Horizontal stress and longwall headgate ground control

C. MARK, T.P. MUCHO AND D. DOLINAR

C. Mark, T.P. Mucho, members SME, and **D. Dolinar** are acting branch chief and mining engineers, respectively, with the National Institute for Occupational Safety and Health (NIOSH), Pittsburgh, PA.

Abstract

Horizontal stresses are caused by global plate-tectonic forces. During 1995 alone they were largely responsible for the closing of two longwall mines in the United States. This paper presents six case histories from Pennsylvania, West Virginia, Kentucky and Alabama. In each case, a mine encountered roof falls or difficult ground conditions at the headgate caused by horizontal-stress concentrations. The problems are detailed, and the control measures adopted are described. In most cases, nearby longwall panels without stress concentrations were trouble free.

The paper also discusses detailed measurements that were made at two adjacent Pennsylvania longwalls. One headgate was oriented to avoid a horizontal-stress concentration, and the other was not. Eliminating the stress concentration dramatically reduced roof support loads and roof deformation.

The paper concludes that proper panel orientation and sequence is the key to maintaining headgate ground control. The optimum orientation is not parallel to the maximum horizontal stress, as previously thought, but rather it is 20° in the stress shadow of the gob. Other stress-control techniques, including artificial support, are briefly discussed.

Horizontal stress

During the past 15 years, horizontal stress has become central to the understanding of coal mine ground control. An important breakthrough was the recognition that the stresses observed in coal mines are caused by global plate-tectonic forces (Mark, 1991). Stress measurements confirmed that, in mines located in the eastern United States, the magnitude of the maximum horizontal stresses are typically three times greater than the vertical stresses (Mark and Mucho, 1994). The horizontal stressfield is biaxial, with the maximum horizontal stress usually about 40% greater than the minimum. In eastern North America, the maximum horizontal direction is typically oriented E-NE (Fig. 1). Near the earth's surface, however, topographic features (such as stream valleys) can influence both the orientation and magnitude of the horizontal stress. Stress mapping procedures have been developed to estimate the direction of the maximum horizontal stress from underground observations (Mucho and Mark, 1994).

The following factors also determine the degree to which horizontal stress will affect ground control:

- Roof type: Weak roof rock is more likely to suffer damage than strong rock, and laminations greatly reduce a roof's ability to resist horizontal stress.
- Entry orientation: Entries that are aligned with the maximum horizontal stress will suffer less damage on development than those perpendicular to it.
- Longwall orientation: Horizontal stress cannot pass through a gob area; therefore, zones of stress relief and stress concentration are created (Fig. 2). Their location depends on the panel orientation, the direction of retreat and the sequence of longwall panel extraction.

Horizontal-stress concentrations are most likely to occur in the headgate or in the tailgate of the first panel. After one panel has been completed, horizontal stresses are largely relieved in the tailgate.

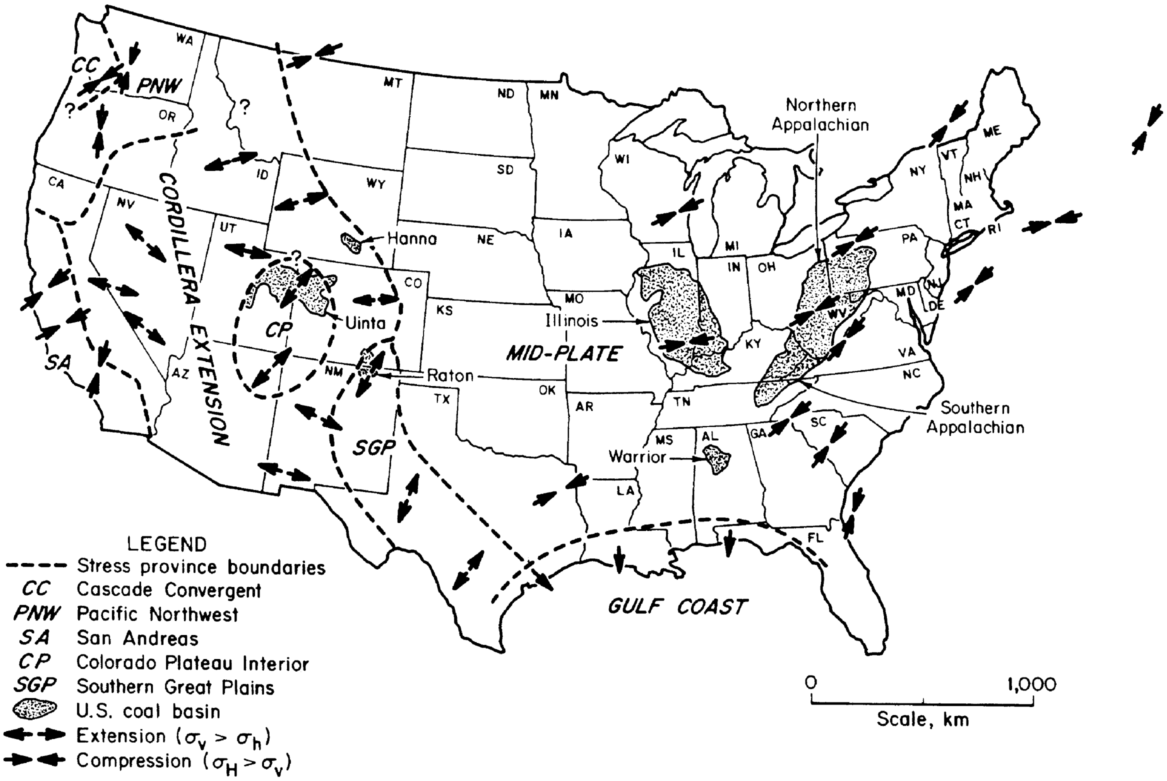
Su and Hasenfus (1995), using three-dimensional finite-element modeling, were the first to quantify the headgate-stress concentration (Fig. 3). Their results may be imperfect because they did not allow for caving or bedding-plane slip, but a framework for analyzing horizontal stress effects was provided. It was found that, when the angle of ϕ (see Fig. 3) is between 0° and 90°, the headgate is in a stress concentration, with the worst case occurring at $\phi = 70°$. The headgate is stress-relieved when $90° < \phi < 180°$, with the best conditions at $\phi = 160°$.

While the concept of the horizontal-stress concentration has been known for some time, it has yet to be fully implemented in mining practice. The result has been extremely hazardous conditions at a number of longwalls. These conditions include:

- exposure to falling rock as miners struggle to regain control of the ground;
- materials handling injuries as miners install extra support or even recover a face in extremely confined conditions; and
- loss of ventilation or emergency travelways, particularly when the instability occurs in a bleeder or first tailgate.

FIGURE 1

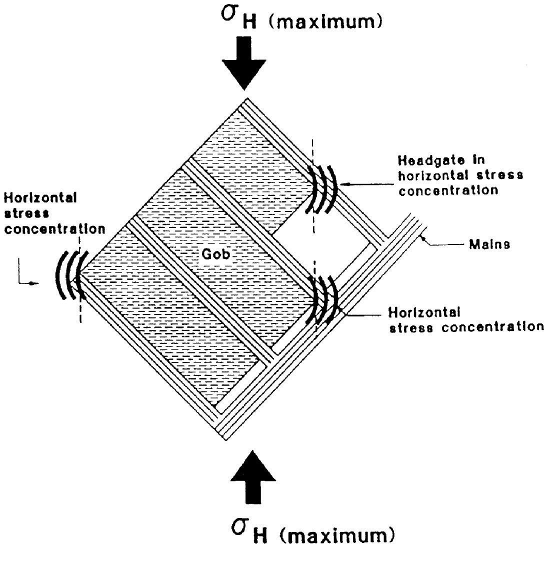
Stress provinces of the continental United States. Arrows indicate orientation of the maximum horizontal stress (after Zoback and Zoback, 1989).



Of course the financial costs of headgate downtime are also substantial. The case histories presented below illustrate the extent of the problem.

FIGURE 2

Horizontal stress concentration caused by retreat mining.



Case histories

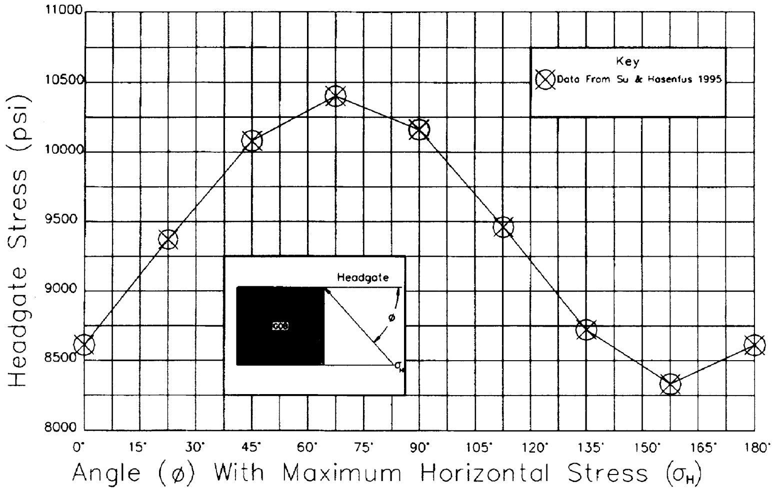
Case history No. 1. Mines A and B are adjacent Pittsburgh seam longwall mines located in southwestern Pennsylvania. The overburden averages approximately 215 m (700 ft) in hilly topography interlaced with stream valleys. The immediate roof rock is comprised of typical Pittsburgh seam sequences of coals and laminated shales. CMRRs range in the high 30s at these two mines. Horizontal stresses can cause occasional development drivage problems — usually associated with stream valleys. However, the more serious problems have been associated with longwall mining and the affects of horizontal stress concentrations. Stress mapping at the mines has determined the horizontal-stress direction to be between N70°E and E-W.

At mine A, the primary longwall ground-control problems have been on the headgate. This is due to the panel sequence (Fig 4) that results in $\phi = 35°$. The effects are usually controlled by the primary support of 2.5-m- (8-t-) long, 13.6-t- (15-st-) capacity roof bolts. Some exceptions to this have occurred when the longwall panel, especially the headgate, has not had some stress relief from an adjacent panel. Notably, this occurred when one normal length panel was adjacent to a panel that had been shortened for subsidence considerations. More recently, headgate problems occurred on a previous record-breaking panel, once the longer panel's headgate appeared from the shadow of the neighboring panel's gob (see Fig. 4).

Interestingly, the headgate-stress concentration can also cause tailgate problems at this mine. This occurs because, while the panel's entries are favorably orientated to the horizontal-stress field, the angled crosscuts of the miner-bolter driven gate road are less favorably aligned. Mild cutters are often formed on the outby rib of the crosscuts during development mining — most generally in the area of final hole-through into the entry. The roof damage is slight initially, but the approach of the headgate often causes it to run through the crosscuts and into the future tailgate entry.

FIGURE 3

Affect of panel orientation on horizontal stresses (Mises shear stresses) calculated by finite element modeling (after Su and Hasenfus, 1995).



Mine B is similarly aligned to the stress field as Mine A, but, because the current panel sequence is opposite that of mine A, the headgate experiences stress-relief conditions during longwall retreat (ϕ = 135°). However, the first panels in this sequence encountered stress concentrations and several major headgate roof falls (see Fig. 4). A recent lengthening of a panel relative to its neighbors produced a "stress window." The severe conditions overwhelmed the original tailgate support and required that the longwall be down about one shift per day while supplemental cable slings were installed.

Case history No. 2. Mines C and D are located in southern West Virginia, and both are extracting the Eagle seam. More than 30 panels were recovered at Mine C without any headgate problems. The roof was supported by 1.2-m- (4-ft-) long fully grouted bolts. The typical roof was a fairly competent shale with rough, moderately-spaced bedding and a CMRR of about 55. The seam is often more than 300-m (1,000-ft) deep, and tailgate ground control has been a major concern.

Stress mapping at the mine indicated that the major horizontal stress is oriented approximately N65°E. The longwalls were oriented N86°E and were sequenced such that they are stress relieved (ϕ = 159°). Recently, mining has commenced in a new set of panels with a less favorable orientation (N47°W, ϕ = 112°). The headgate is still stress-relieved, however, and no problems have yet been reported.

Longwall mining commenced at Mine D in 1995. The geology was very similar to Mine C, except that the depth of cover was about 100 m (300 ft) less. Using Mine C's experience as a guide, the panels at Mine D were oriented E-W, and 1.2-m (4-ft) bolts were used for support. The one difference was the panel sequence, which caused the headgate at Mine D to be in a stress concentration (ϕ = 25°).

Mining had advanced just 800 m (2,500 ft) when 55 m (180 ft) of roof collapsed on the stage loader. The rock had to be shot and then loaded by hand to clear the entry. Six days of hazardous work were required to get the wall moving. A pattern of roof failure developed, with the crosscut failing when the face was 6 to 10 m (20 to 30 ft) inby. Cable trusses were then installed on 1.2-m (4-ft) centers for the remainder of the headgate, and no further major roof falls occurred.

The roof fall over the stage loader occurred beneath a minor E-W stream valley, where the depth of cover was only 150 m (500 ft). A number of mines in the area have associated poor ground conditions with stream valleys, and N-S stream valleys are usually the most troublesome because they concentrate the maximum horizontal stress.

Interestingly, a set of overcoring stress measurements were made in an overlying seam several miles from Mine C (Molinda et al., 1991). There, the maximum

FIGURE 4

Mines A and B (Case history No. 1).

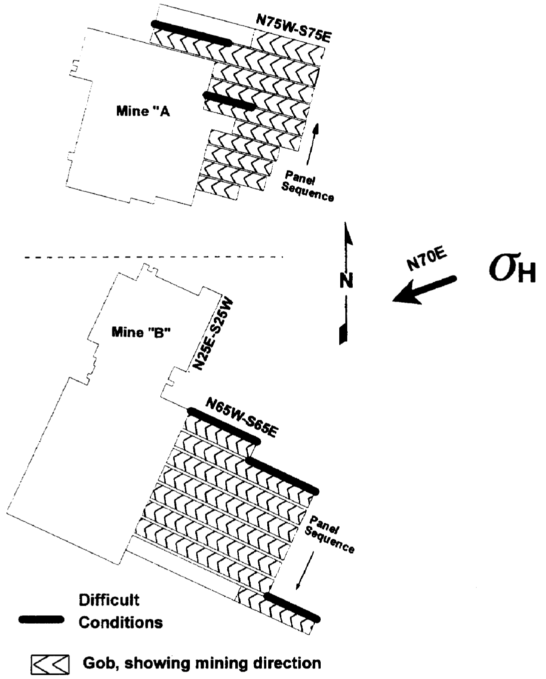
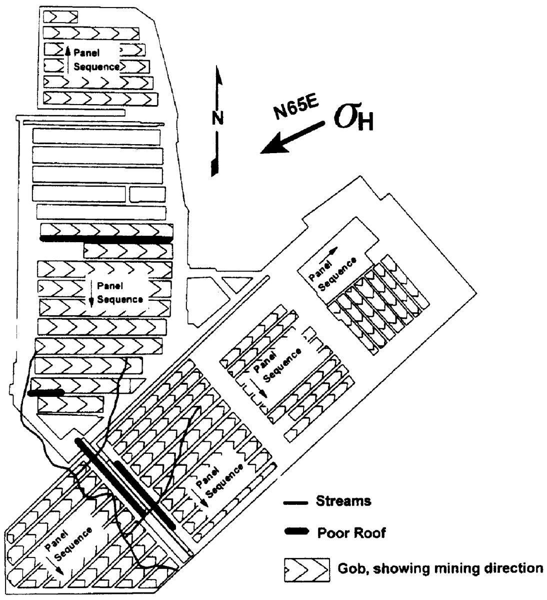


FIGURE 5

Mine E (Case history No. 3)



horizontal stress was N70°W, almost perpendicular to the regional E-NE stressfield observed in Mines C and D. The overlying seam nearly outcrops beneath a broad N-S valley located just 1 km (0.6 mile) from where the measurements were made. It seems likely that the regional stresses were largely relieved by the stream valley. The implication is that, in mountainous terrain, the stressfield will rotate as mining approaches the outcrop. At Mine D, for example, the seam outcrops approximately 1 km (0.6 mile) from the outby end of some planned longwall panels. A completely different stressfield may be encountered there.

Case history No. 3. Mine E is also located in southern West Virginia. Seven sets of longwall panels, totaling more than 50 panels in all, were extracted before 1992 without headgate problems. The depth of cover often exceeds 300 m (1,000 ft), and tailgate ground control has been an issue for the longwall. The roof is typically a semimassive shale with a CMRR of about 50.

Headgate ground conditions deteriorated dramatically on the first panel in the southern set of E-W panels (see Fig. 5). One major roof fall occurred, and a consistent pattern was observed, with unstable roof beginning 15 m (50 ft) after passing an intersection. Following this experience, the headgate primary support bolts were upgraded from 1.8-m (6-ft) resin bolts to 2.4-m (8-ft) "super bolts."

Headgate conditions improved, and the support was reduced as further panels were recovered. The roof again deteriorated when the development of the ninth panel headgate approached a stream valley. When the longwall tried to retreat through the area, the "super bolts" popped, 200 x 200-mm (8 x 8-in.) posts cracked and major roof falls blocked the headgate. After a month of excruciating difficulty, the roof was finally brought under control by 27-t (30-st) cable trusses. The relatively wide, 6.8 m (22 ft), entry may have been a contributing factor.

Mapping at Mine E indicated that the stressfield conforms to the regional trend, oriented approximately N65°E. Panel orientations have been relatively favorable, with some sets oriented E-W and others oriented about N40°E. The headgates in the first seven sets were all stress relieved, with $\phi = 155°$. The eighth set was also E-W, but the sequence placed the headgate in a stress concentration with $\phi = 25°$.

There are numerous other indications of horizontal stress at Mine E. The set-up rooms for the seventh set of panels run parallel to a major N-S stream valley and were extremely difficult to develop. Some submains, also located beneath stream valleys, have also experienced numerous roof falls. Control techniques such as stress-relief headings have been used successfully. The hard, sandy fireclay floor typically fails by buckling, caused by horizontal stress, rather than by heaving.

Case History No. 4. Mine F, located in Alabama, is another veteran longwall mine. In the spring of 1995, a new set of longwall panels was opened with a brand-new set of face equipment. Shortly after retreat mining began, the headgate conditions became, in the words of the headgate operator, "like mining under a roof fall." Posts had to be set under roof bolts to prevent them from injuring workers as they shot from the roof. A cutter would start on the pillar rib, staying about 13 m (40 ft) ahead of the face. When it reached an intersection, the cutter would turn into the crosscut. The top would usually improve briefly after the face passed the intersection, but then the pattern would repeat itself.

The headgate entry had been driven with tight vertical clearance, but up to 0.6 m (2 ft) of roof movement now pinched the stage loader. To allow the face to advance, 150 m (500 ft) of belt was removed every weekend, and the bottom was shot to add height. The panel was completed, fortunately without any serious injuries to personnel. The bottom line was not so lucky. The cost was estimated at about $1 million due to lost production, labor for entry maintenance and extra rock at the cleaning plant.

Conditions improved on subsequent panels. One important change was that the headgates were developed with extra clearance. Another was that the trusses, which are installed on 1.2-m (4-ft) centers, were beefed up from 16 to 19 mm (5/8 to 3/4 in.). The roof geology may have also improved. On the first panel it was a stack rock of thinly interbedded sandstone and shale. The rock had a CMRR of 43. Later, it appeared less laminated with a CMRR of 50. The stress relief provided by longwall gobs may also have been significant. The last 150 to 300 m (500 to 1,000 ft), when the panels emerge from the stress shadow, were reported to be significantly more difficult.

Mapping indicated that the maximum horizontal stress is oriented N60°E at Mine F, which corresponds to other observations in Alabama (Mucho and Mark, 1994). These longwall panels were oriented N13°E, and were sequenced so that the stress was concentrated in the headgate ($\phi = 47°$). The previous set of panels were oriented N40°E, and they were, therefore, in a less severe stress concentration ($\phi = 20°$). Headgate ground control was not a major concern on the earlier set of panels. The depth of cover is about 200 m (650 ft).

Case history No. 5. Mine G was opened in western Kentucky in the 1970s as a room-and-pillar mine. It operates under about 120 m (400 ft) of cover, with an abandoned room-and-pillar mine located approximately 45 m (150 ft) above it.

A longwall was installed in late 1994. The first face had retreated about 300 m (1,000 ft) when it suddenly encountered a large inrush of water. Mine G had always been dry, and the abandoned upper mine had been dewatered, so there were no preparations for the inrush. The water proved to be just the start of the troubles, however.

While the face was slowed, the roof in the headgate collapsed on the stage loader. Heroic efforts kept the face moving, but the roof collapse followed right along. After retreating just 45 m (150 ft) in two months, the headgate was still blocked by a 45-m- (150-ft) long roof fall. New set-up rooms were driven, the face was recovered and the panel was abandoned.

A number of steps were taken to prevent a reoccurrence. The next headgate was rebolted with 3.6-m (12-ft) bolts and 22-mm (7/8-in.) straps.

The entry width was also reduced by 0.6 m (2 ft), and an impressive water-handling facility was installed underground.

The roof was a weak, laminated black shale with a CMRR of 38. About 1.5 m (5 ft) above the seam, the roof became siltier and the CMRR approached 50. A number of very clear roof pots indicated that the horizontal stress direction was E-W, consistent with other observations from the southern portion of the Illinois basin. The headgate was in a stress concentration, and the longwall was oriented N46°W, resulting in a $\phi = 46°$. Other than the occasional pot, horizontal stress had not previously been noticeable at the mine.

Case history No. 6. Mine H was also located in western Kentucky. It was a longwall mine operating under relatively deep cover (350 m (1,150 ft)). The roof was a thinly laminated black shale and was very troublesome due to horizontal stress. Many large roof pots limited cut lengths and slowed development, particularly in N-S drivages.

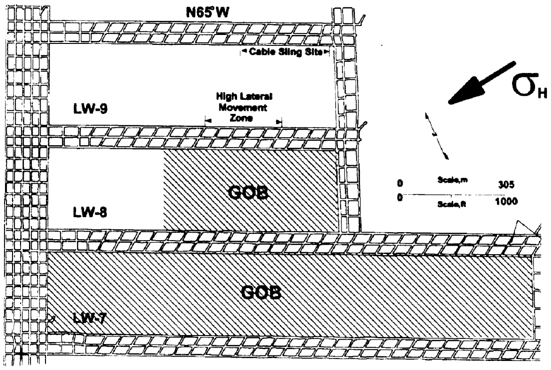
Unfortunately, the longwalls were oriented so that the headgates were always in a stress concentration. In response to the severe conditions, headgates were double bolted with the addition of a truss and a pair of 2.4-m (8-ft) bolts. These efforts were not entirely successful, and two panels were abandoned early because of headgate failure.

The panels at Mine H were mined in sets of two or three, with a "breaker gate" left between sets. The first panel in each set was reported to be consistently the most difficult. Within each panel, the roof failure became severe in the last 6 m (20 ft) before each intersection. Observation boreholes were typically closed off by a horizontal movement of 45 m (150 ft) in front of the face.

In 1995, a longwall was installed in Mine I, a sister mine working an overlying seam. The roof in Mine I is also quite weak, a slickensided mudstone with a CMRR of 45. It has been plagued by roof falls, including one recently on a belt line that temporarily shut the mine. The headgate, however, has been a consistent bright spot. The direction of longwall panel retreat was reversed, so the headgate is now stress-relieved. The headgate has encountered no serious problems, and early longwall production was well ahead of budget. Due in part to the success of the new longwall, the troubled Mine H longwall was closed early in 1996.

FIGURE 6

Mine J (Case history No. 7).



Respect for the power of horizontal stress was recently renewed at Mine I. The second panel in a new set of longwalls was extended 450 m (1,500 ft) beyond the first. As the longwall retreated, a "stress window" similar to that at Mine B was created. Extensive supplemental support could not hold the roof, and a 30-m- (100-ft-) long fall finally occurred.

Case history No. 7. Ground-control problems caused by horizontal stress are not restricted to the eastern United States. Mine J, located in northwestern Colorado, has extracted nine panels with varying degrees of roof-control problems in the headgate (Fig. 6). Cutters typically develop just ahead of the face on the pillar side of the headgate entry for a distance about 15 m(50 ft). When the cutter approaches an intersection, it turns down the crosscuts, damaging supports placed along the pillar side of the entry. In some cases, the cutter has moved all the way through the crosscut into the tailgate, damaging the roof and secondary support there (Dolinar et al., 1996).

Conventional trusses have not been able to control the cutter. The truss bolts that anchor in the zone where the cutter develops are damaged, while the cross members are deformed by lateral roof movements. Cable trusses were more successful in controlling the roof, because of their greater flexibility and the fact that they have no critical junctions that can fail from lateral movement.

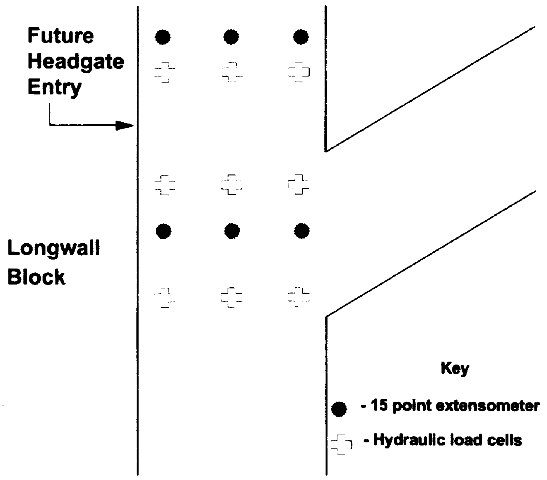
Measurements have shown that the 15 MPa (2,100 psi) maximum horizontal stress at Mine J is oriented N73°E, and that the minimum stress is 10 MPa (1,400 psi) (Maleki et al., 1995). The orientation of the panels is N65°W, with the panels mined in a SE to NW direction ($\phi = 42°$). The degree of horizontal stress damage has been related to the geology of the immediate roof. The critical parameter is the interburden between the mined seam and a 0.6-m- (2-ft-) thick rider seam, which can vary from 0.6 m (2 ft) to 6 m (20 ft). Thin interburden consists mainly of thinly laminated shales or stack rock and is subject to the most damage. When the interburden is thicker, it is primarily sandstone and siltstone, and little or no damage is observed.

Headgate roof behavior in response to horizontal stress

Further evidence of the importance of horizontal

FIGURE 7

Sketch of study sites in headgate entries at Mines A and B showing the approximate location of the instrumentation.



stress to headgate ground control was obtained in a pair of recent field studies. The studies were conducted in headgates at Mines A and B in Pennsylvania. The primary goal was to obtain information on roof-bolt performance for a nationwide NIOSH study (Mucho et al., 1995). At Mine A the study site was in a stress concentration, while at Mine B it was stress relieved.

The entries were developed by miner bolters. Roof bolts were installed in a three-bolt pattern, with rows 1.2 m (4 ft) apart. The outside bolts were installed by the miner-bolter as the entry was cut. The center row was installed by a center bolter approximately 12 hours later (Fig. 7).

Roof bolt loads were monitored by pressure cells consisting of hydraulic bladders sandwiched between steel bearing plates. Roof movements were monitored using multipoint sonic extensometers. The extensometer holes were drilled 4 to 6 m (13 to 20 ft) into the roof and contained 10 to 15 anchors spaced 0.3 to 0.6 m (1 to 2 ft) apart. The close anchor spacing allows roof strain, defined as the movement between any two anchors divided by the initial distance between those anchors, to be determined. Particular attention is paid to roof strains occurring above the tops of the bolts.

The instruments were installed when the sites were first mined, and final readings were taken just before the instruments were covered by the shield tips.

At Mine A, the primary headgate roof supports consisted of two-piece, grade-75, resin-assisted mechanical anchor bolts that were 2.4-m (8-ft) long and 18-mm (3/4-in.) diameter. Bolts from two manufacturers, designated as "X" and "Y," were compared. The most obvious difference between the two bolts was that the "X" bolts used 0.6 m (2 ft) of resin, while the "Y" bolts used only 0.3 m (1 ft) of resin with a compression ring.

The following four bolting systems were compared in consecutive intersections at Mine B:

- 1.5-m- (5-ft-) long resin bolts with a row spacing of 1.4 m (4.5 ft),
- 1.5-m- (5 ft-) long resin bolts with a row spacing of 1 m (3 ft),
- 1.5-m- (5 ft-) long resin-assisted tensioned bolts with a row spacing of 1.4 m (4.5 ft) and
- 2.4-m- (8-ft-) long resin-assisted tensioned bolts with a row spacing of 1.4 m (4.5 ft).

The fourth bolting system was essentially identical to that employed at Mine A.

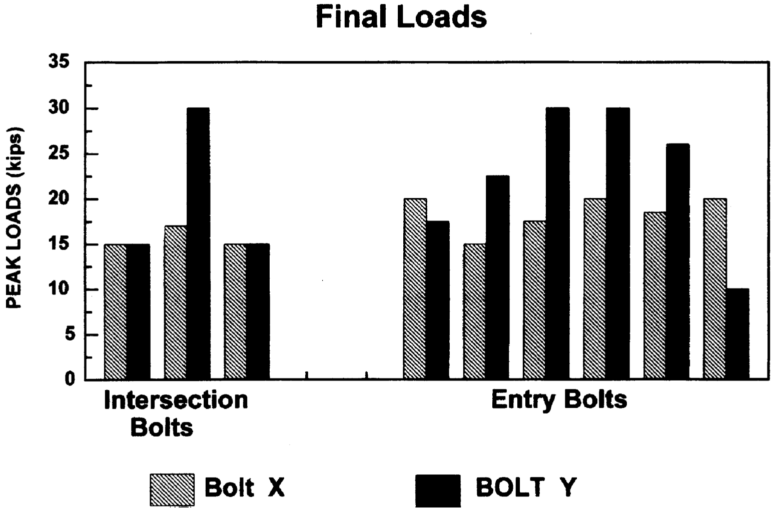
The observed roof conditions appeared to be excellent during both studies. The instrumentation revealed some radical differences, however.

Mine A results. The final loadings on the Mine A bolts are shown in Fig. 8. Several "X" bolts achieved their design maximum load of 13.6 t (15 st), and most continued to increase their load up until the final reading. The maximum load achieved by the "Y" bolts averaged 8.2 t (9 st), but the average dropped to 6.8 t (7.5 st) as the longwall approached. The lower capacity of the "Y" bolts was attributed to anchor slippage due to insufficient resin (Mucho, et al., 1995).

Roof strains measured during the approach of the longwall are shown in Fig. 9. At the "Y" bolt stations, roof strains in excess of 2% were measured at four locations within the bolted horizon. At one intersection location, a roof strain of 6% was measured above the bolts. The "Y" bolts apparently began to lose control of the ground as the horizontal-stress

FIGURE 8

Final loads measured on the instrumented bolts at Mine A. Bolts are paired by location (i.e., the first pair shows the right-hand intersection "X" bolt compared to the right-hand intersection "Y" bolt.



concentration developed.

Mine B results. At Mine B, very little change in roof deformation and almost no change in bolt load was observed at any of the four sites as the longwall approached. The maximum increase in roof strain averaged a mere 0.2%, and all of this occurred below the bolt horizon. Final loads on the tensioned bolts ranged between 7.3 and 13.6 t (8 and 15 st), considerably less than their 17.2-t (19-st) yield strength. As the longwall approached, some bolts even decreased load slightly (Fig. 10). It appears that relief of the horizontal stress may actually have enhanced roof stability.

FIGURE 9

Maximum roof strains measured during the approach of the longwall at Mine A. The right-hand data shows strains measured within the bolted horizon, and the left hand data shows strains measured from above the top of the bolts.

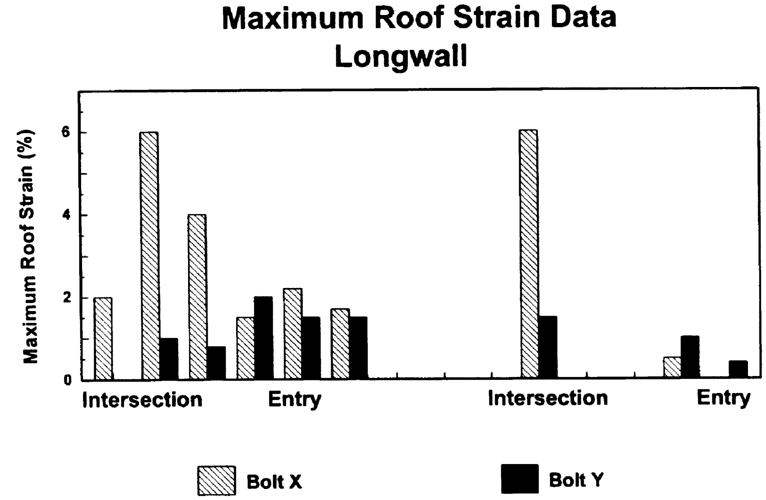
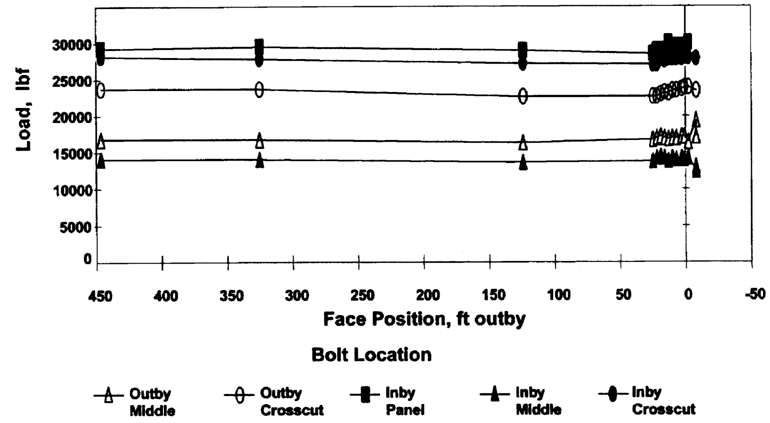


FIGURE 10

Roof bolt loads measured in the headgate at Mine B.



Control of horizontal stress

A number of stress-control techniques have been proposed for longwalls, including:

- **Change panel orientation:** This can eliminate the headgate stress concentration, but it is seldom feasible once the mine has been developed.
- **Change panel extraction sequence:** This can also eliminate the stress concentration, but it may not be possible because of the coal seam's dip and the need for drainage.
- **Reduce entry width:** Because rock load increases by the square of the entry width, narrower entries greatly reduce the support requirements,
- **Angled crosscuts:** Crosscuts aligned with the maximum horizontal stress should be more stable.
- **Three-way intersections:** Replacing four-way intersections is one way to reduce spans. Unfortunately, each four-way requires two three-ways to replace it. The small amount of data available indicates that three-way intersections are about half as likely to collapse, so the incidence of roof falls is about the same.

The remaining strategy is artificial support. In many cases it seems that better primary support can eliminate the problem before it starts. Recent research indicates that increasing the length or capacity of the roof bolts results in improved ground control. An engineered support design focuses support where it is most needed — in the headgate entry (particularly the intersections). Statistics show that intersections are typically ten times more likely to collapse as are entries. Considering what is at stake in a headgate intersection, it doesn't make sense to use the same roof bolts employed at other locations in the mine.

In extreme cases, supplemental support will be necessary. The new cable bolting systems, both vertical and "sling" type, are ideal for headgate applications. These bolts combine high capacity with a reduced stiffness that matches the large deformations that can occur within a stress concentration zone.

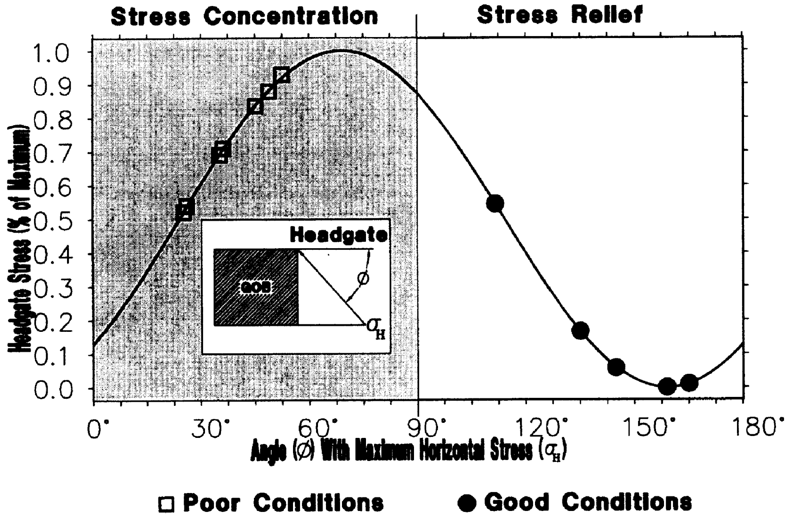
The loss of skin control can diminish the effectiveness of the roof bolts, contributing to larger roof falls. When the immediate roof tends to break apart, many mines use straps to prevent it from falling out between the bolts. Trusses usually provide reasonably effective skin control, unless the roof is highly uneven. The heavy mats recommended for use with trusses also provide effective skin control.

Conclusions

The case histories provide overwhelming evidence

FIGURE 11

Phi (ϕ) angles calculated for all case histories.



that horizontal-stress concentrations are created by full extraction mining. Figure 11 summarizes the data. In every instance in which problems were encountered, the headgate (or tailgate of a first panel) was in stress concentration.

The following other symptoms of a horizontal-stress concentration were identified in the case histories:

- The roof problems occur under lighter-than-average cover, so vertical stress is evidently not a factor.
- The roof in the other gate is in excellent shape, implying it is stress-relieved.
- There is a stream valley above the problem area.
- The problems show a recurring pattern, with each crosscut becoming unstable when the face approaches an intersection.
- The roof is weak, particularly a laminated shale or stack-rock sandstone.
- The panel is the first in a set or lengthening of a panel has created a "stress window."

The most effective control technique is mine design. Proper orientation and sequencing of panels can eliminate the problem before it begins. If a potential stress concentration must be created, then additional primary support should be installed on development. Cable bolt supplemental-support systems are available as a last resort. ■

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