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HORIZONTAL STRESSES AS INDICATORS OF ROOF STABILITY

J.F.T. Agapito and L.J. Gilbride
Agapito Assocs, Inc
Grand Junction, CO

ABSTRACT

High horizontal stresses were recognized to impact roof stability more than 60 years ago. Since then, numerous measurements associated high horizontal stresses with difficult ground conditions. This paper presents case histories illustrating the practical usage of roof stress determinations for helping assess stability, not only in the case of high horizontal stresses but also of low stresses. Examples are given of high stresses associated with faults, mine design changes, quantification of stress shadow effect, and anistrophy. The paper concludes with a comparative evaluation on the effect of various stress fields on ground support requirements.

INTRODUCTION

The critical role of horizontal stresses in mine stability gained visibility in the first half of the last century. High horizontal stresses were recognized as causes of sudden failures, including violent bursts, at shallow depths. Subsequent stress measurements helped quantify these observations, showing horizontal stresses much higher than vertical stresses in many areas of the world.

Linkage of high horizontal stress to ground control problems highlighted the need for a better understanding of the role of horizontal stress (both high and very low) in mine stability. It helped in the further application and development of improved stress control, mine design, and ground support.

This paper is focused on the roof stability of mines in flat-bedded sedimentary deposits. It has two major objectives:

1. Review the role of roof horizontal stress measurements in stability evaluations.
2. Compare the role of ground support in high and low horizontal stress fields.

Overcoring measurements made during the last 30 years by Agapito Associates, Inc., (AAI) personnel provided the data for the review. The ground support evaluation was based on a comparative analysis using a distinct element model capable of simulating roof collapse.

RECOGNITION OF HIGH HORIZONTAL STRESS STABILITY PROBLEMS

Evidence of stability problems due to high horizontal stresses was obtained from sudden fracturing and rock bursting at shallow depths where vertical stresses were low. White (1946) documented some of these failures in granite quarries. Spalling of corners of larger rock blocks would occur soon after being freed on three sides from the rock mass. Crushing of the webs of holes drilled at close spacings due to expansion of the rock suggested high horizontal stresses. Bird (1942) describes bursts at less than 150-m depth during tunneling in massive granite. The existence of high horizontal stresses was linked to nearby thrust faulting and tight folding.

These and other observations gave credence to the existence of high horizontal stresses greatly exceeding vertical stresses. Later stress measurements confirmed and quantified the high horizontal stresses.

In the Kolar Gold Field, India, high horizontal stress had long been regarded as the cause of bursting at depths of only 150 m. Stress measurements showed horizontal stress greatly exceeding the vertical stress (Isaacson 1957). Measurements in igneous and metamorphic rocks indicated widespread horizontal stress, as much as eight times higher than vertical stress (Terzaghi and Richart 1952; Terzaghi 1962).

An extensive review of stress measurements throughout the world found horizontal stress exceeding vertical stress at depths of less than 1000 m, and tending to equalize at greater depths (Hoek and Brown 1980). In the authors' opinion, stress measurements are "essential" in site characterization because of the difficulty in predicting horizontal stress.

One of the earliest mining case histories for sedimentary strata was given by Parker (1966). High horizontal stresses at White Pine, a copper mine in Michigan, were recognized from observations of low-angle shear failure (cutters) near the roof corners of entries, crushing at mid-span, and lateral offsetting of strata in roof bolt holes. Failures seemed more prevalent in certain directions and occurred mostly in development. Overcoring measurements showed average horizontal stresses of 13.8 MPa at a depth of 150 m. Mapping of roof geology linked the orientation of certain joints and faults with the maximum (P) and minimum (Q) horizontal stress directions. Panel orientation and other mine design changes were introduced for better stress control. Measurements made during the next 25 years showed consistent high horizontal stresses, with steeper depth gradients than vertical stresses, and P oriented most in a northeast direction (Agapito and Litsenberger 1993).

Overcoring measurements by the U.S. Bureau of Mines in a coal mine in south-central West Virginia indicated that high horizontal stresses were probably the major cause of ground problems in the mines of this region (Aggson 1978a, 1978b). The U.S. Bureau of Mines commissioned an extensive study of horizontal stress determinations in the Beckley Seam in these mines (Agapito et al. 1980). Numerous overcoring measurements made in five mines confirmed the presence of high horizontal stresses, three to five times higher than the calculated vertical stresses. The direction of P was parallel to major structural features of the region.

During the last 20 years, the role of high horizontal stress in coal mine stability was further investigated. A review of longwall mine design for control of high horizontal stresses found that more than 20 years after recognition of their impact, the industry seldom considered horizontal stresses in mine design (Mark and Mucho 1994). This was found "perplexing" since some mines had been forced to close because of stability problems caused by high horizontal stresses. Three major symptoms of high horizontal stress effects were compressional roof failure (cutters), roof falls in predominant directions, and more ground problems in headgates as compared to tailgates. This study also reviewed the effectiveness of stress control techniques, such as panel orientation, cut sequence, stress shadowing, and the use of high-strength roof support.

Recent studies have evaluated best panel orientations (Su and Hasenfus 1995; Mark et al. 1998), roof support performance (Mucho et al. 1995), stress shadowing (Dolinar et al. 2001), and advancing greater percentage of headings in the most favorable direction, including using a wedge-shaped mining front (Iannacchione et al. 2001).

LEARNING FROM MINES WITH HIGH HORIZONTAL STRESS PROBLEMS

Significant information was gained from horizontal stress measurements in mines with stress-related ground problems. Measurements in two previously mentioned areas — the White Pine Mine, Michigan, and the coal mines in south-central West Virginia — were chosen to illustrate this point.

The types of failure in both areas have been described in previous papers (Parker 1966, 1973; Aggson 1978a, 1978b). One of the most severe problems was the occurrence of high roof falls with little or no warning. These falls occurred in laminated (thin) strata and could be more than 6-m high by 45-m long. Aside from obvious safety issues, their impact to operations was major, especially if located in major travel/airways, conveyor belt entries, etc. Figures 1 and 2 show two such roof falls from both mining areas. In Figure 1, the fall occurred in a conveyor entry. The high arch and laminated strata are clearly seen. The fall was being cleaned up and the ground stabilized with steel sets, bolts, and mats. Figure 2 has been shown in previous papers and shows typical cutter failure in laminated strata and a high arch.

Figure 1. Dome of White Pine Roof Fall

Figure 3 shows the last three profiles taken in the White Pine Mine a few years before it was shut down, in great part due to ground control problems. Profiles A and B were taken at depths of 685 and 625 m, respectively, and at a distance of 8 km from each other. Reasonably good agreement in magnitude and direction was obtained between the holes. P is on the order of 33 to 41 MPa, and Q is 9 to 20 MPa. Average direction of Q is N82°E in Hole A and N70°E in Hole B. Most of the previous measurements showed a northeast direction. The third profile (C), at a depth of 700 m and about one km from Profile B, shows higher stresses, with P varying from 43 to 56 MPa and Q from 31 to 40 MPa. A consistently different orientation, with P at N66°W, and small variation between measurements was obtained. The large difference in stress directions from most other holes was at first (hopefully) thought to be due to instrument or calculation error, but having found none, the "anomalous" direction was attributed to a nearby fault system and/or proximity to an abutment pillar (Agapito and Litsenberger 1993). P/vertical stress ratios varied from 2 to 3.

All the overcore logs showed considerable disking, indicative of high stresses (Figure 3). In addition to the fracture logs, a core photograph from Hole A clearly shows disking.

Three common profile shapes, due to different stress distributions, are illustrated in Figure 3. Profile A shows three stress distribution zones: (1) a zone of lower stresses near the roof line due to geologic discontinuities, stress, and blast-induced fracturing; (2) a zone of higher stresses due to effect of the opening; and (3) a zone with low or no disturbance, with stresses at or near pre-mining levels. In Profile B, Zone 2 occurs very near the roof line because the rock was a very competent, high modulus siltstone, with few discontinuities and fractures. Profile C shows mostly Zone 3 because measurements in the other two zones were not possible due to disking.

Figure 4 shows a stress profile taken in the West Virginia mine where the roof fall shown in Figure 2 occurred. Bed parting and stress-induced disking prevented measurements in the lower portion of the hole near the roof. This was typical in other holes. Measurements were obtained mostly in Zone 3. Mine-wide and district-wide stress ellipsoids are also shown in Figure 4. Good statistical correlation among individual measurements was obtained, indicating the presence of a fairly consistent horizontal stress field. The district average for all the mines was P = 22.5 MPa oriented N64°E and Q = 17.5 MPa oriented N26°W (Agapito et al. 1980). The district average P/vertical stress ratio was 4.

The above, and subsequent measurements in other mines with high horizontal stress problems, suggests that a rough guideline indicating ground control problems may be given by using the ratio of the laboratory uniaxial compressive strength (UCS) and the measured horizontal stresses at a given horizon. Significant roof problems seem to begin at UCS/horizontal stress ratios of 5 and become critical at ratios of 2.5 or lower. For example, similar UCS/horizontal stress ratios of 2.7 were obtained from Profiles A and B and a ratio of 1.6 was obtained in Profile C in Figure 3. Ratios of 2 to 5 occurred in the West Virginia mines. Ratios in laminated rock can be much lower than calculated because of lower strengths parallel to bedding. Stress is usually applied perpendicular to bedding in UCS testing of core from flat-bedded strata.

VERY LOW HORIZONTAL STRESSES SELDOM CONSIDERED

The effect of very low horizontal stress on roof stability has been recognized for many years, but it is seldom considered in underground mines. Yet, there are geologic settings when the horizontal stresses are very low and gravity-type, block falls occur with little warning. In this case, stability relies on the strength of joints and other discontinuities. Often the presence of these features is unnoticed until the falls occur.

Figure 2. Beckley Mine Roof Fall

Foreknowledge of very low horizontal stress is important. It indicates a higher probability of roof falls, especially in areas of high joint density, and allows a better usage of ground supports.

Figure 5 shows two stress profiles taken at approximately the same depth of 275 m in an oil shale (marlstone) mine. Stability was very marginal due to undersized pillars and blasting damage (Agapito 1986). Profile A was taken after a pillar at a distance of 8 m had failed and a roof fall at a distance of 20 m had occurred. Stresses varied between low compression and tension. Only at a depth of 6 m did the horizontal stresses reach an adequate value to provide reasonable confining stability. The whole profile seems indicative of a Zone 1-type stress distribution. The overcore log shows extensive fracturing in the first meter, where measurements were not possible, and three major bed separations (the deeper at 5 m). Roof bolts would have to be 6+-m long to provide a reasonable suspension of the broken rock mass.

The three-dimensional stress field consisted of a major stress, consistent with the gravity overburden load, and two horizontal, minor principal stresses approximately equal and very low magnitude (1.2 and 1.9 MPa). The location of the mine near a canyon wall may explain the very low horizontal stresses. It is likely that the horizontal stress would increase further into the mountain. Similar and consistent low horizontal stresses were also measured in another mine at a distance of 5 km located near canyon walls.

The gravity-type roof falls in the mine showed no preferential orientation and tended to be more circular than the elongated falls in high horizontal stress mines. The fallen rock pile showed larger blocks as well, and the arch height was generally lower, as shown by a 4-m height in Figure 5. However, higher roof falls (6+ m) occurred in the other mine due to the presence of long, steeply inclined joints.

The Profile B in Figure 5 is shown for comparative purposes. The measurements were made in a stable area before crosscuts were made and pillars formed. Higher stresses measured from 0.5 to 2 m above the roof indicate a Zone 2 stress distribution. After a depth of 3 m, the stresses remained near the pre-mining stresses (Zone 3). The log showed no bed separations and less fracturing.

EXAMPLES OF HORIZONTAL STRESSES AS STABILITY INDICATORS

Measurements are important in establishing the existence of high or low horizontal stresses, and in providing critical information for stress control design, ground support, and evaluation of stability problems. The following are some examples.

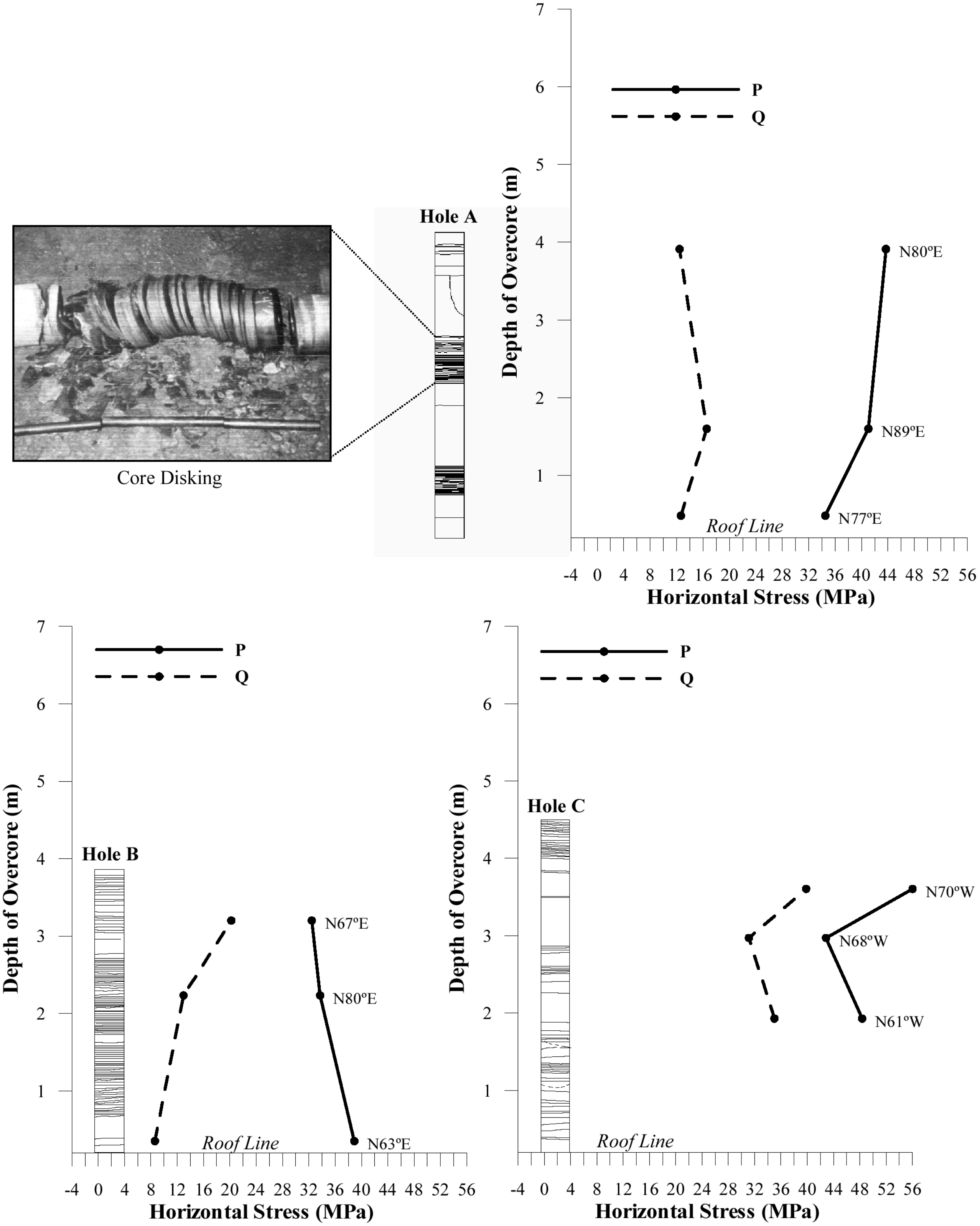

Figure 3. Roof Stress Profiles, White Pine Mine

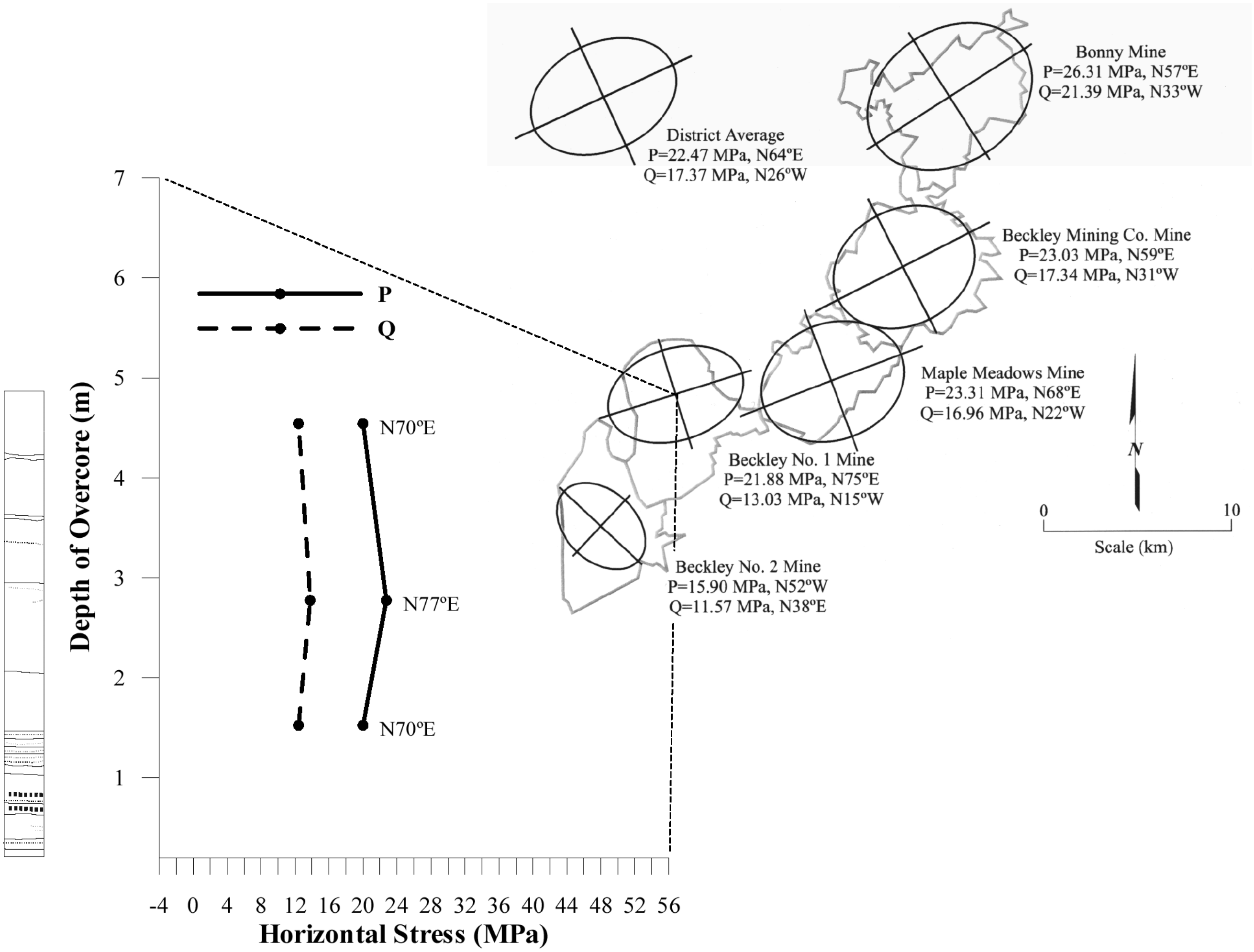

Figure 4. Typical Roof Stress Profile and Stress Ellipsoids, Beckley District

Stresses associated with faults

There is extensive evidence showing that both high and low stresses are associated with many faults and other geologic structures, such as channels. Abnormally high stresses have been linked to faulting in many areas of the world. Extensive ground problems in Utah coal mines, due to high stresses near fault zones, were described by Peperakis (1958). Parker (1966) mentions a 31 MPa horizontal stress measurement at a depth of 150 m near a fault. Anisotropic stress conditions from overcoring measurements suggested the influence of a local fault zone in producing an increase in directional roof failures in an Illinois coal mine (Ingram and Molinda 1988).

Recent overcoring measurements across a graben fault system in a coal mine in Utah showed the occurrence of abnormally high horizontal and vertical stresses, and low vertical stress (Goodrich et al. 1998). Figure 6 shows the longwall panels, the graben, and three horizontal stress ellipsoids from various areas of the mine. The abnormal anisotropic stresses, with a high east-west component in the graben, contrasts significantly with lower isotropic conditions in the other areas. Horizontal stresses in area B were as high as 18 MPa, compared to about 6 MPa in the other three areas. The results of the measurements were used in a stability analysis of the longwall retreat across the graben, which indicated the possibility of high closure and difficult ground conditions. Longwall mining operations across the graben were accomplished with high amounts of floor heave in the tailgate.

These and other examples indicate that anomalous stresses associated with local geologic structures are probably widespread and can cover large mining areas. They can impact mine stability and increase operational costs significantly.

Change in mine design

Another application of horizontal stress measurements was in helping determine roof stability after entries were widened and yield pillars adopted in a trona mine (Agapito and Hunter 1989).

Figure 7 shows a profile taken at the center of a 9-m-wide conveyor intersection. The measurements taken at a depth of 260 m showed that adequate compressive stresses had be retained for good stability. No tensile stresses had been introduced as a result of a 30 percent increase in roof span, and no significant fracturing occurred in the overcore. Stresses at 2.5 m are close to pre-mining values. A decrease in stresses at 2 m is probably due to a softer, fine-grained mudstone interbedded with shale and trona. Stress distribution Zones 1 and 2 seem to occur close to the roof and are of low magnitude, maybe because of pillar yielding.

Most of the roof falls in the mine are shallow (2 m or less), gravity-blocking types (Figure 7). A few larger and quite different types of roof falls occurred in a mine area with gas pockets. These falls at first seemed to have been due to rock stresses. However, measurements made in close proximity to falls found no high horizontal or vertical stresses, and indicated that gas pressure was the major cause of the failures.

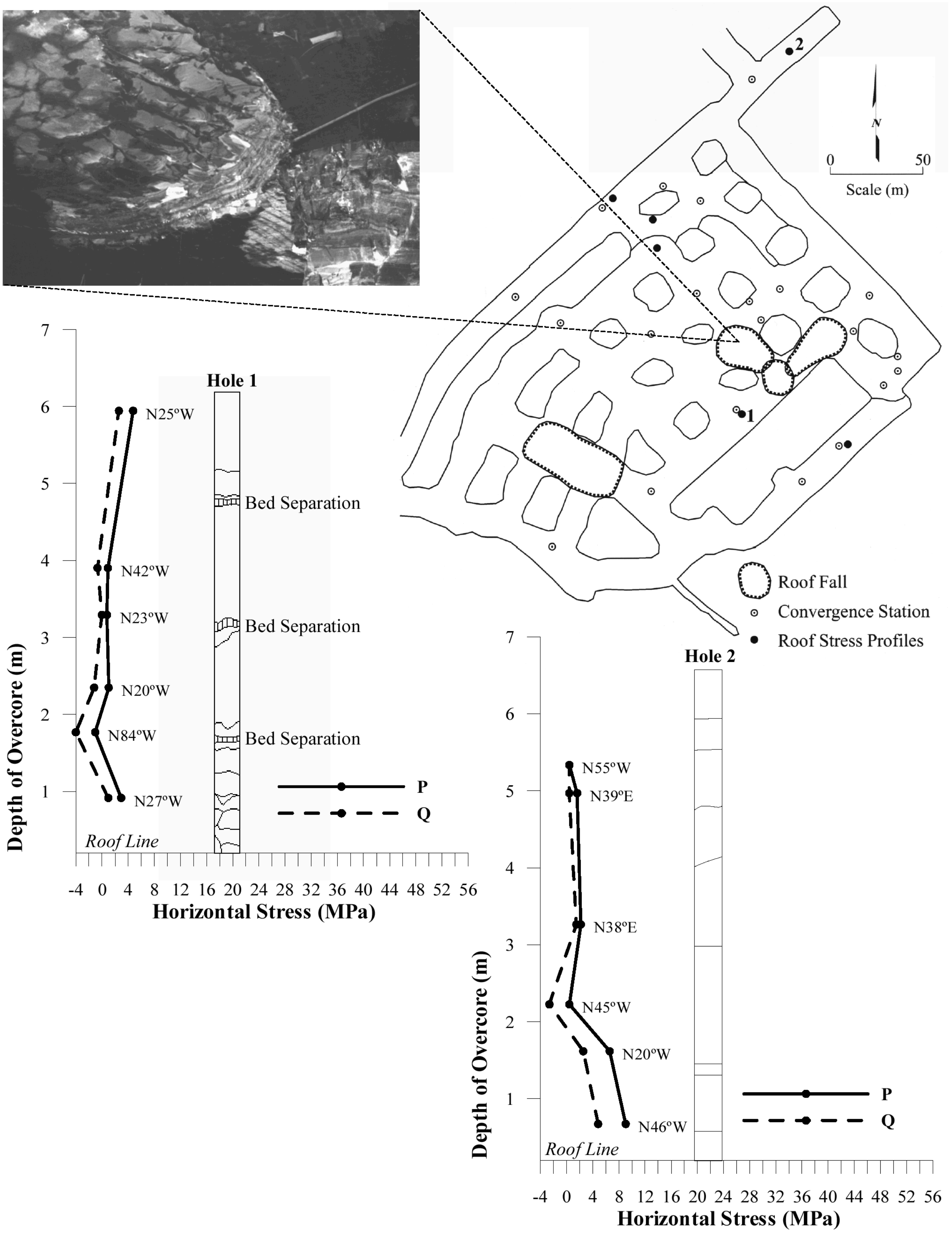

Figure 5. Roof Stress Profiles, Colony Mine

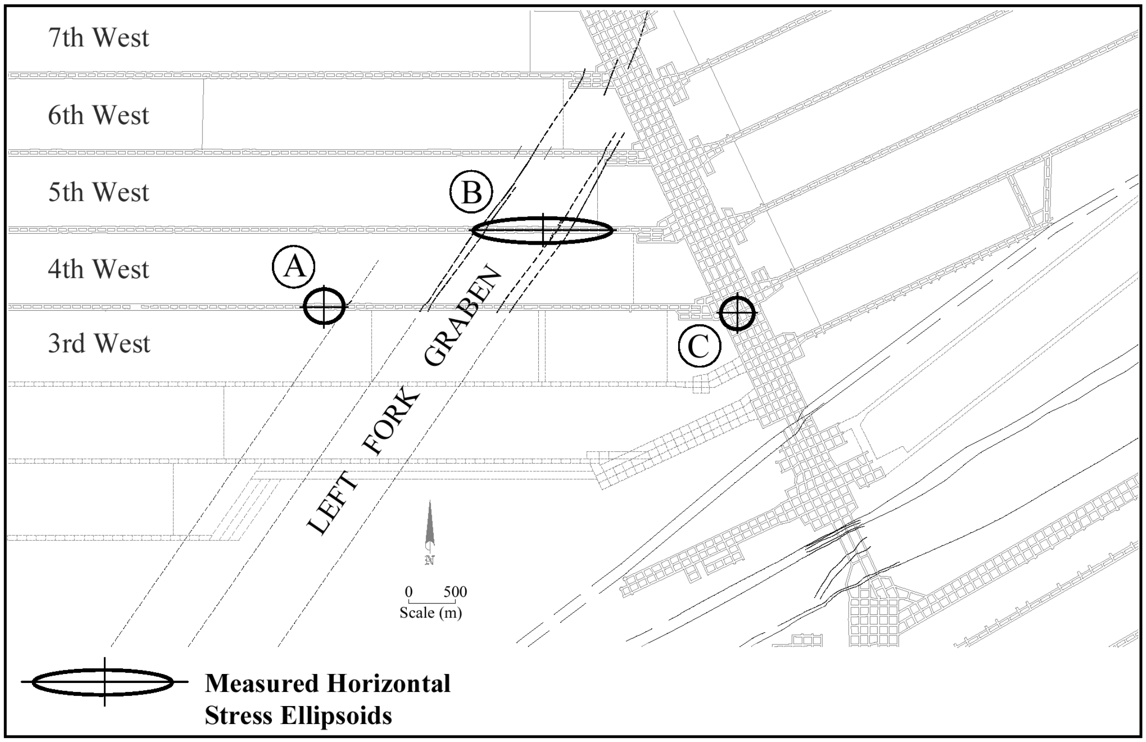

Figure 6. Horizontal Stress Ellipsoids in a Utah Coal Mine

Quantification of stress shadow effect

Horizontal stress measurements were used to verify the extent of a stress shadow (stress relief) area established by a central arched entry of a three-heading development in a West Virginia coal mine with extreme cutter problems (Aggson 1988). Cutters had been almost eliminated in the two adjacent headings after adoption of the central arched entry.

Figure 8 shows the stress shadow as much lower horizontal stress in Hole 2 as compared to Hole 3. The arch in the central Entry 2 disrupted the transmission of high horizontal stresses in the roof on Entry 1, thereby eliminating most of the ground control problems. The overcore measurement verified that the roofs of the outside entries were within the zone of stress relief created by the arch.

Anisotropic horizontal stress effects

Significant anisotropy occurs when P ≥ 3Q. Under these conditions, a “mix” of the disadvantages of high and very low horizontal stresses can exist. A low Q can allow block fall-outs and a high P can produce cutter failures. Shearstrengths tend to be lower than in more isotropic stress fields and long, high-dome roof falls can happen.

Stress determinations in the North Fork Valley coal mines in western Colorado have shown the existence of high anisotropy in many measurements. Figure 9 shows a horizontal stress profile from one of these mines. The measurements were taken in a gateroad at a depth of 625 m before retreat longwall mining began. The profile shows the three previously discussed stress distribution zones; a lower P of 14 MPa (Zone 1), increasing to a maximum 24 MPa (Zone 2), and then decreasing to 19 MPa (Zone 3). The average P/Q (anisotropy) ratio is 4.6. P is nearly parallel to strike-slip faults encountered in the mine. These faults seemed to have been formed by northeast oriented forces caused by the intrusion of a pluton into the sedimentary strata. The faults in the mine have little or no surface expression, indicating that they were initiated at depth as the pluton penetrated the sediments. Vertical stresses were also measured and are identical to the calculated overburden stresses.

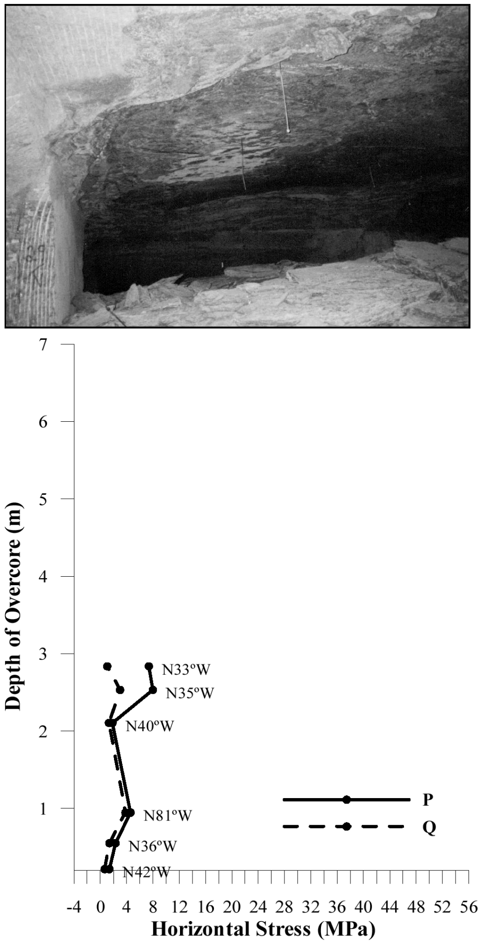

Figure 7. Roof Stress Profile and Typical Fall in a Wyoming Trona Mine

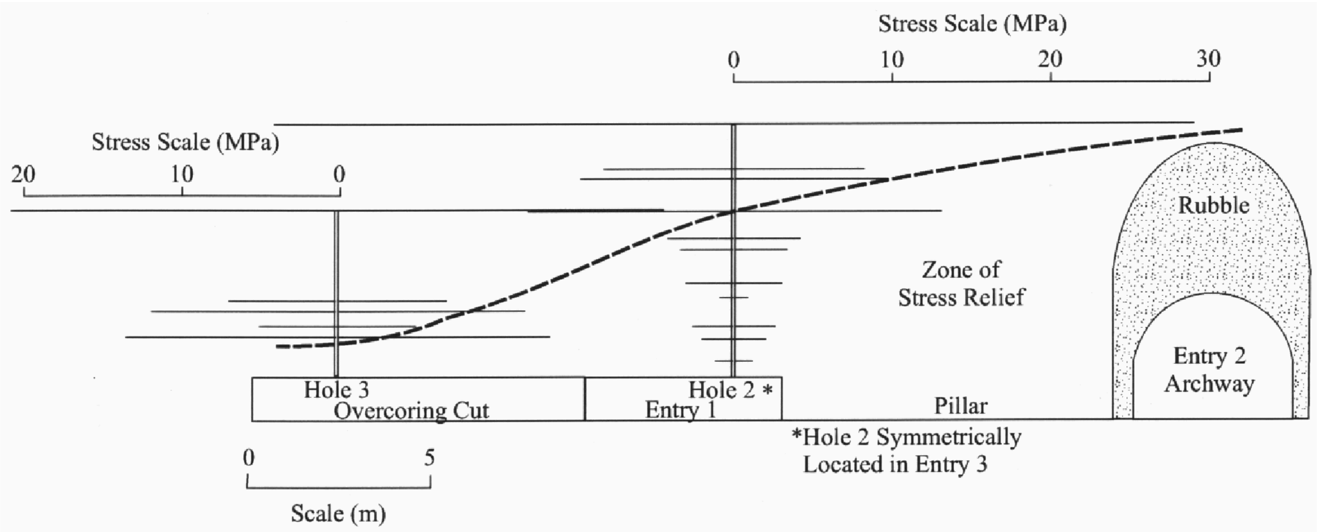

Figure 8. Illustration of Stress Shadow Generated by an Arched Entry, West Virginia Coal Mine

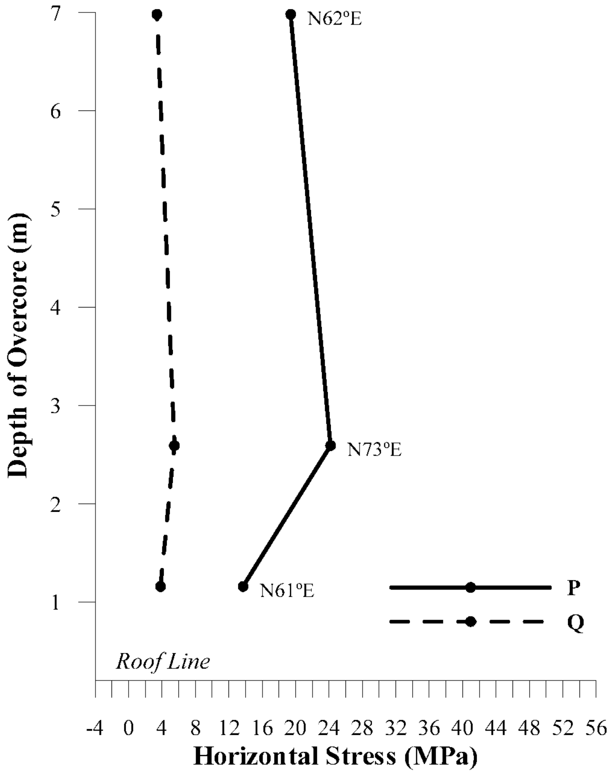

Figure 9. Roof Stress Profile Showing High Anistrophy, Colorado Coal Mine

COMPARISON OF STRESS FIELD ON GROUND SUPPORT REQUIREMENTS

A good understanding of the *in situ* stress field combined with knowledge of rock mass properties and structure is key to the proper design of ground support. While such data are often scarce, their value to the design engineer should not be overlooked. This is particularly true for knowledge of horizontal stresses, which can control requirements for ground support in some circumstances. To demonstrate this point, a comparative analysis of ground stability and support requirements was conducted using the distinct element code UDEC (Itasca 2000).

For analytical purposes, a single two-dimensional plane strain model of a rectangular opening featuring a laminated and vertically jointed roof was constructed. The model geometry and material properties are shown in Figure 10. Pre-mining vertical stress was initialized to 11.4 MPa at the mining horizon, representing a nominal depth of 457 m. Pre-mining horizontal stresses were varied from mild tension to compression three times greater than the vertical stress to analyze their influence on roof stability.

Stable conditions were achieved in the model for a hydrostatic stress state, i.e., where horizontal and vertical stresses are equal. As shown in Figure 10, no plastic failure occurred in the roof at this stress level. The destabilizing effect of increasing horizontal stress is illustrated in Figures 11 and 12, which show the extent of roof collapse associated with horizontal stresses two and three times the vertical stress, respectively.

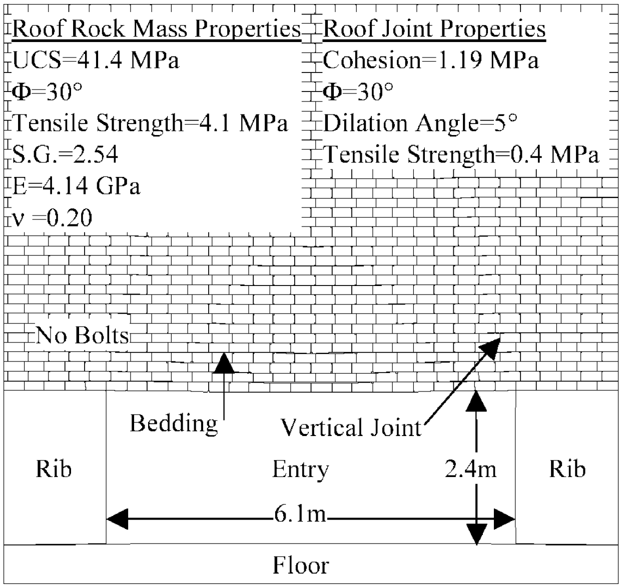

Figure 10. UDEC Model—Stable Roof Conditions for Mining in a Hydrostatic Stress Field

A variety of ground support alternatives were tested with the model. Figure 13 shows that stable conditions were achieved with a four-bolt pattern when horizontal stresses were less than two times the vertical stress. However, this same design failed when horizontal stresses were increased to three times the vertical stress, as illustrated by Figure 14. Figure 15 shows that stability can be achieved by upgrading to longer and larger diameter fully-grouted resin bolts. Other successful support designs are also possible.

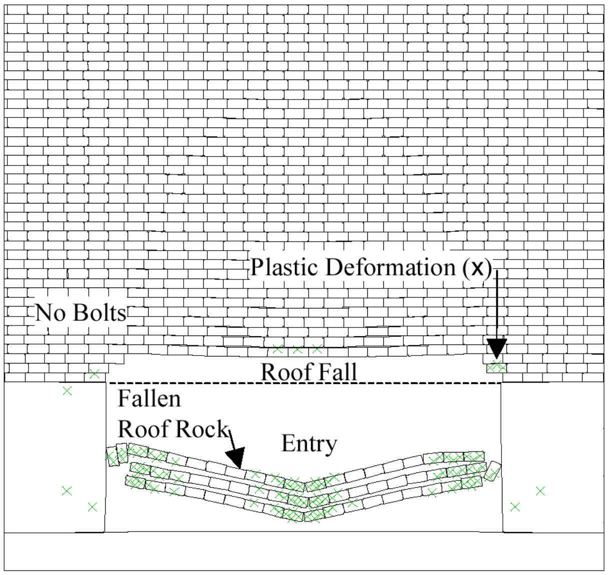

Figure 11. Roof Collapse Associated with a 2:1 Horizontal to Vertical Stress Ratio

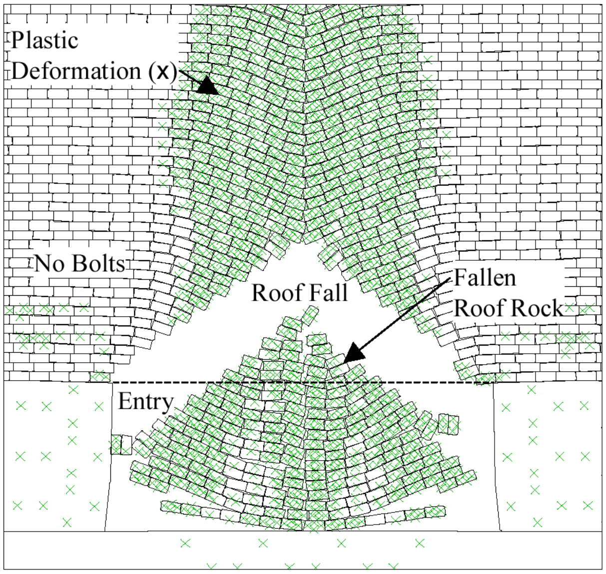

Figure 12. Roof Collapse Associated with a 3:1 Horizontal to Vertical Stress Ratio

Low horizontal stresses can also be problematic. Figure 16 shows tension-induced roof collapse where horizontal stresses are mildly tensile (P = -1.1 MPa), as possible near an outcrop or a fault. Substantial roof support is required to achieve stability. As shown in Figure 17, angled bolts are effective for reaching a stable anchorage over the ribs. Additional bolts are necessary near the center of the entry to preserve the self-supporting capacity of the roof.

These analytical examples illustrate the point that horizontal stresses, when known, can be a particularly meaningful indicator of roof stability and can facilitate intelligent support design. Bearing this in mind, the authors wish to emphasize the value of investigating and accurately interpreting stress conditions, even if only to confirm favorable ground conditions.

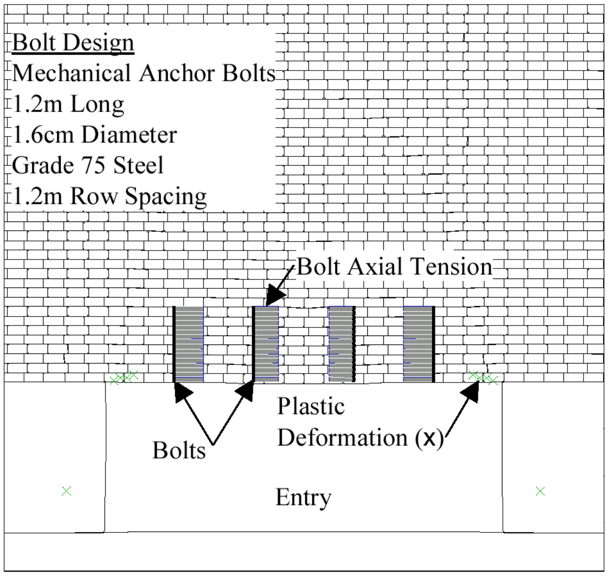

Figure 13. Stable Roof Support Design for a 2:1 Horizontal to Vertical Stress Ratio

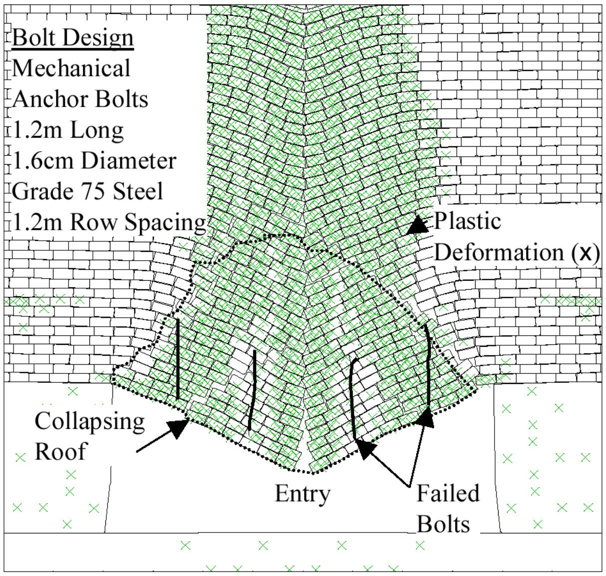

Figure 14. Unstable Roof Support Design for a 3:1 Horizontal to Vertical Stress Ratio

CONCLUSIONS

Horizontal stress measurements in the immediate roof give insight into roof behavior and are very useful stability indicators. They help with a better understanding of many ground control problems by providing information on the existence of very low or very high stresses, establish the need and verify the effectiveness of stress control methods, and provide a rational basis for opening and ground support design.

A comparison of stress fields or ground support requirements showed the important role of including the measurement data in the design. Roof instability under some stress conditions may be avoided if the immediate roof stresses are taken into consideration in the support design.

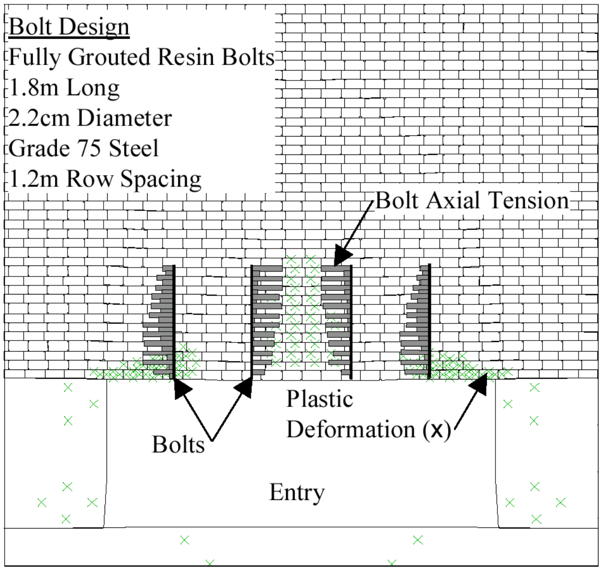

Figure 15. Stable Roof Support Design for a 3:1 Horizontal to Vertical Stress Ratio

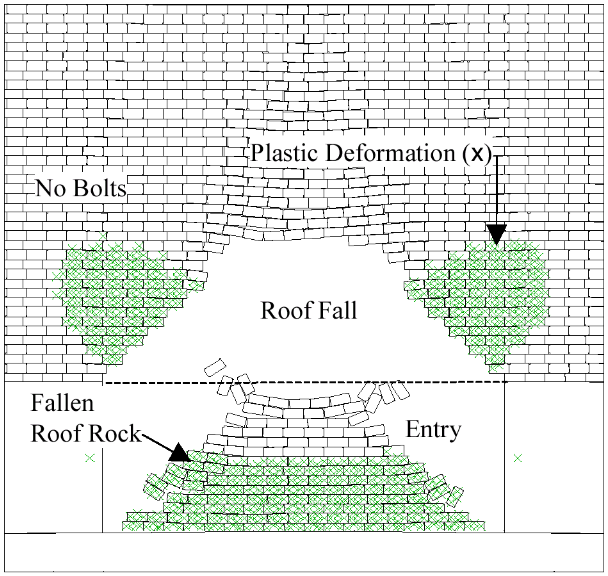

Figure 16. Roof Collapse Associated with a Mild Tensile Stress Field (P = -1.1 MPa)

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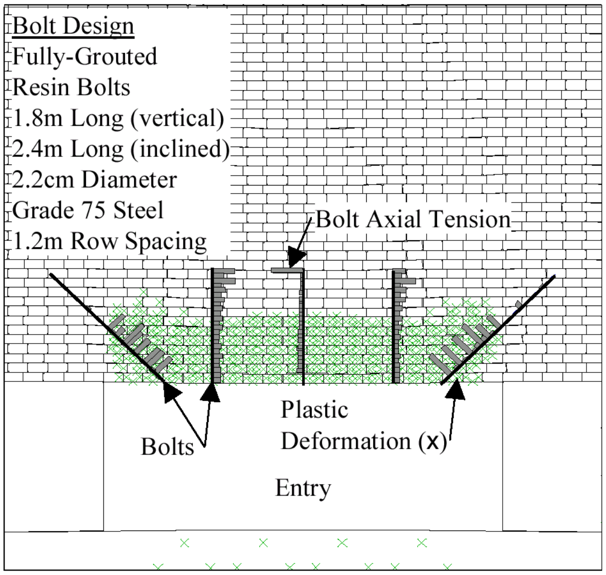

Figure 17. Stable Roof Support Design for a Mild Tensile Stress Field (P = -1.1 MPa)

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