ABSTRACT

Roof and rib failures remain a major cause for fatal and non-fatal injuries in underground coal mines in Illinois and the USA. Over 80% of these incidents in Illinois occur at intersections. Roof control costs today vary 7-20% of total production costs depending upon site-specific geological and geotechnical conditions. Design of roof control systems at a particular site is still based mostly on recommendations from support manufacturers rather than upon scientific investigations of roof, floor and coal seam geology and geotechnical properties as well as roof bolt performance characteristics.

This project has: 1) Analyzed roof fall data for Illinois underground coal mines from 2004 through 2008, 2) Developed a better understanding of failure mechanisms around intersections, 3) Identified alternate concepts for primary and secondary roof support systems, 4) Initiated a preliminary field study to validate these concepts, 5) Performed geotechnical studies at mines to evaluate the applicability of the Coal Mine Roof Rating (CMRR) system for characterizing immediate roof strata above coal seams, 6) Assessed numerically whether a floor rating system needs to be incorporated into the CMRR for more effective design of primary support systems, and 7) Shared study results with industry, MSHA and NIOSH.

Results indicate that: 1) Over 80% of reportable roof falls occur at intersections and most of these occur at four-way intersections, 2) Nearly one-third of falls occur within 90 days of development, 3) Most falls occur 1-2 ft above the length of installed bolts, 4) The effectiveness of primary supports, such as partially-grouted tensioned bolts, double-lock bolts, etc., to control rock falls needs to be assessed through scientific studies, 5) Floor characteristics for typical geologic conditions in Illinois do not need to be considered in designing primary roof supports systems, 6) CMRR rating does not appear to be a good indicator of the need for primary roof supports, 7) Shear strength of different laminae within shale beds is generally extremely low and may be controlling failure behavior in mine excavations, and 8) An understanding of the time-dependent performance of primary supports is essential for design of primary support systems.
EXECUTIVE SUMMARY

The objective of this project was to develop improved roof support design approaches with the overall goal of achieving higher productivity, lower production costs, and better safety and efficiency. In 2006, falls of roof and ribs accounted for 10 fatal and 530 non-fatal injuries in coal mines in the US (Spearing and Mueller, 2008). Therefore, this is a very important area for additional research and development. Currently, ground control costs in Illinois mines vary from $1.50/ton to over $3.50/ton. Also, it costs about $100,000 to clean up a typical roof fall in an Illinois mine, not including the cost of lost production. Most coal companies plan for three (3) to five (5) roof falls each year.

The current Illinois Basin coal market requires very high productivity to supply an ever increasing demand. The Mine Safety and Health Administration (MSHA) has established a goal of zero roof falls nationally. They have also identified control of roof falls as a priority in Illinois Basin mines. Over the long term, this project should enhance Illinois coal production by lowering production costs and improving ground control. Improved ground control should also result in less fatal and non-fatal injuries with associated reduced costs.

Roof control is one of the most critical elements in the mining production system and ranks very highly in assessing economic mineability of a reserve. Hence, a critical factor in enhancing the Illinois coal industry is development of roof control systems that are scientifically based to promote rational design, allow for optimization of the mining system in terms of cost effectiveness, and reduce falls of roof and ribs. Toward these goals, this project has performed the following studies:

- Analyzed the MSHA reportable roof fall data base for coal mines in Illinois from 2004 to 2008. This required collection of data on primary roof support plans and roof falls (from MSHA) for all active underground mines in Illinois. These analyses led to identification of roof fall characteristics such as stand-up time, size of roof falls, location of falls, and some indication of the effectiveness of primary roof support systems currently used in Illinois.
- Performed a two-dimensional numerical analysis of the effects of weak floor on stress redistribution around a mine opening. This was done to assess if weak floor characteristics should be considered in evaluating primary support requirements.
- Visited several underground mines to assess ground control problems and make recommendations for improvements.
- Conducted Coal Mine Roof Rating (CMRR) evaluations on exploration cores and in-situ sites at selected mines.
- Performed a three-dimensional numerical analysis of a typical four-way intersection for Illinois conditions. This led to development of an alternate methodology for evaluating intersection stability and a much better understanding of primary and secondary support requirements for an intersection.
- Developed alternate concepts for primary and secondary support systems around an intersection. Initiated a preliminary field study of an alternate support system for an intersection.
These studies have led to the following conclusions and recommendations:

**Roof Fall Characteristics**

- Over 80% of the reportable roof falls occur at intersections and most of these occur at four-way intersections.
- 85% of falls occur either within 90 days of or 180 days after development. Those occurring within 90 days of development are critical since workers may be still be present in the area and thus exposed to the danger the fall presents.
- Most falls have a height about 1-2 ft above the length of installed bolts. This is true irrespective of the length or type of bolt involved.
- The effectiveness of conventional bolts and special primary supports, such as partially-grouted tensioned bolts, double-lock bolts, etc., to control rock falls needs to be assessed through scientific studies. The available data suggests that they may not be effective.
- An understanding of the time-dependent performance of primary supports is essential for developing effective primary support systems.

**Analyses of Weak Floor on Excavation Stability**

- Attempts to relate floor structure to moisture content and Atterberg Limits at specific sites were not successful.
- For typical geologic conditions in Illinois, floor characteristics do not need to be considered in design of primary roof supports during mine development.
- In most mines, moisture content and thickness of immediate floor strata remain the best parameters for design of pillars.

**Coal Mine Roof Rating Evaluation**

- For most of the sites that were evaluated, CMRR values range from 30 to 45.
- Visits to several mines indicated that most falls were associated with geologic anomalies rather than CMRR-based factors. These included shear zones, compressional faults, clay dikes, and litho-facies changes, etc. Based on this study, CMRR may not be a good indicator of the need for primary roof supports.
- Shear strength of different laminae within shale beds, based on the Diametral Point Loading Test, is generally extremely low and dominates the calculation of CMRR values. This may explain the stepped nature of typical roof falls in Illinois and the cutter roof behavior even under moderately high lateral stress fields.
- In transitional roof lithology areas around channels, the time-dependent performance of primary roof supports becomes more important since rock mass deformations do occur as a result of pre-existing discontinuities and degradation of rock mass properties due to moisture absorption and migration.
**Three-dimensional Analyses of a Coal Mine Intersection**

- A displacement-based approach for analyzing stability of an intersection was developed. It helps to visualize problems around an intersection much better than using just a stress-based approach. Specifically, it explains intersection pillar corners failure as well as cutter-roof development much better than stress-based analyses.
- Analyses suggest the need for stiffer support around pillar edges. However, stiffness of the support must be engineered depending upon site-specific rock mass characteristics.
- Alternate concepts for primary and secondary roof supports around an intersection were developed based on an understanding of stresses and displacements.
- A preliminary field study of an alternate support system around an intersection was initiated.

**Pre-mining Investigations**

- Guidelines were prepared for a drill rig geologist to document appropriate geologic and geotechnical characteristics that affect ground control in mining.

Since many stakeholders from coal companies, NIOSH, and MSHA were actively involved with the project, information transfer and commercialization of developed ideas have occurred as research tasks were completed. More specifically, MSHA provided a significant amount of data on roof falls within Illinois and results of the roof fall data base analysis were discussed with them. NIOSH and Peabody Energy professionals assisted with approaches for appropriate numerical analyses. Results of numerical analyses were presented at an international conference with good feedback. Results were also shared with NIOSH and some coal company professionals. A coal company agreed to demonstrate the concept developed for intersection support.
OBJECTIVES

The overall goal of this project is to enhance Illinois’ coal industry through development of roof control systems that are scientifically based to promote rational design, allow for optimization of the mining system in terms of cost effectiveness, and reduce falls of roof and rib. More specifically, the objectives of this project were to: 1) Identify characteristics of roof falls through roof fall data base analyses, 2) Perform in-mine and field geotechnical studies to assess ground control problems as they relate to development of primary roof support requirements, 3) Develop a better understanding of stability problems around intersections, and 4) Develop and evaluate alternate concepts for primary supports around intersections.

INTRODUCTION AND BACKGROUND

Based on an analysis of rock falls related to fatal and non-fatal injuries in the USA for the period 2002 to 2007, Spearing and Mueller (2008) identified that rock falls are still a major concern. About 70% of these falls occur at intersections even though they represent only about 20-25% of the area mined. Chugh and Kollipara (2009) analyzed the MSHA reportable roof falls database (RFDB) for Illinois mines for the period 2004 to 2008. They found that 642 roof falls occurred during this period, or about four (4) falls per million tons of coal mined. Over 80% of these falls occurred at intersections. Thus, there is a significant need for technical studies to improve stability of coal mine excavations with emphasis on intersections. It costs about $100,000 to clean up a typical roof fall in an Illinois mine, not including the cost of lost production. The current Illinois Basin coal market demands very high productivity to supply increasing demand. MSHA has established the goal of zero roof falls nationally. They have also identified control of roof falls as a high priority in Illinois Basin mines. This project will enhance Illinois coal production by lowering production costs and improving ground control. Improved ground control should also result in fewer injuries with associated reduced costs.

EXPERIMENTAL PROCEDURES

Experimental procedures for different tasks varied widely and discussion of these procedures is more appropriate in the following section of the report.

RESULTS AND DISCUSSION

Roof Fall Data Base Analysis (Task 1)

Background: Identification of causes and characteristics of roof falls is extremely important to minimize the number of falls, control their impacts, and plan for artificial supports. An analysis of the MSHA reportable roof fall database (RFDB) for Illinois mines for the period 2004 to 2008 was undertaken. A total of 642 roof falls were reported and analyses were performed to identify relationships for variables such as fall volume, stand-up time, height of roof fall, type of primary support, length of roof bolt, and frequency of roof falls by month.
**Mining conditions:** This discussion is based on Hopkins (1980). The No. 6 and No. 5 seams account for almost 100% of underground coal production in Illinois. Most underground mines are 300-500 ft deep, although some large mines operate in the depth range of 550-700 ft. Coal seam thickness varies 4-6 ft. Most common geologic factors affecting ground control include shallow mining depth, weak floor strata, deep bedrock valleys filled with glacial drift, clay dikes, coal balls and concretions, and tectonic and non-tectonic faults. At shallow mining depths, bedrock valleys filled with water-saturated glacial drift are encountered. Poor roof conditions, floor heave and water problems are common when mining underneath such valleys. The water-saturated glacial drift has very low cohesion and acts as “dead load” on lower competent beds. Localized lenses of sand and gravel near the surface are used as drinking water sources and can be impacted during the subsidence process. Surface fractures may serve as conduits for water movement into the mine.

The immediate roof strata overlying Illinois’ No. 6 and No. 5 coal seams typically have two (2) lithologic sequences – black shale-limestone or thick gray shale. These coals are generally overlain by about 2-5 ft of black shale. This bed is typically overlain by a limestone bed 2-4 ft thick for No. 6 coal and about 1-2 ft thick for No. 5 coal. The black shale-limestone sequence is typical above high sulfur coal areas. The second sequence, thick silty-gray shale, varies typically from 20-50 ft thick but may be occasionally 100 ft thick. This lithology typically underlies the black shale-limestone. It is more localized and is associated with sandstone channels. Areas adjacent to these sandstone channels are characterized by compactional faults, rolls, split coal and washouts. The gray shale sequence in the No. 6 coal seam (Energy shale) is associated with the Walshville Channel. The Dykersburg shale is associated with the Galatia Channel for the No. 5 coal seam. Coal deposits underlying gray shale areas are typically lower in sulfur content as compared to black shale-limestone sequence areas. In transition zones between the black shale-limestone sequence and the gray shale sequence, one encounters geologically anomalous structures such as split coal, differential compactional structures, randomly oriented joints, and highly water sensitive geologic materials.

**Analysis procedures:** MSHA requires that a fall must be reported if it causes injury, its height is longer than the roof bolt, it obstructs ventilation or escape paths, or it interferes with production for over 30 minutes. An analysis of such falls in Illinois mines for the period 1986 to 1990 was reported by Singh et al. (1992). An analysis of roof falls in US coal mines for 1999 was presented by Molinda et al. (2000). The authors here present an analysis of RFDB for Illinois underground mines for the period 2004 to 2008. Although the absolute number of reportable falls in Illinois has decreased over the years, the number of falls per unit ton of production and percent contribution by falls to total injuries still remains high. Therefore, the identification of their causes and characteristics is extremely important.

The RFDB on the MSHA website provides limited information on fall characteristics. During the period January 1, 2004 to December 8, 2008, MSHA reported 642 falls for Illinois mines; 427 and 215 in No. 6 and No. 5 coal seams, respectively. Additional data on falls characteristics was obtained through visits to coal mines, reviewing mine maps,
and discussions with mine engineers and MSHA roof control staff. Production and man-hour worked data by month was provided by the Illinois Department of Natural Resources (IDNR) Benton office. Since fall data cannot be normalized with available well documented information, analyses could only be performed on the characteristics of roof falls. The only data that could be normalized was number of falls per month per million tons of production.

Even though many falls are investigated by MSHA, there is no uniform data collection format and considerable relevant data was not available. The following limitations were observed in the collected data: 1) Data on whether falls occurred at intersections or entries was available for only 20% of falls, 2) Such data for three-way or four-way intersections was available for only 10% of falls, 3) Layout of bolting pattern and supplementary support was generally not reported, 4) Location of roof falls in strategic entries (belt entries, travel ways, etc.) was not specified, 5) Information was not available to compare performance of different primary supports at a mine, and 6) Data on date of development and therefore stand-up time was available for only 38% of falls. It is suggested that uniform investigation and data collection procedures be implemented for roof falls that will allow meaningful data analyses. Long-term field performance of primary supports can only be achieved through such data collection.

**Location of falls:** Data was available for 143 falls. Based on rough estimates of production from No. 6 and No. 5 seams, one may expect similar fall rates for both seams. Over 86% of falls occurred at intersections; about 67% in No. 6 seam and 33% in No. 5 seam. Of intersection falls, 8% occurred at three-way and 92% occurred at four-way intersections. About 43% occurred at intersections with 20-ft wide entries, 20% at intersections with entries wider than 20 ft, and 37% at intersections with entries less than 20 ft wide. Since data on frequency of different size intersections is not available, appropriate comments cannot be made as to whether 20 ft or more entry width is more critical than smaller entry width. Stand-up times were compared for intersections with entries less than 20 ft and intersections with entries over 20 ft. Similarly, standup times for falls in three-way and four-way intersections were also compared. However, no conclusions could be made since data were limited.

**Falls by month:** Data were available for 642 falls. The average number of falls for each month for the entire period (2004 to 2008) was normalized by the production for that month. Results were analyzed to determine if there are significant differences in falls during certain periods of the year. Table 1 suggests that the average rate of falls from February to May is lower than similar data for June to January. Hypothesis testing for mean values with unequal variances for these two (2) periods using a t-test at p = 0.05 also showed significant differences. Thus, it was concluded that the average fall rate/unit of production is significantly lower from February to May than from June to January. This is probably due to high humidity during summer months affecting immediate roof strata that are sensitive to moisture.

**Stand-up time and fall volume:** Data for these variables were available for 241 falls; 91 in No. 6 seam and 150 in No. 5 seam (see Table 2). In No. 6 seam mines, about 37% of
falls had stand-up times less than 90 days, and 40% less than 120 days. Similar data for No. 5 seam mines are 28% and 32%, respectively. This is critical information since miners may still be actively involved in those areas. Frequency of falls in both seams increases after 180 days stand-up time. These falls may be occurring in belt and travel entries that must remain open for the life of the mine. However, data were not available to verify how many falls occurred in belt and travel entries. Over 68% of falls had volumes in the range of 1,800 cu ft to 7,200 cu ft, while about 85% had volumes ranging from 1,800 cu ft to 14,400 cu ft. Since most falls occur at intersections and typical entry size is 20 ft wide and 6 ft high, these falls would extend about 5 ft into each entry around the intersection. About 26% of falls exceed 7,200 cu ft in volume. Of these, about 8% are very large, exceeding 14,400 cu ft. Most of these falls may have occurred in belt entries where vibrations may be affecting bolt performance.

Analyses comparing stand-up time and fall volume suggest a slightly increasing trend in fall volume with increasing stand-up time. However, regression analyses did not prove this to be a valid hypothesis. This statement applies to No. 6 and No. 5 seam data separately and also for combined data.

**Type of bolt and fall volume:** Such data available for 309 falls, 204 in the No. 6 seam and 105 in the No. 5 seam, are summarized in Table 3. A conventional bolt uses a shell anchor on a smooth rod. A fully-grouted bolt is a passive bolt consisting of ribbed-rebar with resin grout along the entire length. A point-anchored bolt is a resin-grouted bolt with resin along a portion of the length of the bolt only. A tension-rebar or torque-tension bolt is a partially or fully grouted bolt with tension applied to the lower portion of the bolt. A double-lock bolt has an expansion shell at the top and a resin grouted rebar at the bottom. In a combination bolt, the upper part consists of ribbed rebar for better mixing while the lower part is a headed smooth bar with shear-pin system for tensioning.

- The use of conventional bolts should be reconsidered in Illinois. Only one (1) mine uses conventional bolts. While it produces 5-7% of Illinois’ total production, it accounts for about 9% of roof falls.
- About 50% of falls in the No. 6 seam occurred in areas using point-anchored bolts. About 24% and 13% of all falls occurred in areas using 6-ft and 8-ft point-anchored bolts, respectively. Since point-anchored bolts are not commonly used in Illinois, it is inferred, based on the large number of falls, that using this primary support system in Illinois mines should be reconsidered.
- About 77% of falls in the No. 5 seam occurred in areas using fully-grouted bolts. About 26% and 11% of all falls occurred in areas using 6-ft and 8-ft fully-grouted bolts, respectively. Longer (greater than 6-ft) fully-grouted bolts should be avoided as experience indicates higher fall rates in areas supported by such bolts.
- Data suggest that larger fall volumes occur in areas where point-anchored bolts are used than in areas where fully-grouted bolts are used.

The analysis was complicated by the fact that a single mine uses several types of bolts based on geologic conditions. Among primary supports currently used, fully-grouted resin bolts seem to be more effective than other bolts. While data shows larger numbers
of falls occurring in areas with fully grouted bolts, this can be misinterpreted without normalizing this data with respect to tons produced or length of entries driven for each type of bolt. While such data are not available at present, it is known, based on common industry knowledge, that most Illinois production uses fully grouted, passive bolts.

**Fall height and bolt length:** Analyses comparing fall height to bolt length, for different types of bolts, are shown in Table 4 and in Figure 1. The average height of falls in No. 5 seam mine workings is larger (9-11 ft) than in No. 6 seam mine workings (7-8 ft). Most mines use 6-ft or 8-ft bolts. Fall height is typically larger than bolt length by 1-2 ft for all types of bolts used as primary support.

**No 5 Seam:** Data were available for 93 falls. About 25% occurred in areas using 6-ft bolts. All of these falls had heights greater than 5 ft and 56% had heights greater than 7 ft. About 57% of falls occurred in areas using 8-ft bolts. Almost all of these falls had heights greater than 7 ft and about 80% greater than 9 ft.

**No 6 Seam:** Data were available for 199 falls. About 73% occurred in areas using 6-ft bolts. About 80% of these falls had heights greater than 7 ft and about 52% had heights of 7-9 ft. About 20% of falls occurred in areas using 8-ft bolts. Over 90% of these had fall heights greater than 7 ft, about 30% greater than 9 ft, and 25% greater than 11 ft.

Using longer bolts may not be the best approach to control bad roof conditions. It is the principal investigator’s opinion that stiffer bolts should be considered instead of longer bolts for improved ground control. For example, #6 rebar or #7 rebar should be used instead of #5 rebar, while minimizing the annulus. This approach will limit rock mass movements and make the rock mass more self-supporting.

Analysis of stand-up time as a function of bolt length typically suggests a slight increase in stand-up time with increasing bolt length but regression analyses do not validate that hypothesis. The concept of increasing bolt length for improved ground support in Illinois coal mines should be further evaluated through scientific experiments in the field.

**Comparing RFDB analysis results for the 2004-2008 and 1986-1990 period:**

- Number of reportable falls during the 2004-2008 period is about 50% of those during the 1986-1990 period. However, the average number of falls per million ton of coal produced during the two (2) periods is similar. The percentage of roof falls at intersections during the two (2) periods is also similar (~80%).
- For 1986-1990, there was a decrease in roof fall volume with increasing stand-up time for all types of bolts used. However, for 2004-2008, an increase in fall volume with increase in stand-up time is noted.
- Observations related to fall height and bolt length are very similar for both periods. The fall height is typically 1-2 ft greater than the bolt length.
- The concept that fully-grouted bolts are more effective than conventional and point-anchored bolts is valid for both periods. For 1986-1990 period, the data suggests that fully-grouted bolts may not be better than point-anchored bolts in
No. 5 seam workings and point-anchored bolts may not provide adequate support. However, similar observations could not be made for the 2004-2008 period.

- For the 1986-1990 data, the proportion of falls with heights greater than bolt length decreased with an increase in bolt length. However, this statement is not valid for the 2004-2008 data.

**Observations during mine visits:** Several mines were visited to observe some roof fall sites and develop coal mine roof rating (CMRR) data.

- CMRR values were similar in areas with and without falls. Therefore, CMRR data at fall sites was not a good indicator of bad roof areas.
- Most falls were associated with geologic anomalies such as clay dikes, differential compaction faults, shear zones, and geologic structures. The likelihood of locating these geologic anomalies during limited pre-mining exploration is very low. Therefore, technologies need to be developed that would allow an assessment of geologic conditions about 20-30 ft ahead of mining.
- There was no clear indication that high pre-mining lateral stresses were a major contributor in causing falls. Instead, observations suggest that a decrease in strength of immediate roof strata might be responsible for poor ground conditions.
- Most falls showed stepped shape. Strength testing of shales overlying coal seams showed very low cohesion within shale beds and along contact planes between shales and other beds. This may be a very important variable affecting roof falls.
- A more careful geological evaluation of cores recovered from immediate roof strata (20 ft) above the coal seam and immediate floor strata (20 ft) below the coal seam is being suggested to drill rig geologists.

**Summary of RFDB analysis:** Results of these analyses have been discussed with MSHA and several mining professionals to formulate recommendations for in-mine primary support studies. In addition, a focused effort needs to be launched on development and evaluation of primary and secondary supports at intersections. The findings of this study are also being used to develop data collection strategies for pre-mining and roof fall investigations so that appropriate primary support recommendations can be made.

**Coal Mine Roof Rating (CMRR) Evaluation Studies (Task 2)**

**Background:** CMRR was developed by the U.S. Bureau of Mines as a system to assign a value to the structural competence of a mine roof for the purpose of roof support selection and coal pillar design (Molinda and Mark, 1994). Detailed directions for determining CMRR in the field and on exploration cores are provided in Molinda and Mark (1994) and Mark et al. (2002). CMRR evaluation studies were done at three (3) mines and on two (2) cores. Results are presented below.

**Mine 1:** Data was collected from three (3) locations where there was access to sufficiently exposed roof. The first location was mined approximately 8 ft high to accommodate the belt conveyor. The immediate roof stratum in this area was black shale. Some moisture was adhering to the surface of the exposed roof. The CMRR value
calculated from data collected at this site was 46. The second site also had a mining height of about 8 ft to accommodate belt conveyor installation. Ground water was dripping from the roof and a large “slip” with slicken-side surfaces extended diagonally across the entry. A large discontinuity in the immediate roof stratum was also observed near the site. The immediate roof at this site was also black shale and the calculated CMRR was 48, but with adjustment for ground water, this was reduced to 41. At the third site, 5 ft of immediate roof had been mined. The immediate roof was black shale that was completely dry and competent. The calculated CMRR value was 52 at this site.

Mine 2: Data was collected at three (3) sites with NIOSH professionals. The first site was a roof fall in the belt entry. Exposed roof extended approximately 12 ft above the coal seam. It was composed of dark gray shale (Energy shale) pods. The CMRR value was 36, but with a ground water adjustment, it was reduced to 29. The roof at the second site was divided into two (2) units. The first unit was 4 ft of dark gray Energy shale and the second unit was 2 ft of limestone. The CMRR value was 61 but with ground water adjustment it was reduced to 58. The third location was also divided into two (2) structural units. Unit 1 was 0.5 ft of dark gray Energy shale; Unit 2 was 2 ft of limestone. The CMRR value at this site was 82 with no ground water adjustment.

Mine 3: Data was collected at three (3) sites. The first location was near a roof fall. The immediate roof strata consisted of dark gray and black layered shale and it was divided into three (3) structural units. There was ground water dripping from the roof and it resulted in reducing the calculated CMRR value from 43 to 36. The second site was an overcast exposure. The roof was composed of dark shale and divided into two (2) structural units. The area was dry and the calculated CMRR value was 50. The third site was a belt entry. The roof was black shale and dry. Two (2) adjacent areas were used to calculate a CMRR value of 38.

Exploration cores: Two (2) companies collaborated to provide exploration cores for CMRR evaluation. These evaluations were performed according to procedures outlined in Mark et al. (2002). Results of these studies are summarized below and in Table 5.

- Diametral Point Load Index values were extremely low and below 34.7. For such values, a Diametral Rating of 25 is suggested. Since this number is the dominant factor in calculating CMRR, it is the principal investigator’s opinion that the approach described by Mark et al. (2002) may not provide reasonable CMRR values for Illinois mines.
- Water sensitivity deduction based on immersion testing can be large (-5 to -7) for the both mine cores investigated.
- There does not seem to be any relationship between roof support density and CMRR values.

Effects of Weak Floor Strata on Mine Opening Stability (Task 6)

Two-Dimensional Finite Element Analysis (FEA): The goal of this task was to assess the effect of weak floor strata on stress distribution in the immediate roof strata and
decide whether floor characteristics should be considered in conjunction with roof characteristics to decide primary support requirements. The finite element model developed (see Figure 2) represents typical geologic conditions in Illinois No. 6 seam. The overall model is about 80 ft wide and 85 ft high with coal seam thickness of 6.5 ft. The entry width is 20 ft and pillars are 60 ft center-to-center. The linear and non-linear rock mass properties used in modeling are shown in Table 6. These were selected based on previous studies that yielded good correlations between field-measured and FEA-estimated displacements. Vertical planes were constrained by applying roller boundary conditions. Similarly, the bottom model boundary was assigned zero vertical displacement. Uniform vertical stress of 362 psi was applied at the upper model boundary and uniform horizontal stress of 580 psi was applied to the entire model prior to entry excavation. Analyses were developed with free slippage of different bedding planes. All models (see Table 7) were run non-linearly with the assumption of large strains.

**Effect of uniform weak floor thickness:** For a 2-ft and a 4-ft thick uniform claystone layer below the coal seam, the vertical stress acting on the horizontal plane 0.3 ft above the roof-coal seam interface is shown in Figure 3. The peak values of horizontal, vertical, and shear stresses due to various weak floor strata conditions (2-ft thick uniform claystone layer, 4-ft thick uniform claystone layer, and 4-ft thick non-uniform claystone layer) are given in Table 8. The 4-ft weak floor layer was present only below half the entry width while the other half was competent floor as shown in Figure 2. Results show that the change in stress values due to different weak floor strata conditions are less than 20%. Thus, weak floor characteristics do not significantly affect immediate roof stress distribution. Non-uniform weak floor distribution reduces peak stress distribution. Therefore, it was decided not to modify the current CMRR system to incorporate effects of weak floor characteristics for typical geologic conditions.

**Effect of bolt stiffness on stress redistribution around a mining opening:** Having eliminated weak floor strata from consideration in designing primary supports, the goal was to assess the effect of roof bolt stiffness on stress distribution in the immediate roof strata with multiple layers as shown in Figure 2. Five (5) fully-grouted passive bolts were simulated across the entry as shown in Figure 4. The effect of bolt stiffness was assessed using three (3) different diameter (5/8 of an inch, 3/4 of an inch, and 7/8 of an inch) Grade 75 bolts as shown in Table 9. Uniform horizontal stress of 580 psi was applied to the entire model with no weak floor layer.

Vertical displacement of three (3) roof layers without bolting is shown in Figure 5. Yielded zones around the opening without and with bolting are shown in Figures 6 and 7, respectively. Vertical displacement of a horizontal plane 0.3 ft above the roof-coal interface for different bolts is shown in Figure 8. The axial force in the bolt adjacent to the rib, for different size bolts, is shown in Figure 9. Similar data for the third bolt from the edge of the entry is shown in Figure 10. Clearly, bolt stiffness affects excavation stability with #7 rebar (7/8-in diameter) bolts demonstrating significantly better results.
Three-Dimensional Analytical Study of a Coal Mine Intersection (Tasks 3, 4 and 5)

**Background:** There is a significant need for technical studies to improve stability of coal mine intersections. Towards the goal of improving stability at intersections, an attempt is made here to develop a better understanding of stress and displacements around an intersection and evaluate the effect of variables such as width of entry, thickness of weak floor strata, in-situ lateral stress fields, and the effect of laminations in the immediate roof. A displacement-based approach, similar to an analysis of mine subsidence, is developed that seems to more clearly delineate stability issues around an intersection. To the best of the authors’ knowledge, this approach has not been reported for evaluating stability of mine excavations. Stress and displacement-based approaches should be used together to better analyze stability problems for design of primary supports.

**Analytical studies:** The model developed for this task simulates a coal seam overlain by black shale, weak shaley-limestone, gray shale, and limestone to a height of about 39.3 ft above the coal seam. The immediate floor strata consist of claystone, limey-gray shale, and limestone down to a similar depth below the coal seam. The coal seam is 6.5 ft thick. The model extended 41 ft above the coal seam and 41 ft below the coal seam. The model was initially validated using a previous study (Chandrashekar, 1990). Analyses were performed in the elastic, layered-media domain. Analyses were initially performed for: 1) Layered, but with no slippage or separation between layers, 2) No weak floor strata, 3) Zero tectonically-induced lateral stress field, and 4) Entry width of 20 ft. Then, effects of one weak floor strata thickness, one set of values for horizontal stress field typically reported for Illinois, and layered-media capable of delamination, were evaluated (see Table 10). In model 6, a 6-in x 6-in x 6.5–ft post was installed 2 ft away from the corner of the intersection. The stiffness of the post was equivalent to a 0.6-in diameter, 6-ft long, fully-grouted bolt. In model 8, the stiffness of the post was increased to represent a 0.75-in diameter, 3-ft long, fully-grouted bolt. Model 10 is similar to model 2 except for 0.6 m of weak floor strata.

**Data analysis:** Initial analyses included horizontal, vertical, and shear stress redistribution along the plane 0.3 ft above the roof-coal interface (see Figures 13 to 15). Safety factor distribution around an intersection (see Figure 16) was also developed using the 3-D Mohr-Coulomb failure criterion with tension-cut off (Pariseau, 1973). Results indicate areas of high stress concentration and potential areas of failure but do not clearly explain the failure potential for cutter-roof and pillar corners. Therefore, analyses involving displacements and associated derivatives of slope, curvature, horizontal displacements and horizontal strain in and around an intersection were performed. Such an analysis for cross-section B-B’ in Figure 11, along the plane 0.3 ft above the roof-coal interface, is presented in Figures 17 and 18. These more clearly delineate zones of
potential failure based on tensile and compressive strains and positive and negative curvatures. Tensile strains and convex curvature are considered positive here.

Curvature and horizontal strain data are plotted along a line joining a point 10 ft from the center of the intersection to the center of the entry (see Figures 17 and 18). Results indicate zones of both high positive curvature or tensile strain and high negative curvature or compressive strain. High positive values are located 0.6 ft away from pillar ribs toward the entry that may cause failures in tension depending upon immediate roof properties. High negative values are located adjacent to the zone of high tensile strains that may cause cutter-roof behavior depending upon the immediate roof stratum shear strength. These values are located about 4 ft away from pillar ribs toward the center of the entry. Around the center of the entry there is relatively low or zero uniform tensile strain that may cause joints and discontinuities to open. The zone of high positive curvature and potential rib failures extends about 1.0-1.6 ft into the pillar. An analysis of the horizontal strain or horizontal stress along this cross-section indicates relatively low tensile or compressive stress depending upon the in-situ horizontal stress around the pillar center. These decrease as pillar ribs are approached. Tensile strains are observed near pillar edges within the solid coal pillar. Thus, one may expect failure of pillar ribs due to lower confinement. Adjacent to tensile strains and within the excavation, high compressive strains are observed that may lead to cutter-roof failure. These approaches may also be used to identify concepts for type and spatial distribution of artificial supports around an entry or an intersection that would minimize areas of high curvature and high horizontal strain.

**Comparisons of displacements and their characteristics in entries and intersections:** The curvature and horizontal strain data for Models 1 to 3 (see Table 10) along the cross-section B-B’ to the center of the entry are shown in Figures 17 and 18. Similar data for intersections along the cross-section A-A’ are given in Figures 21 and 23. The peak curvature values for intersections are about 50% smaller than for an entry. Horizontal strain values are similar and peak values exceeding 0.01 inches/ft or 0.2% strain may cause failures. High compressive horizontal strains are adjacent to pillar corners.

**Effect of selected variables on characteristics of displacements (Models 1-4):** The vertical displacement, slope and curvature data for Models 1 to 4 are given in Figures 19 to 21. The horizontal displacement and horizontal strain data for these same models are given in Figures 22 and 23. The effect of higher horizontal stresses is to reduce overall vertical displacement of the pillar as well as within the opening. The effect of allowing layers to delaminate is to increase vertical displacement within the opening but not of the pillar because the layers overlying the pillar can not delaminate. The effect of higher horizontal stress and allowing layers to delaminate is to increase the slope adjacent to pillar corners only. The maximum slope values are significantly increased (~ 50%).

The inflection point and peak value of positive curvature and its location are significantly affected by higher horizontal stresses and when layers to allowed to delaminate. The cutter-roof due to compressive strains is likely to occur closer to ribs. The positive (convex) curvature (tensile strain) is increased but the negative (concave) curvature (compressive strain) is relatively unaffected.
Horizontal strain data indicate that higher in-situ stresses and allowing layers to delaminate significantly affect peak horizontal strains, their signs and their location. Tensile strains in pillar corners and adjacent to corners into the opening are significantly increased. Allowing shear movement along bedding planes and bed separation reduces maximum tensile strain values in the immediate roof.

*Models 2, 4, and 5:* The effect of increasing entry width is to significantly increase compressive strains adjacent to pillar corners (see Figure 24). The peak horizontal strain is shifted from within the entry to over the pillar. The presence of weak floor strata slightly reduces the value of compressive strain and moves it closer to the pillar corner at the intersection (see Figure 25).

*Models 6 and 8:* Installing a lower stiffness support such as a typical bolt 2 ft away from the pillar corners does not have much effect on displacement redistribution (see Figures 26 and 27). However, increasing stiffness of the support to the equivalent of a 0.75-in diameter, 3-ft long, fully-grouted bolt significantly reduces negative curvature, but slightly increases tensile horizontal strain. Thus, a very high stiffness support can negatively impact stability of an excavation. For support stiffness of only 250,000 lbs/inch, two (2) times the value in Model 6, peak curvature and horizontal strains values are reduced suggesting that support stiffness and location need to be engineered.

*Application of displacement-based analyses for design of primary supports:* Displacement-based analyses presented here more clearly indicate potential zones of failure and likely failure mechanisms. The definition of failure zones must be based on allowable strain and curvature for immediate roof and floor strata similar to analyses in subsidence. These can be established based on a good literature review. FEA analyses and empirical relationships derived from them can be used to select the type of primary support and its stiffness, their spatial distribution, requirements for initial installation.

*Suggested layout for artificial supports at a coal mine intersection:* Based on all of these studies, an artificial support layout for a typical intersection that involves roof bolts and cable bolts is shown in Figure 28. A suggested mining sequence for developing an intersection to minimize stability problems is shown in Figure 29.

**Field Evaluation of Supplemental Supports at Intersections (Tasks 3, 4 and 5)**

*Background:* Wooden cribs are often used in mines as supplemental support. The principal investigator is involved in the development of an engineered crib element as part of a separate project funded by the ICCI. As part of this project, it was decided to evaluate the performance of supplemental crib supports to control roof failure around four-way intersections. The cooperating mine operates in the No. 6 coal seam at a depth ranging from 110 ft to 370 ft. The immediate roof strata consist of 1-2 ft of Anna shale, overlain by limestone and sandy-shales. The coal seam thickness averages 55 inches. The immediate floor strata consist of claystone down to a depth of 4-5 ft and that is underlain by shales and limey-shales.
Experimental Procedures: Four (4) intersections were selected in an area with thin limestone in the immediate roof strata (see Figure 30). The mine operator installs 8-ft long roof bolts when limestone is less than 1-ft thick. These intersections have 8-ft, fully-grouted, tension-rebar bolts installed as primary supports. Supplemental supports were installed diagonally at each corner of the intersection (see Figure 31) based on 3-D finite element modeling described earlier. Crib supports were built 36 inches wide by 72 inches long as six-point cribs. Intersections #1 and #2 had conventional cribs and intersections #3 and #4 had ATLAS engineered cribs (Chugh et al., 2008). Conventional cribs had alternating layers of three (3) 3.25-in x 5.25-in x 36-in elements and two (2) 5.75-in x 5.75-in x 72-in timbers. ATLAS cribs were constructed using six (6), 11-in x 11-in x 3.5-in bases supporting alternating layers of three (3) 6.25-in x 5.75-in x 36-in and two (2) 6.25-in x 5.75-in x 72-in elements. Crib supports were instrumented with convergence points as shown in Figure 32. It should be noted that ATLAS cribs are installed at much larger intersections than conventional cribs. In addition, one (1) post with SIUC load cell was installed at each crib (see Figure 31) to determine the need for additional supports. Crib supports provided an unobstructed travel way at least 8 ft wide. Each intersection had monitoring systems to determine roof-to-floor convergence and loading on the cribs.

Observations: Roof conditions were observed to be good when supplemental supports were installed on January 20–21, 2009. Small amounts of sloughing along the ribs in intersection #4 and in the crosscut connecting intersections #2 and #4 were observed on February 9 and 17, 2009. Intersections #2 and #4 show more roof-to-floor convergence than other intersections (see Table 11). Table 12 indicates that posts in intersection 2, 3 and 4 are experiencing the most load. Some of the negative values are probably due to drying of wooden posts and wood capping material. Crib-mounted convergence points indicate no loading. The PI visited the area on February 17, 2009. Some posts were taking load but most of them were not. Monitoring of these intersections will continue at intervals over a long period of time.

Guidelines for Pre-mining Investigations for Ground Control (Task 7)

Background: The principal investigator has extensive experience with pre-mining investigations in the Illinois Basin and his recommendations have been extensively used in the coal industry (Kester and Chugh, 1980; Chugh et al., 1982). The goal of this task was to provide additional guidance to the coal industry in performing pre-mining investigations. Evaluation of ground control for active coal mines and un-mined reserves is a complex task due to numerous geologic and geotechnical variables that must be considered. The authors here attempt to identify such variables in order to better understand their impact on ground control and assess roof and floor control problems and associated mining conditions.

Studying core obtained from exploration drilling programs, mapping mined-out areas (especially roof falls) within active coal mines, mapping the regional geology to determine coal structure, and studying hydrogeology are crucial to understanding ground control. Although the impact of adverse geologic conditions on ground control is difficult to predict, it is important to thoroughly evaluate them and consider their
interrelationships. Such analyses can provide some indication of the anticipated mining conditions that can be improved once mining operations have begun.

**Evaluating core:** The geologist has numerous responsibilities during core drilling and should be experienced in documenting necessary information. This information includes, but is not limited to, photographing the core and describing the core geologically and geo-technically. The amount of roof and floor strata cored depends on the rock type and variations of these strata. In general, coring approximately 20 ft of roof and 10 ft of floor should provide sufficient strata for ground control evaluation. However, for coal deposits where extremely thick weak roof or weak floor strata occur, coring more than 20 ft of roof or 10 ft of floor strata may be necessary.

**Core descriptions:** An accurate and thorough core description is a valuable tool for mining engineers because it provides detailed information that will allow for a better understanding of potential ground control problems. A suggested core description is included in Figure 33. This information should include primary features, such as rock type, color, and grain size (if applicable). However, secondary features are equally important and are discussed below.

**Bed Spacing:** Bed spacing is the strata thickness between adjacent bedding surfaces. These surfaces represent the original surface of deposition. As bed spacing decreases (i.e. strata thins), the lithology may break more frequently along bedding planes, resulting in more roof control problems.

**Laminae:** These are the thinnest recognizable strata of deposition (less than 1 cm in thickness) and differ from the adjacent strata in color, composition, or grain size. Laminae are very common in sedimentary strata and represent variations in the rate of deposition or differences in material deposited. A lamina surface represents a weak surface plane, and may cause ground control problems.

**Texture:** Texture refers to the physical appearance or character of a rock. Some examples of texture are crystalline, friable, fissile, homogeneous, and nodular. Certain types of texture may minimize ground control problems, whereas others may enhance them. For example, lithologies that are friable, fissile, or nodular may enhance problems.

**Sedimentary Structures:** Some examples of sedimentary structures are cross-banding, convoluted bedding, massive, and carbonaceous material. Similar to texture, not all sedimentary structures are detrimental to roof control. For example, a stratum that is massive is likely to be stronger than a stratum that is layered.

**Rock Hardness Scale:** Rock hardness may be used to estimate rock strength. The American Society of Engineers has devised a qualitative rock hardness test described below that is unrelated to Moh’s scale of hardness for minerals.

- **Very Soft** – Scratches easily with a knife or fingernail, excavates easily with a rock hammer.
• Soft – Grooves easily with a knife or rock hammer, breaks in chips to pieces several inches thick with moderate blow of rock hammer.
• Medium – Grooves \(\frac{1}{16}\) of an inch deep by firm pressure with knife or rock hammer, breaks in small chips to pieces 1 inch maximum size with hard blows of rock hammer.
• Moderately Hard – Scratches with knife or pick point. Grooves up to \(\frac{1}{4}\) of an inch deep can be excavated by hard blow with a rock hammer.
• Hard – Difficult to scratch with knife. Hard blow with rock hammer is required to obtain a hand specimen.
• Very Hard – Cannot be scratched with knife. Several hard blows with rock hammer required to get a hand specimen.

**Rock Quality Designation (RQD):** This core evaluation technique can be described as a modified core recovery approach that incorporates only those pieces of the core that are 100 mm (approximately 4 inches) or larger in length. The smaller pieces are not included since they are caused by jointing, shear zones, faulting, etc. A minimum core diameter of 54 mm (approximately 2 inches) is recommended. It is suggested that RQD be determined as soon as the core is removed from the core barrel. This generally requires 30-45 minutes. In the Illinois Basin, additional natural core breaks typically occur after a period of time and may significantly change RQD values. The cause of these “delayed” breaks is associated with stress, and more specifically with faulting, lineaments, structure anomalies, or rapid changes in strata thickness. RQD alone can be misleading. For example, lithologies with high clay content (e.g. claystones and mudstones) are often very soft and have very low unconfined compressive strength and tensile strength, but can have an RQD of 100% due to binding action of clays. Thus, it is important to study all field and laboratory data when reviewing RQD values.

**Hydrogeology:** This parameter is commonly ignored by the industry. Water inflow into a coal mine either through roof or floor strata is always detrimental to ground control. The vast majority of ground water is associated with sandstone strata. Sandstones occurring within 100 ft of the coal seam should be mapped for bottom structure elevation, thickness, and interburden thickness. Sandstones occurring below the coal seam of interest (e.g. within 20 ft) should be mapped for top structure elevation, thickness, and interburden thickness. Water inflow may be greatest where sandstone is thickest and interburden is thinnest. If large volumes of water are expected, pump tests are needed and dewatering may be needed to allow for productive mining. Fault and lineament mapping should be included because fractures are often avenues for water inflow.

**Geologic Interpretation:** In order to evaluate ground control, proper understanding of geology is required. This includes, but is not limited to, studying data obtained from a coring program (e.g. core photos, core descriptions, and geophysical logs), depositional environments, structural setting, rock strength data obtained from lab testing, and hydrogeology. After these items are studied, specific potential problems should be noted, and mapped to obtain a regional picture of these problems. A single map should be generated to show all potential problems. This map, referred to as a “hazard map”, should
be provided to mining operations staff for more efficient mine planning. Such maps are also valuable in assessing bolt length and density of bolting in different areas of the mine.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

- Over 80% of reportable roof falls occur at intersections and most of these occur at four-way intersections.
- Most falls have a height about 1-2 ft above the length of installed bolts. This is true irrespective of bolt length or type of bolt involved.
- A roof fall database analysis can provide very meaningful observations on the effectiveness of different types of bolts in various geologic settings. However, this can only be achieved if appropriate data for normalization (production, length of entries driven, etc.) are collected.
- For typical geologic conditions in Illinois (~2 ft of weak floor strata), floor characteristics do not need to be considered in design of primary roof supports during mine development.
- In most mines, moisture content of the immediate floor strata and its thickness are the best parameters for consideration in designing pillars. A few attempts to relate floor structure to moisture content and Atterberg Limits at specific sites were not successful.
- Most evaluated sites had very low CMRR values in the range of 30 to 45.
- Most falls were associated with geologic anomalies rather than CMRR values. These included shear zones, compressional faults, clay dikes, and litho-facies changes, etc.
- Shear strength of different laminae within shale beds, based on the Diametral Point Loading Test, is generally extremely low and dominates the calculation of CMRR values.
- In transitional roof lithology areas around sandstone channels, time-dependent performance of primary roof supports becomes more important since rock mass deformations occur due to pre-existing discontinuities and degradation of rock mass properties due to moisture absorption and migration.
- A displacement-based approach, developed as part of this project, helps to explain intersection pillar corner failures as well as cutter-roof development much better than stress-based analyses.
- Analyses conducted as part of this project suggest the need for stiffer support around pillar edges. However, support stiffness must be engineered depending upon site-specific rock mass characteristics.

Recommendations

- There is an urgent need to develop and implement uniform procedures for collection of data on roof falls.
• Performance of different types of roof bolts needs to be investigated in the field in different lithologies typical of Illinois mines. Such investigations should include time-dependent performance.
• Alternate intersection support concepts should be evaluated using numerical analyses before considering field implementation.
• Long-term monitoring of intersections in the field should be undertaken to understand the mechanics of failures.
• The proposed supplementary supports, evaluated in this project as intersection support, may have significant potential in longwall mining for bleeder entries.

REFERENCES


**TABLES**

**Table 1:** Falls per million tons of production by month.

<table>
<thead>
<tr>
<th>Month</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>July</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Falls</td>
<td>5</td>
<td>2.5</td>
<td>3.1</td>
<td>3</td>
<td>3</td>
<td>3.8</td>
<td>4.5</td>
<td>5.1</td>
<td>5</td>
<td>5.2</td>
<td>5.1</td>
<td>5.1</td>
</tr>
</tbody>
</table>

**Table 2:** Fall characteristics by standup time and fall volume.

<table>
<thead>
<tr>
<th>Fall vol. (cu. ft×100)</th>
<th>Stand up time (days)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 to 30</td>
<td>31 to 60</td>
</tr>
<tr>
<td>0 – 9</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>9 - 36</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>36-72</td>
<td>11</td>
<td>9</td>
</tr>
<tr>
<td>72-144</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>144-288</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Total</td>
<td>32</td>
<td>25</td>
</tr>
<tr>
<td>%</td>
<td>13</td>
<td>10</td>
</tr>
</tbody>
</table>

**Table 3:** Fall characteristics by type of primary bolt support and fall volume.

<table>
<thead>
<tr>
<th>Type of primary bolt support</th>
<th>Conventional (in)</th>
<th>Point-anchor (in)</th>
<th>Fully-grouted (in)</th>
<th>Tension-rebar (in)</th>
<th>Double-lock (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Falls</td>
<td>48</td>
<td>60</td>
<td>84</td>
<td>96</td>
<td>60</td>
</tr>
<tr>
<td>Falls</td>
<td>2</td>
<td>6</td>
<td>14</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Total</td>
<td>27</td>
<td>118</td>
<td>139</td>
<td>22</td>
<td>3</td>
</tr>
<tr>
<td>%</td>
<td>9</td>
<td>38</td>
<td>45</td>
<td>7</td>
<td>1</td>
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</table>

**Table 4:** Fall characteristics by fall height and bolt length.

<table>
<thead>
<tr>
<th>Fall height (ft)</th>
<th>48</th>
<th>60</th>
<th>72</th>
<th>96</th>
<th>Total</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 and below</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>14</td>
<td>5</td>
</tr>
<tr>
<td>5-7</td>
<td>5</td>
<td>5</td>
<td>36</td>
<td>3</td>
<td>49</td>
<td>17</td>
</tr>
<tr>
<td>7-9</td>
<td>5</td>
<td>2</td>
<td>87</td>
<td>32</td>
<td>126</td>
<td>43</td>
</tr>
<tr>
<td>9-11</td>
<td>2</td>
<td>0</td>
<td>38</td>
<td>26</td>
<td>66</td>
<td>23</td>
</tr>
<tr>
<td>11 and above</td>
<td>0</td>
<td>4</td>
<td>4</td>
<td>29</td>
<td>37</td>
<td>13</td>
</tr>
<tr>
<td>Total</td>
<td>17</td>
<td>14</td>
<td>168</td>
<td>93</td>
<td>292</td>
<td>100</td>
</tr>
<tr>
<td>Percentage</td>
<td>6</td>
<td>5</td>
<td>58</td>
<td>32</td>
<td>100</td>
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</table>
Table 5: CMRR values for different cores from exploration drilling.

<table>
<thead>
<tr>
<th>Mine</th>
<th>CMRR for Core No.</th>
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<tbody>
<tr>
<td>1</td>
<td>34 33 38 27 28</td>
</tr>
<tr>
<td>2</td>
<td>39 43 46 45 43</td>
</tr>
</tbody>
</table>

Table 6: Rock mass properties.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Young's modulus (psi)</th>
<th>Poisson's ratio</th>
<th>Tensile strength (psi)</th>
<th>Cohesion (psi)</th>
<th>Friction angle (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limestone</td>
<td>700,000</td>
<td>0.18</td>
<td>217</td>
<td>1,160</td>
<td>25</td>
</tr>
<tr>
<td>Black Shale</td>
<td>100,000</td>
<td>0.3</td>
<td>65</td>
<td>650</td>
<td>25</td>
</tr>
<tr>
<td>Weak Limestone</td>
<td>435,000</td>
<td>0.22</td>
<td>145</td>
<td>1,750</td>
<td>30</td>
</tr>
<tr>
<td>Lawson Shale</td>
<td>75,000</td>
<td>0.35</td>
<td>50</td>
<td>435</td>
<td>20</td>
</tr>
<tr>
<td>Grey Shale</td>
<td>300,000</td>
<td>0.27</td>
<td>145</td>
<td>940</td>
<td>27</td>
</tr>
<tr>
<td>Coal</td>
<td>150,000</td>
<td>0.32</td>
<td>65</td>
<td>650</td>
<td>26</td>
</tr>
<tr>
<td>Claystone</td>
<td>30,000</td>
<td>0.35</td>
<td>10</td>
<td>130</td>
<td>20</td>
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Table 7: 2-D finite element analysis models for assessing effect of weak floor strata.

<table>
<thead>
<tr>
<th>Model No</th>
<th>Entry Width (ft)</th>
<th>Weak Floor Thickness (ft)</th>
<th>Vertical Stress (psi)</th>
<th>Horizontal stress field (psi)</th>
<th>Bedding plane slippage</th>
<th>Artificial Support</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>362</td>
<td>580</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>0</td>
<td>362</td>
<td>580</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>3</td>
<td>20</td>
<td>2</td>
<td>362</td>
<td>580</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>4</td>
<td>20</td>
<td>4 (non-uniform)</td>
<td>362</td>
<td>580</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>5</td>
<td>20</td>
<td>4 (uniform)</td>
<td>362</td>
<td>580</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 8: Peak stress values around an entry for different conditions.

<table>
<thead>
<tr>
<th>Vertical stress (psi)</th>
<th>No weak Floor</th>
<th>2 ft thick weak floor (uniform)</th>
<th>4 ft thick weak floor (uniform)</th>
<th>4 ft thick weak floor (non-uniform)</th>
</tr>
</thead>
<tbody>
<tr>
<td>565</td>
<td>652</td>
<td>696</td>
<td>580</td>
<td></td>
</tr>
<tr>
<td>Horizontal stress (psi)</td>
<td>957</td>
<td>1,073</td>
<td>1,145</td>
<td>1,000</td>
</tr>
<tr>
<td>Shear stress (psi)</td>
<td>333</td>
<td>392</td>
<td>420</td>
<td>355</td>
</tr>
</tbody>
</table>

Table 9: Finite element models for assessing effect of bolt stiffness.

<table>
<thead>
<tr>
<th>Model</th>
<th>Entry Width (ft)</th>
<th>Weak Floor Thickness (ft)</th>
<th>Vertical Stress (psi)</th>
<th>Horizontal stress field (psi)</th>
<th>Artificial Support (6 ft, Grade 75 fully grouted passive bolt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bolt 1</td>
<td>20</td>
<td>2</td>
<td>362</td>
<td>580</td>
<td>5/8-in diameter</td>
</tr>
<tr>
<td>Bolt 2</td>
<td>20</td>
<td>2</td>
<td>362</td>
<td>580</td>
<td>6/8-in diameter</td>
</tr>
<tr>
<td>Bolt 3</td>
<td>20</td>
<td>2</td>
<td>362</td>
<td>580</td>
<td>7/8-in diameter</td>
</tr>
</tbody>
</table>
Table 10: Matrix of models analyzed.

<table>
<thead>
<tr>
<th>Model</th>
<th>Entry Width (ft)</th>
<th>Weak Floor Thickness (ft)</th>
<th>Horizontal stress filed</th>
<th>Lithologic units bonded or un-bonded</th>
<th>Artificial Support</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20</td>
<td>0</td>
<td>No</td>
<td>Bonded</td>
<td>No</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>0</td>
<td>Yes</td>
<td>Bonded</td>
<td>No</td>
</tr>
<tr>
<td>3</td>
<td>20</td>
<td>0</td>
<td>Yes</td>
<td>Un-bonded</td>
<td>No</td>
</tr>
<tr>
<td>4</td>
<td>22</td>
<td>0</td>
<td>Yes</td>
<td>Un-bonded</td>
<td>No</td>
</tr>
<tr>
<td>5</td>
<td>22</td>
<td>2</td>
<td>Yes</td>
<td>Un-bonded</td>
<td>No</td>
</tr>
<tr>
<td>6</td>
<td>22</td>
<td>2</td>
<td>Yes</td>
<td>Un-bonded</td>
<td>Yes</td>
</tr>
<tr>
<td>8</td>
<td>22</td>
<td>2</td>
<td>Yes</td>
<td>Un-bonded</td>
<td>Yes</td>
</tr>
<tr>
<td>10</td>
<td>20</td>
<td>2</td>
<td>Yes</td>
<td>Bonded</td>
<td>No</td>
</tr>
</tbody>
</table>

Model 6: Stiffness of post is 125,000 lbs/inch.
Model 8: Stiffness of post is 375,000 lbs/inch.

Table 11: Roof-to-floor convergence (1/21/09 to 2/9/09).

<table>
<thead>
<tr>
<th>Intersection</th>
<th>Mean convergence (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.01249</td>
</tr>
<tr>
<td>2</td>
<td>0.03322</td>
</tr>
<tr>
<td>3</td>
<td>0.00265</td>
</tr>
<tr>
<td>4</td>
<td>0.03006</td>
</tr>
</tbody>
</table>

Table 12: Post-mounted SIUC load cell compression (1/21/09 to 2/9/09).

<table>
<thead>
<tr>
<th>Load cell</th>
<th>Interception</th>
<th>Intersection</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>0.0168</td>
<td>-0.0080</td>
</tr>
<tr>
<td>2</td>
<td>-0.0011</td>
<td>0.0075</td>
</tr>
<tr>
<td>3</td>
<td>0.0098</td>
<td>0.0076</td>
</tr>
<tr>
<td>4</td>
<td>0.0128</td>
<td>0.0065</td>
</tr>
</tbody>
</table>
Figure 1: Bolt length vs. fall height.

Figure 2: Two-dimensional finite element model.
Figure 3: Vertical stress 0.3 ft above roof-coal interface for uniform 2 ft and 4 ft thick weak floor.

Figure 4: Typical layout of bolts in an entry.

Figure 5: Vertical displacement of different layers in the immediate roof for 2 ft thick weak floor.
Figure 6: Yielding areas without bolts and zero weak floor.

Figure 7: Yielding areas with bolts (7/8-in) and zero weak floor.

Model 1: No weak floor; all bolts 3/4-in dia., 6 ft long.
Model 2: 2 ft thick weak floor; all bolts 3/4-in dia., 6 ft long.
Model 3: 2 ft thick weak floor; 2 edge bolts 3/4-in dia., 4 ft long;
3 middle bolts 3/4-in dia., 6 ft long.

Figure 8: Vertical displacement 0.3 ft above roof-coal interface.
Figure 9: Axial force in the bolt adjacent to the rib.

Figure 10: Axial force in the third bolt from the rib.

Figure 11: Modeled area of four-way intersection.

Figure 12: 3-D finite element analysis model.
Figure 13: Horizontal stress 0.3 ft above roof-coal interface.

Figure 14: Vertical stress 0.3 ft inches above the roof-coal interface.

Figure 15: Shear stress 0.3 ft above roof-coal interface.

Figure 16: Safety factor contours 0.3 ft above roof-coal interface – Model 2.
Figure 17: Curvature along section B-B’ for Models 1, 2, and 3.

Figure 18: Horizontal strain along section B-B’ for Models 1, 2, and 3.

Figure 19: Vertical displacement along the line A-A’.

Figure 20: Slope along the line A-A’.
Figure 21: Curvature along the line A-A’.

Figure 22: Horizontal displacement along the line A-A’.

Figure 23: Horizontal strain along line A-A’ showing effect of increasing entry width.

Figure 24: Horizontal strain along the line A-A’.
Figure 25: Curvature along the line A-A’ showing effect of weak floor strata.

Figure 26: Curvature along the line A-A’ showing effect of bolt stiffness.

Figure 27: Horizontal strain along the line A- A’ showing effect of bolt stiffness.

Figure 28: Proposed layout of artificial supports for roof control at an intersection.
Figure 29: Suggested cut sequence for intersection development.

Figure 30: Mine map of intersection locations.

Figure 31: Intersection supplemental support installation.
Figure 32: Crib convergence points.

Figure 33: Suggested core description.
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