17 (advancing panel), horizontal stress concentrations occur near the cave front both in front of the cave and to the sides. The Sxx stress exceeds 4,000 psi ahead of the face (stress concentration factor of 1.7). This stress increase is significant and may cause structural damage in this zone.

- In panel 15 development ahead of the retreat face in panel 17, horizontal stresses are concentrated in the roof, exceeding the premining stress of 2,400 psi.

- In panel 15 developments behind the retreat face in panel 17, horizontal stresses are significantly reduced in the roof. Clearly, the entries are now within the shadow zone of the gob. The horizontal extent of lateral destressing is shown to be significant.

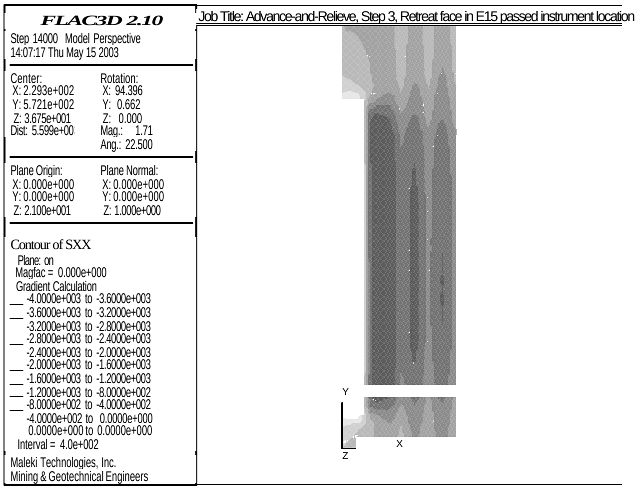

Figure 9. Horizontal stress contours (Sxx) at 17 ft into roof, Modeling step 3. (Lighter shades indicate stress concentration and darker shades indicate stress relief.

Having visualized the three-dimensional stress relief mechanism, one can tailor special panel designs utilizing the advance-and-relieve method. Because horizontal stresses concentrate ahead of the face in panel 17 before lateral destressing is achieved (behind the face), the advance-and-relieve method may not be very effective in reducing ground control problems at the faces in panel 17. However, the stress shadow zone forming behind the retreat face provides protection for entries located to the side of panel 17. Thus, significant stress reductions can be achieved through prudent mine layout designs and sequencing as follows:

1. Mine the first panel (advancing panel) and create a cavity in the roof by extracting the coal to the sides. Because of stress concentrations in this panel, the authors recommend use of additional support.

2. Mine the second panel (advancing panel) after retreat of the first panel. Locating the second panel within the stress shadow of gob of the first panel will benefit from lateral destressing.

3. The degree of lateral destressing in the second panel depends on both geologic conditions and mine layout designs. Minimum width stable pillar designs should be used in the second panel (including both barrier and in-panel pillar designs). This is important because lateral relief is reduced as a function of distance from the gob.

SENSITIVITY ANALYSES

To utilize the potential benefits from lateral destressing, the authors used numerical models to quantify the maximum extent of horizontal stress relief as a function of geologic and mining conditions. Four specific geologic and engineering factors were evaluated:

1. Soft and stiff bedding plane properties.
2. Cave height.
3. Cave or panel length.
4. Cave width

The following factors were kept unchanged: Thickness of the interbedded zone in the mine roof and the far-field stress.

Both two- and three-dimensional modeling was used in this sensitivity analyses while comparing the results with the Tanoma Mine measurements for reference. Using FLAC2D analyses, the authors evaluated both the influence of cave height and interface properties. Figure 10 shows minimal lateral stress relief for roof rock having either stiff or poorly developed interfaces. Obviously, the cave height influences the results significantly. For all cases, the maximum relief occurred near the L2 entry, gradually diminishing farther away from the gob. Thus to take the most advantage of lateral destressing, it is important to optimize pillar designs and consider both vertical and lateral loading conditions. Within the practical ranges used for the cave width (60 to 120 ft), the width of the gob zone does not influence results significantly.

The sensitivity of results to other parameters, including panel length, was evaluated using three-dimensional analyses. Figure 11 presents the results for two panel lengths and three cave heights. Panel length does not influence the results significantly within the analyzed range. Cave height and bedding plane properties are the most significant factors using the results of both two-and three-dimensional analyses.

CONCLUSIONS

The advance-and-relieve method benefits from lateral destressing associated with mining in laminated rocks and a high horizontal stress regime. This stress control method is based on measurements showing that the occurrence of rock failure in the roof and floor of one entry (or caving of roof strata in a panel gob) results in redistribution of stresses in adjacent entries. By locating other entries within the horizontal stress shadow zone of the first "sacrificial" entry (or gob), improvements in stability are achieved.

Field measurements provided important evidence of lateral destressing at distances exceeding 120 ft from the gob. For both anisotropic horizontal stress fields in the study mines, a signature of lateral destressing is shown to be a reduction in the maximum stress, giving the appearance that the horizontal stresses are near-equal within the relief zone or perhaps the stresses have switched orientations. This reduced stress pattern should alert researchers in the field that they are still within the relief zone and that the measurements should be continued deeper into the roof when making stress measurements in regions known to have anisotropic stress fields.

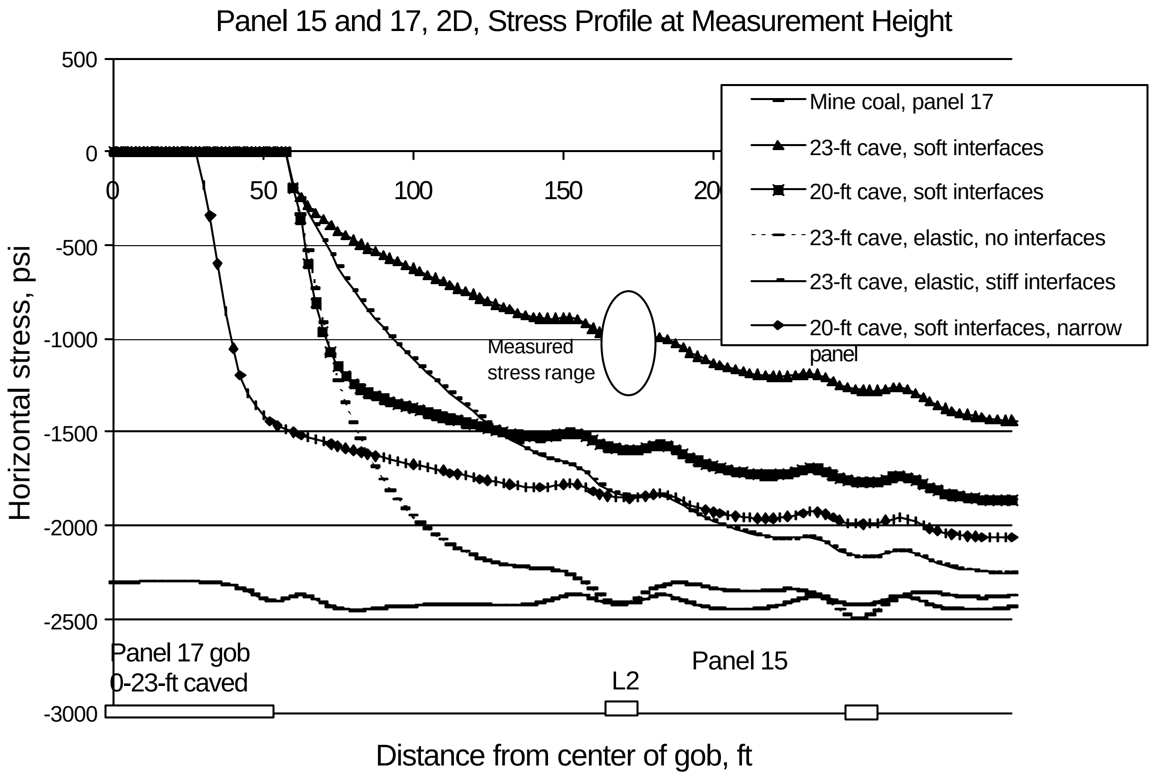

Figure 10. Horizontal stress profile for three interface conditions and two panel widths, 2D analysis.

Numerical modeling proved useful in studying the basic mechanics of lateral relief while investigating the sensitivity of results to different geologic and mining parameters using controlled numerical experiments. It was shown that failure of rocks near an entry results in redistribution of horizontal stress and shifting of the stress to deeper horizons both in the roof and floor. Within the relief zone, the maximum far-field stress is significantly reduced, locally to near-isotropic conditions. Horizontal relief is most effective in laminated rocks with low shear-strength properties. The width of the relief zone is significantly influenced by the height of the softened or cave zone and the rock mass properties. Because of the interdependence of cave height, rock mass properties, and panel layout designs, it is difficult to develop general guidelines for effective implementation of the advance-and-relieve method without additional field studies and numerical modeling. Practical implementation of this method also depends on the spatial distribution and thickness of interbedded rocks with low shear-strength properties, and excavation timing and sequence.

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