Preventing Falls of Ground in Coal Mines with Exceptionally Low-Strength Roof: Two Case Studies

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ABSTRACT

Mines with exceptionally low-strength roof (UCS <3,500 psi and CMRR <40) are much more likely to struggle with roof falls than other mines. Weak roof is a particular problem for many room and pillar mines in the Midwestern and Northern Appalachian coal basins. Traditional roof support techniques are often not up to the challenge at these operations.

This paper focuses on two mines, one operating in the Upper Freeport seam and the other in the Herrin No. 6 seam. Together, the two mines had more than 300 roof falls during a recent 5 year period. Each has experimented with a variety of roof bolt types and lengths, and with different supplemental supports. Detailed statistical analysis was conducted to determine which support combinations have proven to be most effective. Geology, horizontal stress, and time are also important at both mines. Successful control techniques have included:

- Identifying particularly troublesome lithologic roof units;
- Installing longer and stronger roof bolts;
- Installing supplemental support in intersections, and;
- Limiting the duration that a panel remains open.

The lessons learned from these mines, and others like them, could help improve ground control safety for the entire U.S. mining industry.

INTRODUCTION

Roof falls continue to be one of the greatest hazards in underground coal mines. Although fatalities from roof falls reached an all-time low of two in 2003, more than 1,400 major roof collapses were reported to the Mine Safety and Health Administration (MSHA). These roof falls can threaten miners, damage equipment, disrupt ventilation, and block critical emergency escape routes.

Roof falls are not evenly distributed between coal mines. Analysis of MSHA statistics from the years 1995-2002 show that nearly 60% of roof falls occurred in mines accounting for just 20% of all hours worked underground. Miners at these operations were six times more likely than other miners to be exposed to a roof fall. Indeed, just 20 mines accounted for one-fourth of all roof falls during the period.

The probability of a roof fall varies from region to region. Alabama, Utah, and northeast Kentucky all have roof fall rates that are about half the national average. Certain mines in Virginia and Northern Appalachia have high roof fall rates, though on the whole those regions have a moderate risk of roof falls. Roof falls are most troublesome in the Illinois basin, where the rate is approximately twice that in the rest of the country (figure 1).

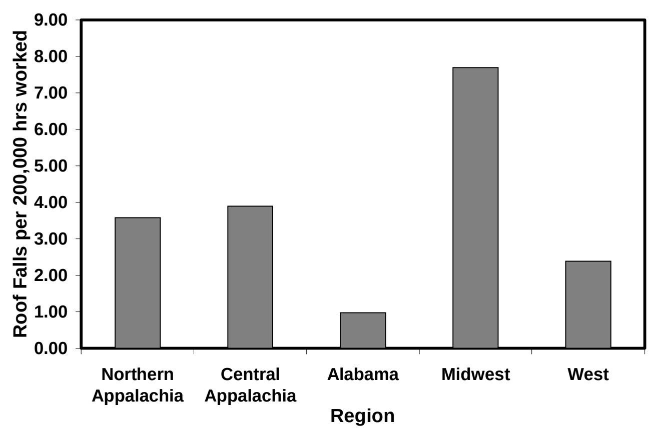

Figure 1. U.S. underground coal mining non-injury roof fall rates, by region.

The variation in roof fall rates is clearly related to geologic conditions. One recent study compared the uniaxial compressive strength of roof rocks in the Illinois basin with those in southern West Virginia (Rusnak and Mark, 2000). The study involved more than 800 rock units and 10,000 laboratory strength tests. It concluded that for each of the three major roof rock types (shale, siltstone, and sandstone), the strength of the Illinois basin variety was less than half that of the same rock in West Virginia (see figure 2).

The Coal Mine Roof Rating (CMRR) can also be used to compare roof strength in different regions. The National Institute for Occupational Safety and Health (NIOSH) has been measuring the CMRR in its ground control studies for more than a decade, and the NIOSH data base now includes nearly 300 CMRR observations. Figure 3 shows that nearly all the weak roof observations (CMRR<41) have been made in either the Northern Appalachian or Midwestern coal basins.

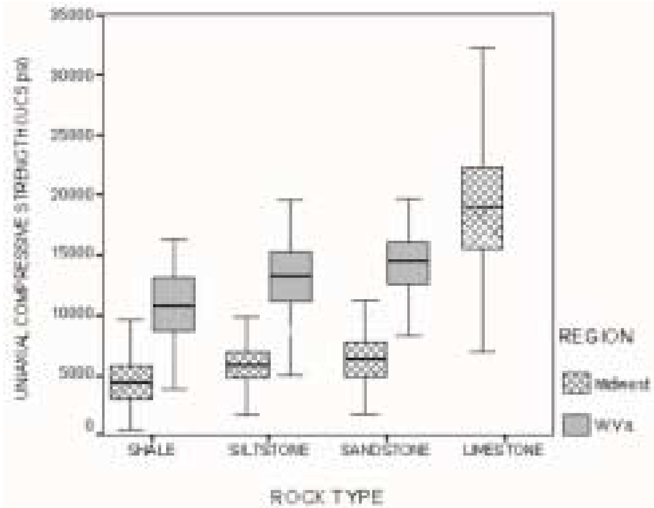

Figure 2. Unconfined compressive strength of roof rock in the Midwestern and Southern Appalachian coal basins (after Rusnak and Mark, 2000).

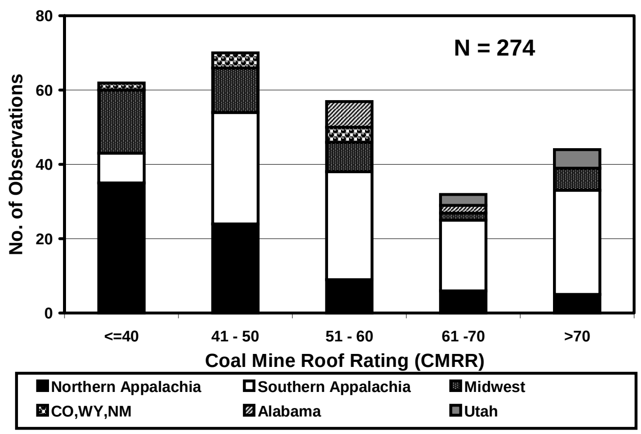

Figure 3. CMRR observations in the NIOSH data base, by region.

High roof fall rates can also be caused by inadequate support, wide spans, and/or high horizontal stress (Mark and Barczak, 2000). However, Mark et al., (2001) found that for the weakest roof, heavy roof support may not be able to prevent roof falls. The Analysis of Roof Bolt Systems (ARBS) data base contains 13 case histories in which the CMRR was less than 40. None of these mines were able to achieve a "satisfactory" roof fall rate (which was arbitrarily defined in the study to be less than 1 roof fall per 25,000 ft of drivage), despite support densities 50% greater than the other mines in the study.

It seems that today's roof control technology may not be fully protecting miners working in low-strength roof environments. NIOSH is currently in the initial phase of a research effort aimed at improving safety for these miners. The first step is to obtain a clearer understanding of the fundamental issues.

This paper describes preliminary studies that were conducted at two mines with low-strength roof. One of these mines is located in the Illinois basin, the other in northern Appalachia. Specific issues that are evaluated include:

- The adequacy of existing techniques for geologic characterization;
- The presence of seasonal and long-term effects;
- The role of horizontal stress;
- The performance of different roof bolt patterns, and;
- The effectiveness of secondary support.

MINE A

Mine A is located in the Illinois basin. Two continuous miner sections are extracting the Herrin No. 6 seam, using room-and-pillar methods with no secondary extraction. The seam height is about 5.5 ft and the depth of cover is about 250 ft. According to MSHA data, there have been 12 rock fall injuries at Mine A during the past 2.5 years.

Geology

Three immediate roof types have been identified at Mine A:

- *Typical shale* which has a uniaxial compressive strength of about 3,000 psi, appears massive but splits easily along bedding, and is moisture sensitive;
- *Weak shale* with a UCS of about 2,000 psi, is highly laminated and splits very easily along bedding, and is moisture sensitive, and;
- *Sandstone* overlying one of the two shale facies, usually accompanied by groundwater.

All of these roof types are quite weak, with CMRR values of 35 or less. However, the weak shale roof is much more troublesome than the typical shale, particularly when it is greater than 6 ft thick. Because the characteristics of the two shale facies are so similar, with the weak shale gradually coarsening upward into the other, it is very difficult to judge a definitive consistent contact between the two units whether underground or in cores. Instead, the weak shale thickness is determined in exploration holes primarily based on RQD (rock quality designation) and lithological observations, and then estimated between holes using a contouring package. The cores are observed fresh in the box and then again approximately 48 hr later, with the final determination of the thickness of the weak shale being made when the rock mechanics data become available. Unfortunately, the accuracy of the estimate undoubtedly diminishes rapidly as the distance from a borehole increases.

The sandstone unit has been troublesome when it approaches to within 20 ft of the top of the seam. It can degrade the competence of the underlying roof shales by causing compaction slips and shears in the transition zones. Because it often carries water, sandstone may also reduce roof strength by increasing the shale's moisture content. In addition, since sandstones are generally much stiffer than shale, they may concentrate horizontal stress. It is not clear which of these mechanisms is the most disruptive, and perhaps they all work together to reduce roof stability in sandstone roof areas.

Horizontal Stress

The effects of horizontal stress are quite evident in Mine A. Cutters or kink zones often occur in the advancing face as it is being cut. Other times, cutters work their way up from outby into the roof, creating hazardous conditions for roof bolt operators. Often, cutters in a particular section seem to follow a consistent pattern, developing only on the right or the left side of the entries. Over time, the cutters can continue to worsen until they result in a roof fall. Once started, roof falls tend to start in non-intersection areas and run for a couple of breaks.

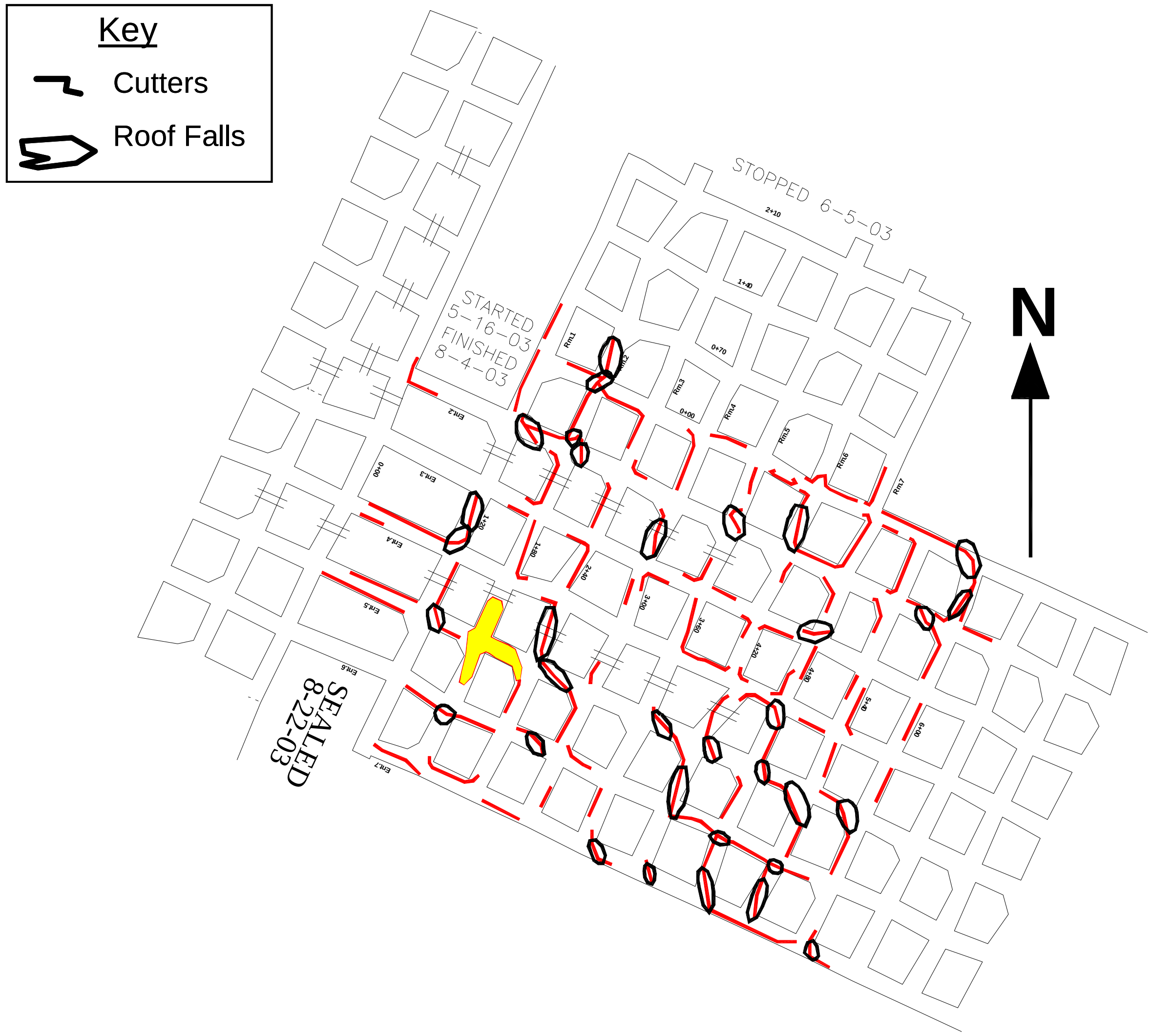

Figure 4. Stress mapping conducted at Mine A.

While no overcoring stress measurements have yet been made at Mine A, a compilation of measurements from elsewhere in the Illinois basin indicate that the regional maximum horizontal stress is typically between N70°E and E-W (Mark and Mucho, 1994). This direction also agrees with the data available from the World Stress Map Project (2004).

Underground stress mapping has been used to estimate the stress direction at Mine A. Roof cutters are the only features that were mapped because they are so common. Since cutters that follow a rib are not very helpful, the focus was on ones that traveled across an intersection or entry from rib to rib (see circles on figure 4). These cutters should be perpendicular to the major principal stress.

Figure 5 shows that the stress mapping measurements cluster around a mean orientation of N10°W. Taking all this information together, it appears that N80°E is probably the best estimate for the direction of the maximum principal horizontal stress at Mine A. This orientation explains the directional patterns of cutting that occur in the faces. The cutters have consistently occurred in the "leading edge" (the corner of the entry that is the first to contact the stress) of the entries being mined as illustrated in figure 6.

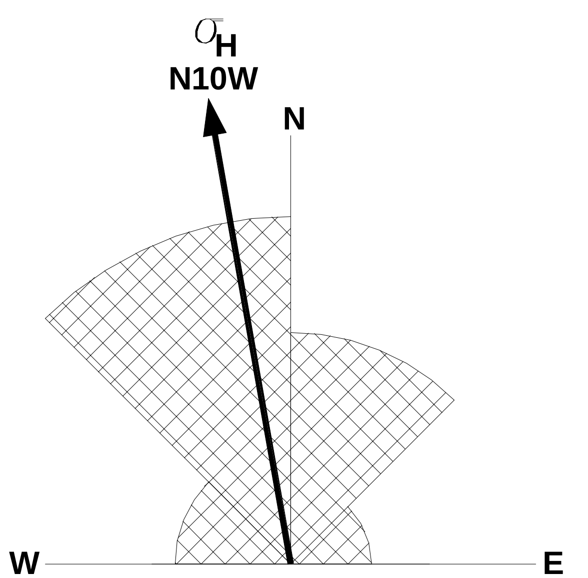

Figure 5. Formation of roof cutters at the "leading edge" of the faces at Mine A.

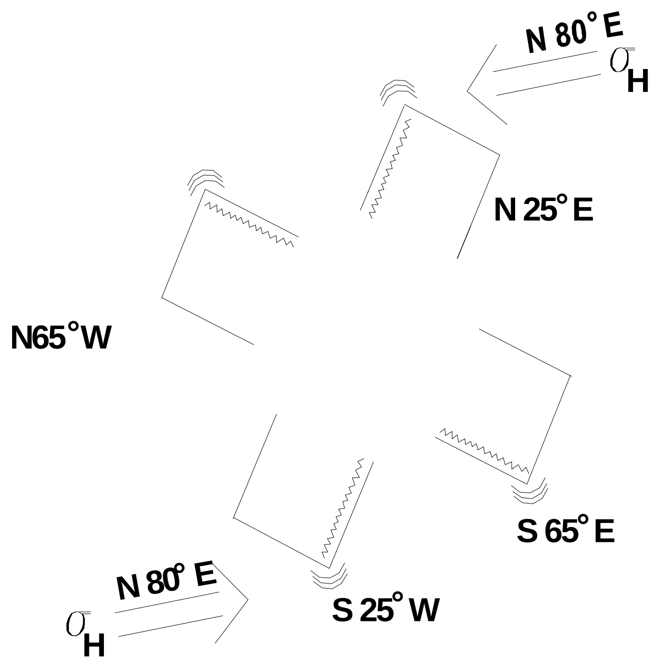

Figure 6. Sketch showing the "leading edges" of entries driven in different directions at Mine "A".

The next issue is the magnitude of the horizontal stress. Recent NIOSH research has shown that the stress magnitude is largely determined by the stiffness (Young's Modulus) of the rock (Dolinar, 2003). Therefore, it is probably "low" in the roof shales, at least compared to some measurements in sandstone or limestone. However, *relative to the strength of the rock*, particularly the shear strength of the laminations in the weak shale, the stress magnitude is clearly quite high. In fact, even the minimum horizontal stress may be large enough to cause rock failure in some instances.

Roof Support

Three main roof support patterns have historically been used at Mine A:

1. *Bolt Pattern 1:* Three, 8-ft long, #7 resin-assisted point-anchor bolts; with two, 6-ft long, #5 fully-grouted rebar (ARBS=17); with 16 ft steel straps;
2. *Bolt Pattern 2:* Two, 12-ft long, #7 resin-assisted point-anchor bolts; with three, 5-ft long, resin-assisted point-anchor bolts (ARBS=14); with either 14 ft steel straps or wire mesh (5'x15' panels, of 8 Gauge wire with 4" square openings), and;
3. *Bolt Pattern 3:* 6 ft long, #5 fully-grouted rebar, 5 per row (ARBS=8.5).

Bolt patterns (1) and (2) have been used in the main drivages, pattern (3) has been confined to short-life panels only.

In addition, steel straps, cable trusses, mesh, and wood posts have been employed in some critical entries such as primary escapeways, beltways, travelways, intakes, and returns. Figure 7 shows the approximate areas in the mine where each of these support systems were used.

Underground observations indicated that a typical sequence of events leading to a roof fall might be as follows:

- On development, a cutter forms on one side of the entry (due to the horizontal stress, as discussed above).
- As the cutter works its way up into the roof, the rock around the roof bolt plates nearest the cutter tends to unravel. If the bolts are point-anchor, they may lose their effectiveness when the bearing plate no longer contacts the roof.
- If the cutter works its way above the bolts, a roof fall may occur. In cases where the only the rib side long bolt had lost its plate load, the fall may be just 6 ft high, and extend half way across the entry.

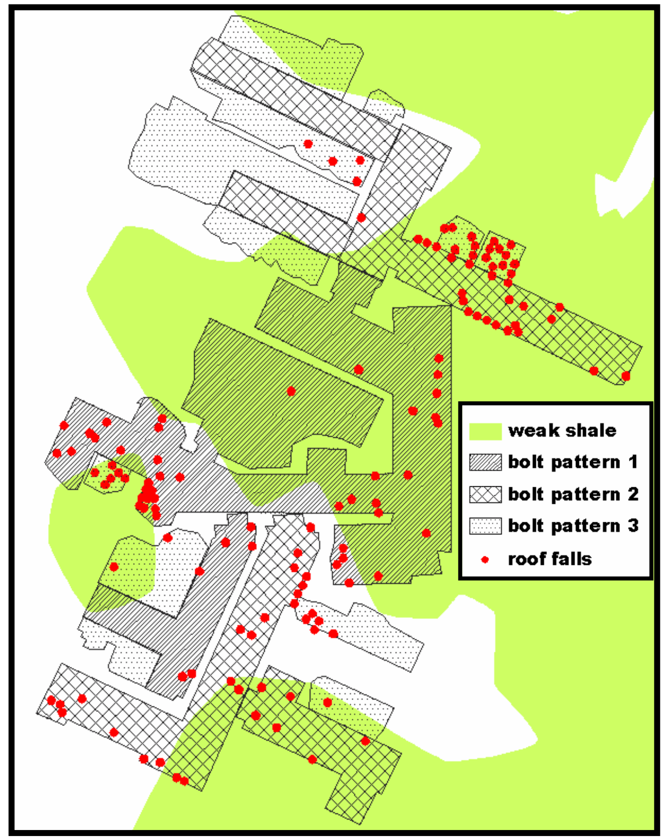

Figure 7. Sketch map of Mine A showing the areas of different roof bolt patterns and thick weak shale. For details on the roof bolt patterns, please refer to the text.

An important, non-traditional "roof support" employed at Mine A is an air conditioning system. Air conditioning demonstrated its effectiveness at a nearby mine where it dramatically reduced the number of long-term roof falls (Laswell, 1999). The air conditioning system at Mine A employs three, 400-ton air cooled chillers. The units are typically operated five months per year, from May 1st to October 1st. The temperature is controlled to achieve dew point on the air conditioning coils to remove moisture from the mine intake air and reduce slaking of the mine roof rock. Typical temperature drops are in the 20 to 25 °F range.

Roof Fall Analysis

A total of 110 roof falls are included in the Mine A database[1]. Each of these falls was identified as to:

- Roof bolt pattern;

[1] Only about half of these roof falls met the criteria in the Code of Federal Regulations (30 CFR 50.20-5) to be reportable to MSHA. The others were documented by the mine.

- Geology;
- Drivage orientation;
- Stand-up time, and;
- Number of intersections or entry/crosscut segments involved.

The statistics indicate that 70% the falls at Mine A have occurred within 6 months after mining, and 83% have occurred within 18 months.

Geology: The statistical analysis indicated that roof falls were approximately twice as likely beneath thick weak shale roof than beneath the typical shale (table 1). In addition, the relatively small area where sandstone affected the underlying shale roof, the roof fall rate was several times greater than the rest of the mine.

Table 1. Roof fall data from Mine A.

Geology	Bolt Pattern	Drivage (10,000 ft)	Roof Falls[1]	Falls/10,000 ft
Typical Shale	1	6.2	37	6.0
	2	9.0	50	5.6
	3	7.2	25	3.5
Weak Shale	1	10.9	19	1.7
	2	6.6	72	9.2
	3	3.2	81	25.3

[1]Each fallen intersection, entry segment, or crosscut segment is counted as one roof fall.

Roof bolt pattern: Statistical analysis confirmed the importance of bolt pattern at Mine A. In the weak shale roof, where the 6 ft bolts (bolt patterns) were used, the roof fall rate was nearly 5 times higher than the rate for the rest of the mine. This was true even though the 6-ft bolts were only used in panels that are open for relatively short periods of time. Bolt pattern (2), with 2-12 ft bolts, was also significantly less successful than bolt pattern (1). It seems the roof failure may quickly extend to the top of the thick weak shale, above the 6 ft bolts. Bolt pattern 1 may be most successful because it has three bolts that extend beyond 6 ft.

In contrast, in the typical shale roof, all three patterns had similar roof fall rates (in fact, the 6 ft bolts had the lowest rate, perhaps attributable to their short exposure time). Here it seems that the 6 ft bolts may be able to fully contribute to the performance of the roof support system.

Drivage Orientation did not appear to be a significant factor, once other variables were controlled. Most of the mine's drivage is oriented either N65°W or N25°E. Assuming that the maximum horizontal stress is oriented N80°E, then the N65°W drivage should be a slightly more favorable direction. The statistics show that in the typical shale roof, or where the bolts were at least 8 ft long, the N25°E drivage was at most 20% more likely to be involved in a roof fall.

However, one significant observation was that in either drivage direction, falls were more than twice as likely in entries than in crosscuts. One explanation is that the stress damage that occurs in the faces on development may be more severe in the entries, making them more prone to subsequent collapse. Similar trends have been observed at other mines (Mucho and Mark, 1994).

Intersection span also seemed to be a factor. Mine A typically turns crosscuts from entry No. 2 and entry No. 5 in their 7-entry development sections. The turnout intersections have spans (sum-of-the-diagonals) averaging about 63 ft, versus 54 ft for the typical intersections. The data indicates that turnouts were nearly twice as likely to be involved in roof falls than typical intersections.

Surprisingly, three-way intersections were nearly 2.5 times as likely to collapse as four-ways. The most likely explanation is that three-ways are located at the edge of panels, where the horizontal stress seems to concentrate.

MINE B

Mine B is a room and pillar mine located in the Northern Appalachian coalfields. After rooms are developed, the pillars are extracted by secondary mining. It is a drift mine with cover ranging from 0-480 ft. There have been 17 roof fall injuries in the last 5 years.

Roof Geology

The mining height is 52 in, including approximately 16 in of weak drawrock that would otherwise collapse before it could be bolted. The roof rock is 10-12 ft of weak, laminated clay shale, grading into a 10-12 ft thick sandy shale unit. Locally known as "soapstone", the weak shale (CMRR 30-32) contains frequent clay veins and slickensides. The roof rock is very moisture-sensitive and dissolves quickly when immersed in water. Underground, the rock degrades with time and exposure to humidity, resulting in very slabby, ragged roof. Hanging roof bolts are common where the roof has unraveled between them (figure 8).

Figure 8. Photograph of roof bolts exposed by weathering of weak shale at Mine B.

Horizontal Stress

There are no horizontal stress measurements available at Mine B, though the presumed regional horizontal stress is approximately N70°E. (Mark and Mucho, 1994). Horizontal stress is not as evident at Mine B as at Mine A, though there are some cutters and rock "stitching" that occurs near the face. Roof that has been exposed 3-4 months shows heavy guttering and scaling between bolts. Stress does not appear strongly directional, but only low stress may be required to crush this weak rock. Once guttering occurs, the entire roof beam is susceptible to fracturing.

Roof Support

As the mine started in from the outcrop, fully-grouted, 6 ft long tensioned rebar bolts were used until out of the influence of outcrop and hillseams. At that point the primary support in the mains was switched to 6 ft long, 5/8 in diameter non-tensioned, fully-grouted resin bolts. After numerous roof falls occurred, a test panel was driven to compare 5 ft point-anchored, resin-assisted bolts with a 6 ft non-tensioned fully-grouted resin bolt. Afterwards, 5 ft fully grouted tensioned rebar bolt became the primary support in the mains, while 6 ft, ¾-in-diameter fully grouted resin bolts were used in the panels. In addition, supplemental support consisting of eight, 14 ft long cable bolts in the intersections and roof screen was routinely installed throughout the belt, track, and primary escapeway entries.

Roof Fall Analysis—Short-Term

In the 6 years the mine operated through May, 2003, a total of 206 roof falls were carefully tabulated. Many of these falls occurred in inactive parts of the mine and so did not meet the criteria for a "reportable" roof fall as defined by MSHA. As in mine A, a number of ground fall-related variables were tabulated throughout the mine. The drivage in the mains was partitioned into individual cases by the following variables:

- Depth of cover
- Primary roof bolt
- Supplemental support
- Mine orientation

The stand-up time was also determined for each fall. At Mine B, a number of falls have occurred long after mining, and these long-term falls were evaluated separately. In the short-term analysis, only roof falls which took place within 18 months of development were considered. Panels that were open less than 18 months, and their associated roof falls, were not included in the analysis.

Depth of cover: At Mine B, the workings under shallow cover have been much more troublesome. For this analysis, the mine was divided into two zones:

- *Shallow cover* (less than 240 ft), and;
- *Deep cover* (more than 240 ft).

Statistical analysis showed that the overall roof fall rate when mining under less than 240 ft of cover is more than 3 times higher than when mining with more than 240 ft**.** In one area where all the other variables were constant, the roof fall rate under shallow cover was more than 5 times greater than when mining under deeper cover.

Shallow cover can be associated with mining near outcrop or beneath stream valleys. Poor rock quality, concentrated horizontal stress, and water inflow have all been documented beneath stream valleys (Molinda et al., 1992). Additionally, joint sets and weathering are commonly found near the outcrop.

Primary Roof Bolts: Since the depth of cover has such a large affect on the roof fall rate, it is necessary to remove this variable before evaluating the other variables. Only the deep-cover areas were used in the analysis of the primary roof bolt systems.

Two outcome measures were used to compare roof bolt effectiveness:

- Drivage roof fall rate (roof falls/10,000 ft of drivage), and;
- Four way intersection roof fall rate (number of four-way intersection roof falls/total number of four way intersections developed).

Three bolt types were considered in the analysis:

1. 6 ft long, fully grouted, untensioned rebar (ARBS=6.1);
2. 5 and 6 ft tensioned rebar, fully grouted (ARBS=7.4), and;
3. 5 ft point-anchored, resin-assisted (PAR) bolts, installed with 3 ft of resin (ARBS=9.2).

Using the drivage measure, the non-tensioned rebar bolt performed slightly better than the other two systems (table 2). However, using the 4 way intersection roof fall rate, the PAR bolts and the tensioned rebar performed slightly better. Overall, it does not appear that any of the bolt systems was significantly more effective.

Table 2. Roof fall data from Mine B.

Depth of cover	Bolt pattern	Drivage (10,000 ft)	Roof falls[1]	Falls/10,000 ft
Deep	1	7.1	14	2.0
	2	17.3	46	2.7
	3	4.1	16	3.9
Shallow	-	7.5	57	7.6

[1]Each fallen intersection, entry segment, or crosscut segment is counted as one roof fall.

Supplemental Support was systematically installed on cycle or very close to on cycle in the belt, track, and primary escapeway entries in about half of the mains drivage. When supplemental support was used, it normally consisted of eight, 14-ft cable bolts in the intersections, with welded steel screen added for skin control.

The analysis showed that the supplemental support reduced the 4 way intersection roof fall rate to less than half of what it was where no cable bolts were installed on cycle. However, it appears that at least 5 intersections have collapsed even with supplemental support.

Mine orientation: Two main drivage directions have been used at Mine B, N28°W and N66°E. The N66°E drivage is very nearly parallel the presumed major horizontal stress, and therefore might be expected to be a more favorable mining direction than N28°W. However, the roof fall rates in both directions were almost identical. The shallow cover drivage directions were N28°W and N60°W, but again there was no significant difference between roof fall rates. It appears that the stress field at Mine B is not strongly biaxial (i.e., it is approximately the same magnitude in all directions).

Roof Fall Analysis—Effect of Time

The roof falls at Mine B exhibit two types of time-dependency. First, the roof fall rate during the humid summer months is more than twice what it is during the fall and winter (figure 9). Second, while most of the falls have occurred within 12 months of mining, many continue to occur several years after mining (figure 10).

The roof fall rate is the highest in the initial mains drivage near the portal. Mine openings there have been open nearly 7 years, and the effect of humidity on the moisture-sensitive "soapstone" is clearly evident. Incoming ventilation air has no chance to equilibrate in temperature and adversely affects the weak rock.

Progressive roof falls have created very difficult conditions in the beltway and intake air courses.

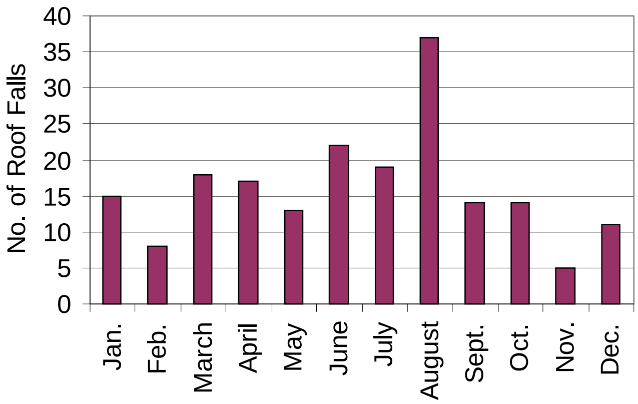

Figure 9. Roof falls at Mine B, by month.

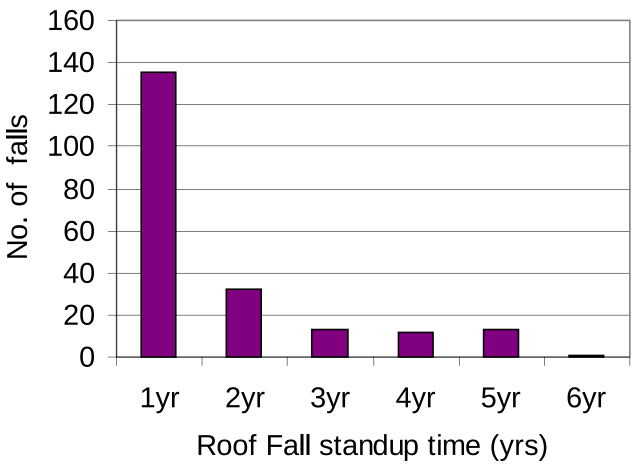

Figure 10. Roof falls at Mine B, entry by stand-up time.

Since most of the falls occur in the first 12 months of exposure, the mine moved to shorten the panels which allows the operator to develop and retreat panels quickly. In this weak roof, less panel exposure time means less chance for roof falls. In the mains, which must remain open for a longer time, the installation of supplemental support on cycle has resulted in more stable intersections. The success of these measures can be seen in figure 11, which shows that the number of short term roof falls at mine B have been dropping year to year.

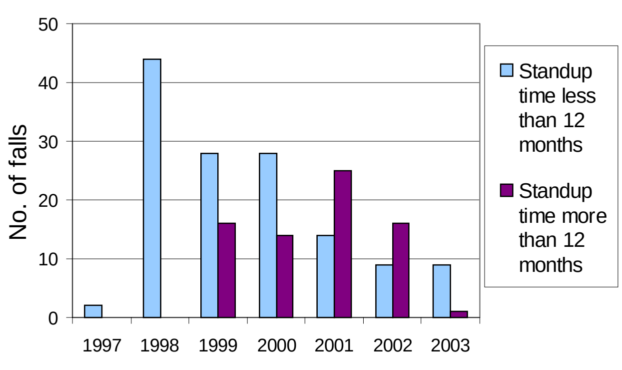

Figure 11. Roof falls at Mine B, by year in which the entries were driven.

Evidence for another potentially successful control technique can be found in the initial mains development. Nearly 1,300 ft of the track entry roof was sprayed with gunite when it was developed, and this section of entry has experienced only 1 roof fall. In contrast, the adjacent belt entry roof was not sealed, and 13 roof falls have taken place in the same distance.

DISCUSSION AND CONCLUSIONS

Ground control is a significant challenge in exceptionally low-strength roof conditions. Reducing the number of roof falls requires concerted efforts in a number of areas:

- *Improved geologic characterization:* At mines like mine A, more detailed knowledge of the thickness of the extremely weak roof strata could be a big help in pinpointing areas that might benefit from more support. Mechanical tests (like UCS) can be difficult to conduct in weak, moisture sensitive rocks. An alternative might instead be to measure in situ moisture content, which has been shown to be strongly correlated with UCS in the Illinois basin (Bauer, 1982). However, surface borings may seldom be spaced closely enough to accurately define the thickness of weak units (Mark et al., 2004). Better techniques for identifying rock characteristics underground could prove very useful (Peng et al., 2003).
- *Better definition of horizontal stress*: Although horizontal stress magnitudes seem relatively low in weak rock, due to the lower rock strengths they can affect ground control significantly. Orientation did not appear to be a major factor at either of these mines. In fact, the case of Mine B indicates that sometimes the horizontal stress may not have a preferred orientation. Nonetheless, site-specific knowledge of the horizontal stress would be very helpful in the mine planning stage, because reorientation of an operating mine is not easily accomplished.
- *Optimized roof support:* Both of these operations expend considerable effort on roof support. Mine A's experience is that using longer, stronger primary bolts in pattern can reduce roof fall rates, while Mine B has achieved success with cable bolts installed on cycle. In both cases, however, the roof support patterns depend upon the heavier supports working with shorter, lighter, fully grouted bolts. Basic scientific and systematic testing of such combination roof support systems in coal mines would be very useful, especially for low strength roof rock.
- Both mines have also found that unraveling of the roof skin can reduce the effectiveness of even heavy roof bolt supports. Achieving skin control with mesh (or even straps or large plates) can therefore help reduce the number of roof falls while also protecting miners from falling rock.

Another important conclusion from this study is the importance of moisture sensitivity to ground control in weak roof. It seems that roof falls at these mines can be divided into two classes:

1. *Falls that occur soon after mining*, which may be related to a combination of roof defects (clay veins, slickensides, weak bedding, and other defects) and horizontal stress.

2. *Falls occurring years after development*, often related to progressive unraveling upward in cutters and between roof bolts. The high moisture sensitivity of the weak shale, "soapstone," and clay veins causes them to deteriorate over time, and perhaps to swell and induce internal pressures.

Preventing this second category of roof falls is essential for the long-term viability of mines in low-strength roof environments. Spray-on sealants seemed to show their potential at Mine B, while air conditioning appears to have been helpful at Mine A.

Now, more than ever, coal is essential to the energy security of the United States. The easy reserves have been depleted, and future mining will of necessity require dealing with more difficult conditions. The mines described in this paper are currently in the forefront of the struggle to develop better methods for controlling roof falls. Their strides and success will serve as an example for future mines with similar geologic conditions.

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