ISRM Congress 2015 Proceedings - Int'l Symposium on Rock Mechanics - ISBN: 978-1-926872-25-4

SHALE FAILURE MECHANICS AND INTERVENTION MEASURES IN UNDERGROUND COAL MINES: RESULTS FROM 50 YEARS OF GROUND CONTROL SAFETY RESEARCH

KEYNOTE

M.M. MURPHY
NIOSH – OFFICE OF MINE SAFETY AND HEALTH RESEARCH
Pittsburgh, PA
mmu5@cdc.gov

ABSTRACT

Ground control research in underground coal mines has been ongoing for over 50 years. One of the most problematic issues in underground coal mines is roof failures associated with weak shale. This paper will present a historical narrative on the research the National Institute for Occupational Safety and Health has conducted in relation to rock mechanics and shale. This paper begins by first discussing how shale is classified in relation to coal mining. Characterizing and planning for weak roof sequences is an important step in developing an engineering solution to prevent roof failures. Next, the failure mechanics associated with the weak characteristics of shale will be discussed. Understanding these failure mechanics also aids in applying the correct engineering solutions. The various solutions that have been implemented in the underground coal mining industry to control the different modes of failure will be summarized. Finally, a discussion on current and future research relating to rock mechanics and shale is presented. The overall goal of the paper is to share the collective ground control experience of controlling roof structures dominated by shale rock in underground coal mining.

KEYWORDS

Ground control, rock mechanics, shale, underground coal mining

INTRODUCTION

The National Institute for Occupational Safety and Health's (NIOSH) Office of Mine Safety and Health Research (OMSHR), formerly the United States Bureau of Mines, has been conducting research on ground control safety for over 50 years. The overall objective of the research is to reduce underground mining injuries and fatalities by characterizing roof conditions, improving roof support performance and application, and optimizing pillar design and mine layout. Underground mining has one of the highest fatal injury rates of any industry in the United States—more than five times the national average compared to other industries (CDC, 2012). Roof fall injuries can be severe, resulting in lacerations, bone fractures, amputations, and death. Non-injury roof falls can also be problematic, resulting in lost production, delays, blockage of primary escape routes, disruption to ventilation, and hazardous rehabilitation conditions.

Coal mining is increasingly subject to more adverse geological conditions. Weak roof can be found in all coal mining regions in the United States, but there are a few geographically isolated areas with higher roof fall rates contributed to by particularly poor roof conditions, as represented in Figure 1. This figure shows that when non-injury roof fall rates are normalized to production, the Illinois Basin and Central/Northern Appalachia regions have the highest rates. These isolated regions have inherently weak roof even before mining has occurred, and this roof is easily damaged during the mining process. The weak roof in these regions consists primarily of shale. Shale can be troublesome in underground coal mining because it can appear massive but easily splits along bedding planes and is often moisture-sensitive.

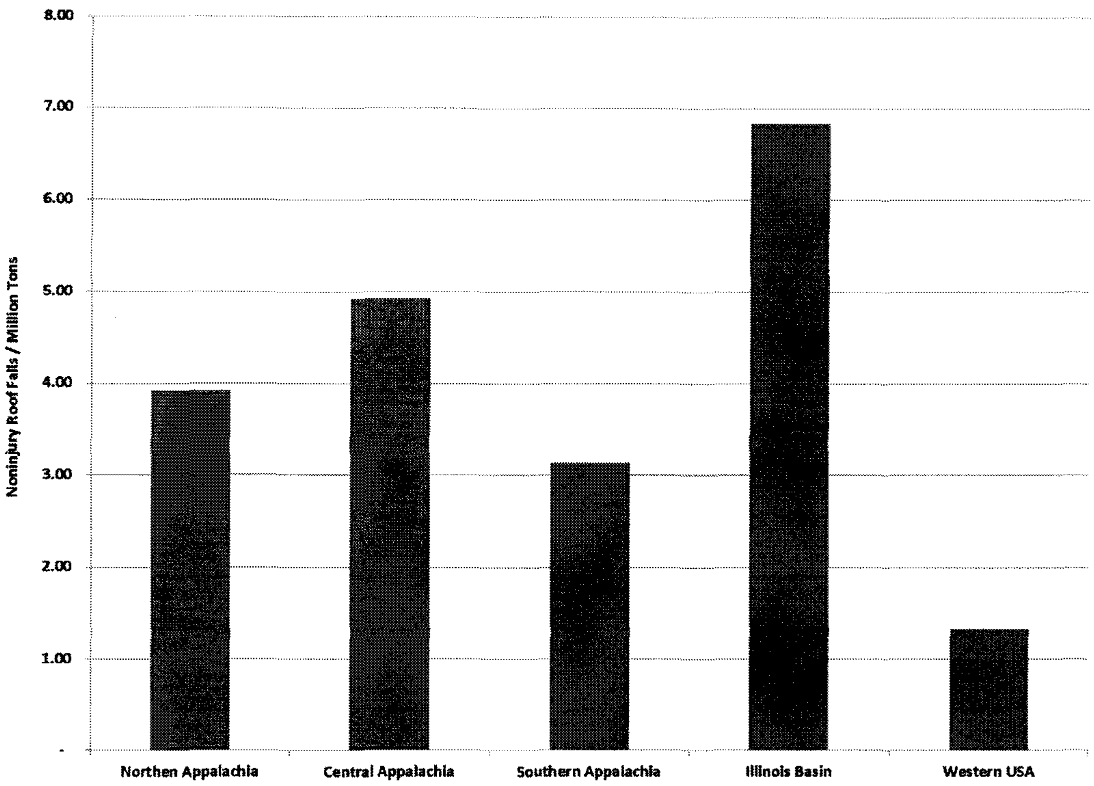

Figure 1 – Non-injury roof fall rates by U.S. region from 1983 to 2013.

The focus of this paper is to first discuss how shale is classified in relation to coal mining. Characterizing and planning for weak roof sequences is an important step in developing an engineering solution to prevent roof falls. Next, the failure mechanics associated with the weak characteristics of shale will be discussed. Understanding the failure mechanics also aids in applying the correct engineering solutions. Finally, the various solutions that have been implemented in the underground coal mining industry to control the different modes of failure will be summarized.

CLASSIFICATION OF SHALE

Shale is present in every coal mining region; however the geological makeup of shale between these regions can be vastly different. The shale rocks in these regions are typically from the Pennsylvanian period. To a geologist, shale can be described as bedded rocks that are so fine-grained they can appear to be smooth when rubbed against one's teeth. The grain size of shale is typically finer than 3.9 microns (Ellenberger, 2014). Shale differentiates from other weak rock such as mudstone due to the presence of bedding. The color of shale can give a rudimentary visual indication to the strength of the rock, as it is generally noted that the lighter the color, the weaker the shale (Molinda, 2003). The different physical and mechanical properties of shale need to be quantified and standardized in relation to the mine environment.

Rock mass classification gives mining engineers a qualitative evaluation of the geological characterization of the coal mine roof. Classification is valuable in ground control because geological conditions and characteristics can vary between different coal mining regions, and more importantly, can vary suddenly even within the same coal mine seam. The Coal Mine Roof Rating (CMRR) was developed as a rock mass classification scheme for bedded coal measure rock (Molinda and Mark, 1994). The CMRR is similar to Bieniawski's Rock Mass Rating (Bieniawski, 1973), where individual ratings are summarized to a scale of 0-100 for a final rating. However, the CMRR differs and applies specifically to a coal mine environment so that bedding discontinuities, in addition to joints, can be taken into account. CMRR also allows multiple units of rock to be included in the rating.

Prior to the development of the CMRR, bedding was consistently cited as a factor in causing roof failures (Mark and Molinda, 2007). The two main sources of bedding in a coal mine environment are weak laminations within shale or thinly interbedded sandstone and shale sequences, often known as "stack rock". A photograph demonstrating thin beds within shale is shown in Figure 2.

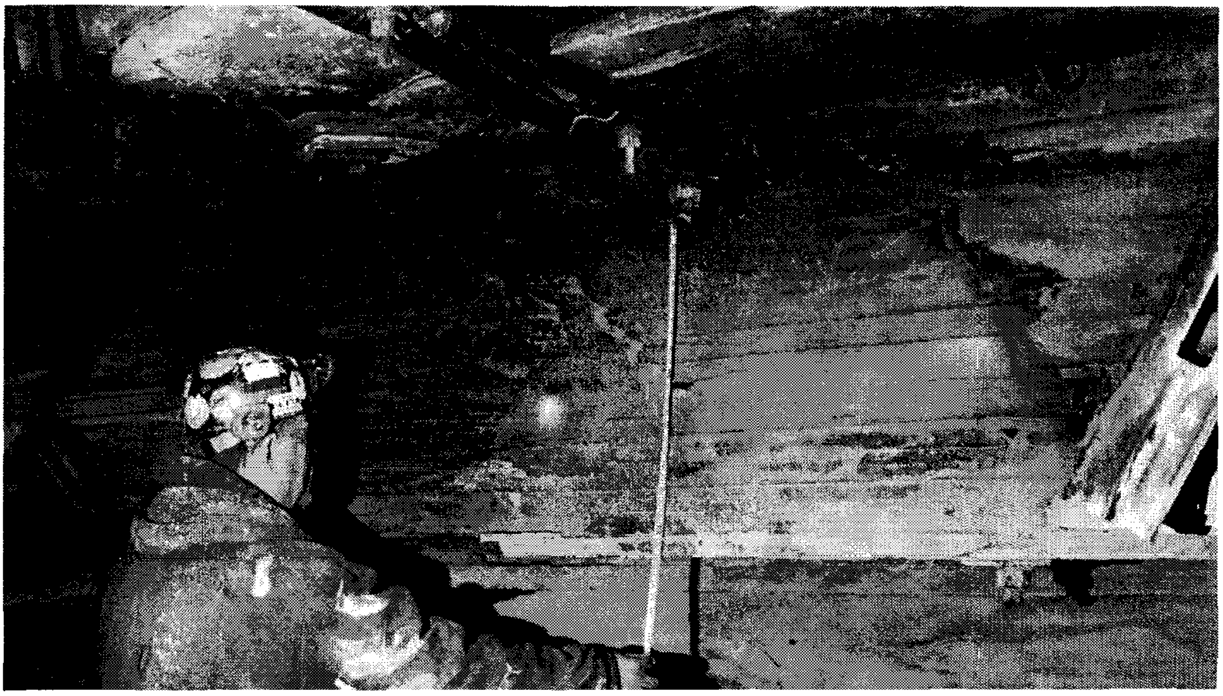

Figure 2 – Photograph showing a shale mine roof with thin beds.

Often shale sequences might appear to be massive, but in fact are highly laminated. The spacing, persistence, cohesion, and roughness of the bedding planes are factored into the final CMMR rating to include these weak bedding characteristics.

Another factor that is included in the CMRR, but ignored in other rock mass classification systems, is moisture sensitivity. Moisture sensitivity is extremely important when classifying shale because two shale units might have similar mechanical properties and strengths, but behave differently in the presence of ground water. The effect of water on a moisture-sensitive shale sample is shown in Figure 3. The left sample in the photograph is nearly impervious to water but the right sample essentially becomes mud when coming into contact with water. In some cases, this behavior can be observed within minutes of moisture contact. More details on the failure mechanisms associated with moisture sensitivity are discussed later.

Figure 3 – The effect of water on a moisture-sensitive shale (from Mark and Molinda 2007).

Coal mine roof ratings of less than 45 are classified as 'weak roof' according to the methodology. Approximately 70% of the mines in the CMRR database with a value of less than 45 are in the Illinois or Northern Appalachian basins, where the mine roof is typically comprised of highly laminated, moisture-sensitive shale (Rusnak and Mark, 2000). These are the regions where mining engineers have the most difficultly solving ground control issues associated with shale, and these regions were identified earlier as having the highest non-injury roof fall rates. The following two sections discuss the failure mechanisms behind the roof falls associated with these weak shale environments.

SHALE AS A BEDDED MATERIAL

Failure Mechanisms

At the field scale, bedded shale can be relatively strong perpendicular to bedding, but is often considerably weaker parallel to bedding (Molinda and Mark, 1996). When subjected to horizontal tectonic stresses, the bedded shale becomes unstable when the horizontal stress exceeds the reduced strength parallel to the bedding. At the roof and rib intersection, where stresses are concentrated, the shale beds can progressively crush, creating instability (Hill, 1986). This form of failure is often known as "cutter" roof and is illustrated in Figure 4.

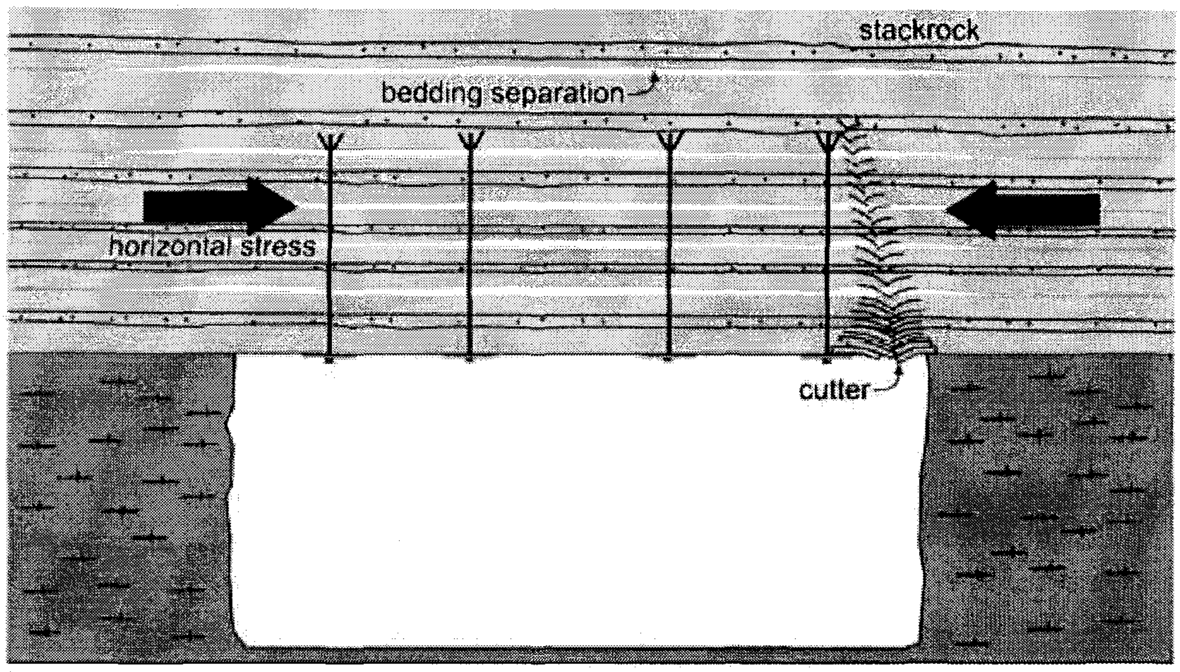

Figure 4 – Cutter formation as a result of high horizontal stress (from Molinda and Mark, 2010).

Historically, cutter roof related failures are one of the most common failure modes in coal mines, and they still create ground control-related problems today (Thomas, 1950; Gale, 1986; Hill, 1986; Gadde and Peng, 2005). An up-close picture of a cutter roof failure at the roof and rib intersection can be seen in Figure 5. In the photo, a large vertical crack has formed at the start of the roof and extends vertically through all the laminations (middle of photo). A roof fall at this location allowed for this visual observation of the cutter propagation.

Figure 5 – Cutter roof failure of a weak shale rock at the roof-rib intersection.

Figure 6 shows an example of a cutter roof failure that started on both sides of the entry and connected at an interface high above when a more competent stratum was reached. The result was a massive dead load of rock that had to be supported by the wood cribs. Figure 7 shows a cutter roof failure that formed massive fracture planes along the edge of the rib. Because of the large fracture plane developed by the cutter, the roof started to cantilever, which can create further instability if the displacement of the beams cannot be controlled.

Cutters can also form in roof consisting of strata other than weak shale. In stack rock, represented by sequences of interlaminated sandstone and shale, horizontal stress can concentrate in the stiffer sandstone layers. These stress concentrations can cause tensional delamination and deflection along the interfaces, which crush the weaker shale layers at the rib abutment (Molinda, 2003), causing the cutter roof failure. In most cutter roof type failures, the fracture propagates at an angle greater than 60 degrees from horizontal and normally requires a strong, competent layer such as sandstone to prevent the failure from propagating further. However, the fracture reaching the strong layer is also likely to cause separation at the interface, resulting in a detached block of roof rock as depicted in the previous photographs.

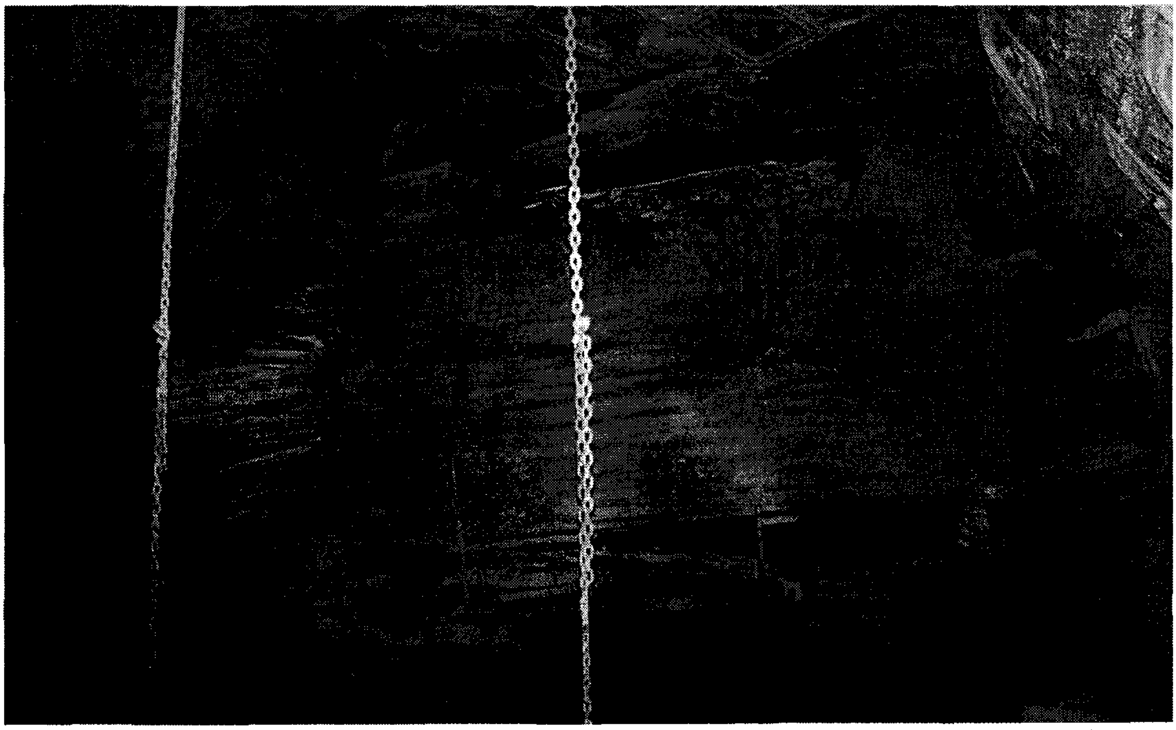

Figure 6 – Cutter failure that caused detached block, leading to a dead load of rock resting on support.

Figure 7 – Buckling of strata associated with cutter formation has defined a vertical discontinuity (seen by the arrow), which in turn has allowed cantilevering off the opposite rib.

Roof sag is another contributing factor to deterioration of a weak roof shale and contributor to cutter roof failure. In a thick shale sequence that contains bedding contacts with low cohesion strength, the roof can bend downward when the bedding contacts are broken in shear or tension. As the roof sags, crushing develops at the roof and rib intersection causing cutter roof failure, or tension cracks can develop in the roof beam (Molinda and Mark, 2010). Figure 8 depicts an illustration of roof sag causing cutter roof failure and tensional cracks.

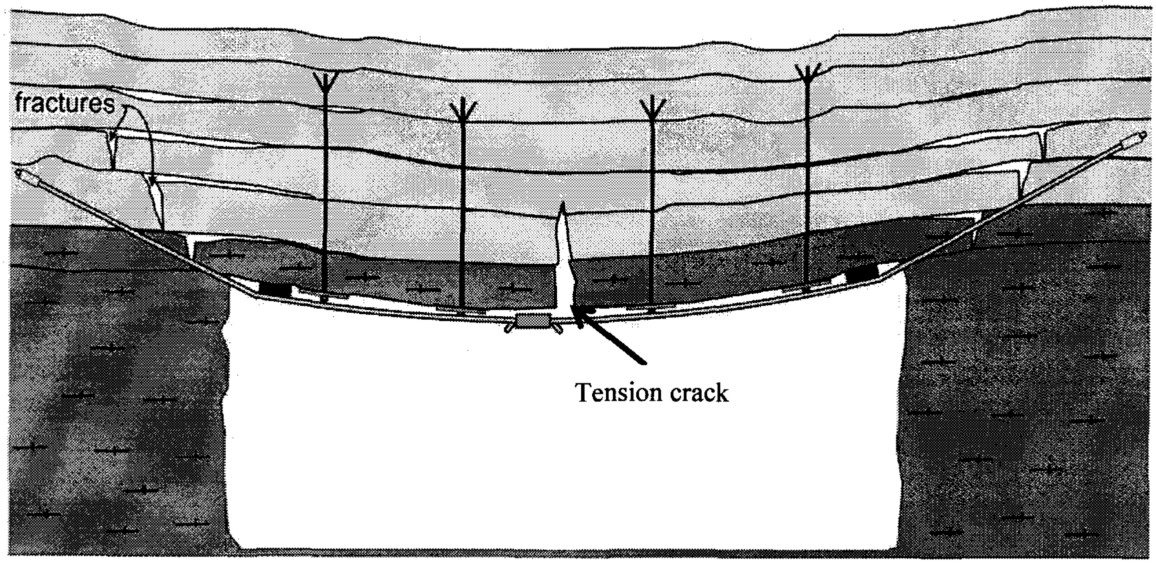

Figure 8 – Cross section of entry showing two modes of failure caused by sagging roof (from Molinda and Mark, 2010).

A problem with predicting cutter roof failures is that often they display inconsistent spatial trends throughout the mine, so predicting and identifying the specific mechanisms behind the failures can be difficult. This is because the rock can gradually become more coarse or less coarse, making visual observations of changes in lithology and prediction of cutter locations challenging. It is well known to the mining industry that cutter failures will form in weak rock under high horizontal stresses, but at times the rock can be weaker than originally characterized during development or the rock can become weaker over time, making the cutter roof failure a problem persistent in many mines.

Control Measures for Bedded Shale

Since cutter roof failure is associated with high horizontal stresses, an initial control measure in preventing this type of failure mechanism is to find the optimum orientation for entry development. If the local horizontal stress field orientation can be determined, the entries should be developed as parallel as possible to the major horizontal stress. This will minimize the cutter roof formation on the entry corners. The stress field can be measured using field stress measurements or can be inferred by analyzing roof fall orientations or mapping developed cutters throughout the mine (Mark and Gadde, 2008). In some cases of very weak mine roof, such as shale with a CMRR of less than 35, the orientation might not matter because the minimum principal stress is still great enough to damage the rock. Trends in the past have shown that a mine can be oriented properly with the major horizontal stress, but can still experience roof falls during entry development (Mark and Mucho, 1994; Mark et al., 2004). In these cases, the mine engineer must use other methods to mitigate the hazard beyond reorienting the mining direction, including additional rock reinforcement, as discussed below.

Reinforcement of bedded shale rock relies on enhancing the strength of strata laminations by developing a competent beam. Failure within the competent beam, such as bedding separation, tension cracks, or cutter roof fractures, weakens the integrity of the beam and leads to roof failure. The roof beam is enhanced through application of roof bolting, using such materials as fully grouted bolts or cable bolts. In coal mining in the United States, roof bolting is nearly universally applied with a 4-ft x 4-ft primary bolt pattern. This pattern means that roof bolts are spaced equally across the mine entry with four feet between bolts, and each row of bolts is spaced four feet apart. Coal mine entries are typically 18–20 ft wide. The type of bolt and length of bolt is often modified relative to the type of roof damage observed during the mining process, but the density of primary bolting is generally not varied substantially in the US except in very weak roof conditions. Historically, mining engineers adopt a bolting design that "has worked in the past," or a new mine might adopt a practice that a neighboring coal mine employs. In weak roof conditions where cutter development can form, the standard 4-ft x 4-ft bolting pattern is often not adequate; therefore secondary supplemental support needs to be added.

In a mine roof susceptible to damage by cutter failures, installing more bolts per row can aid in roof control (Peng, 2008). More bolts per row can simply increase the support density and provide more steel to act as a bulwark against interlaminar sliding. Also, adding more bolts per row causes the two outside bolts to be positioned closer to each respective ribline, which helps resist cutter development. By resisting cutter development, the reduction of strength in the competent beam can be minimized. In some cases in the Illinois basin, the two bolts nearest to the rib are angled over the coal pillar so that the bolt gets anchorage in the undamaged rock material (Peng, 2008). By anchoring the bolt into undamaged rock, the suspension of the competent beam is improved. Adding in cable bolts between rows of primary support, with lengths often between 10 and 16 ft, is also a standard practice in weak roof conditions.

In bedded shale material that contains a large number of thin laminations within the bolted horizon, tensioned bolts can help clamp the laminated layers together to form a stronger roof beam if the tension can be sustained. However, small movements along the bedding planes or fracture development in the weak material can result in a loss of tension. At one study site, the pre-tension on the bolt had been significantly reduced as mining progressed just one crosscut away (Molinda, 2003). Therefore, for weak bedded shale roof, it is also important to use a full column of resin grout in order to maintain contact between the bolt and the rock once the tension has been reduced. In stack rock, described earlier where stress concentrates in the stiff sandstone layers, the fully grouted bolts help to resist shearing along the beds, which results in protection of the shale rock from cutter formation (Molinda and Mark, 2010). Fully grouted bolt systems also have the advantage of promoting better load transfer to the bolt, therefore protecting the integrity of the competent beam. A grout anchor also has an advantage over a mechanical anchor, in that there is less likelihood for damage to occur in the weak rock.

Another critical factor in protecting the competent beam formed within a weak roof is the amount of time in between excavation and bolting the roof. If the roof is not bolted immediately following excavation, significant relaxation of the roof strata can occur, leading to bedding separation and movement along defects. Excessive roof sag prior to bolting can also disrupt the impact of the bolting system. If bedding separation and sag between the different roof layers is excessive, the resin can squeeze into the bedding cracks and prevent the resin bolts from being fully grouted at these locations. The use of advanced machine technology and integrated miner bolter machines has shortened the time between mining the coal and bolting the roof.

A final method of enhancing the strength of a highly fractured, bedded shale roof beam, utilized in extreme cases, is to reinforce the roof with polyurethane injection (Shaller and Russell, 1986). Polyurethane is a two-component system that can chemically bond to the rock mass. The polyurethane is pumped into the roof under pressure and therefore inherently targets fractures that are the paths of the least resistance. With this targeted approach, the polyurethane is able to strengthen the roof beam so that it can better support its own weight and the weight of the overlying fractured rock, similar to a beam created by roof bolting (Molinda, 2008).

SHALE AS A MOISTURE-SENSITIVE MATERIAL

Failure Mechanisms

One of the factors that makes shale particularly weak is its susceptibility to moisture degradation. Some shales encountered in coal mine roof contain clay minerals found in the montmorillonite family that will readily absorb moisture and expand. Numerous past studies have shown that roof shales degrade when coming into contact with humid mine air (Fletcher and Cassidy, 1931; Aughenbaugh and Bruzewski, 1973; Cummings, Singh, and Moebs, 1983). A study conducted by NIOSH found that roof falls were 15% higher in the humid months than the annual average for the same time period (Molinda et al., 2006). The deterioration of shale caused by the seasonal weather changes can occur within days, months, and years after exposure. Some shales might not appear to be moisture-sensitive when immersed in water, but will fail when subjected to repeated wetting and drying cycles, such as years of seasonal weather changes (Aughenbaugh, 1981).

Many studies in the past have focused on the changes of mechanical properties as rocks are exposed to moisture. Studies have shown a significant reduction in uniaxial compressive strength—as much as 75%—when rocks were subjected to immersion (Chugh and Missavage, 1980; Fabjanczyk and Gale, 1999). Some studies showed that shale samples were found to lose weight when subjected to low humidity and gain weight when subjected to high humidity, with the authors inferring moisture absorption and increased pore pressures (Cummings and Singh, 1981). Swelling pressures have been measured up to 34 MPa (5,000 psi), which is high enough to cause tensile and compressive failure within many shales (Kelly, 1969).

Moisture-sensitive shale deterioration starts off as a skin control problem, meaning it can cause pieces of rock to fall in between the roof bolts. When the roof initially relaxes as a result of coal extraction, micro tensile failures can occur. These tension cracks can allow for an increased infiltration of moisture, leading to swelling of the voids inside of the rock. The swelling of the rock causes a downward pressure and is able to create more tensile fractures within the weakly bonded material (Huang et al., 1986). This progressive deterioration is what causes the unraveling process between the roof bolts. If not controlled, it can lead to a larger problem because the unraveling process can progress upwards, eventually rising above the bolted horizon and leading to a massive roof fall. An illustration of the process is given in Figure 9. Figure 10 shows an example of weak shale that has unraveled between roof bolts in an underground coal mine. In this example, the rock unraveled vertically until a more competent layer was reached to stop the failure, and the bolts remained anchored into the stronger strata.

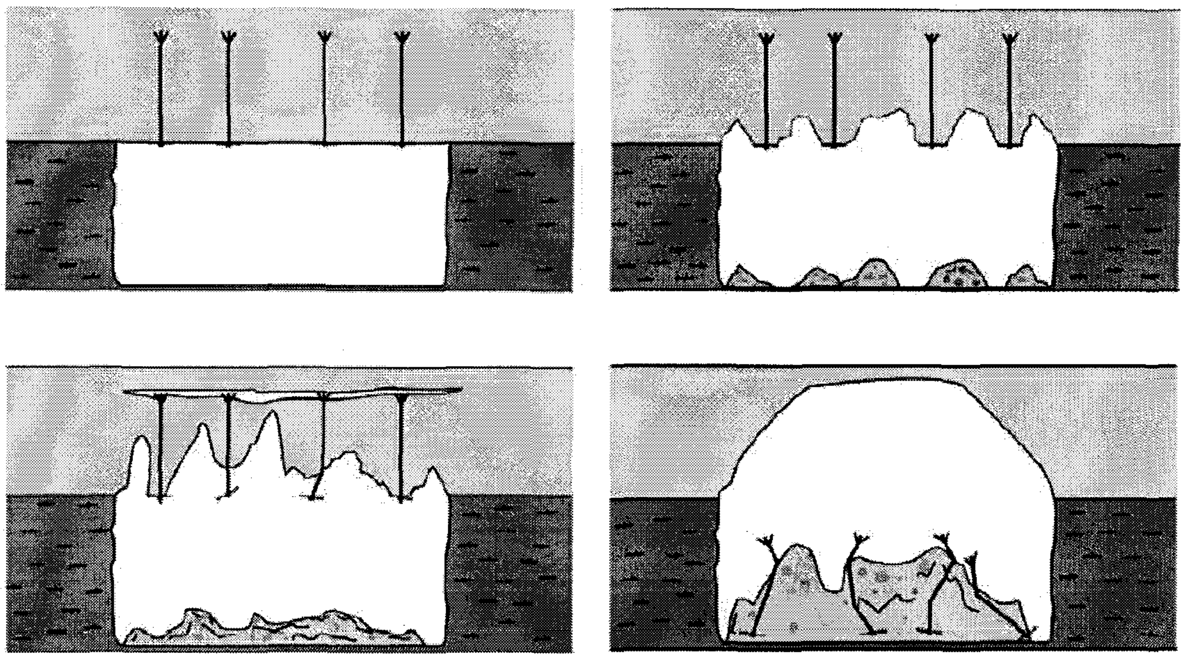

Figure 9 – Moisture-sensitive rock unraveling between the roof bolts and leading to a massive roof fall (from Molinda and Mark, 2010).

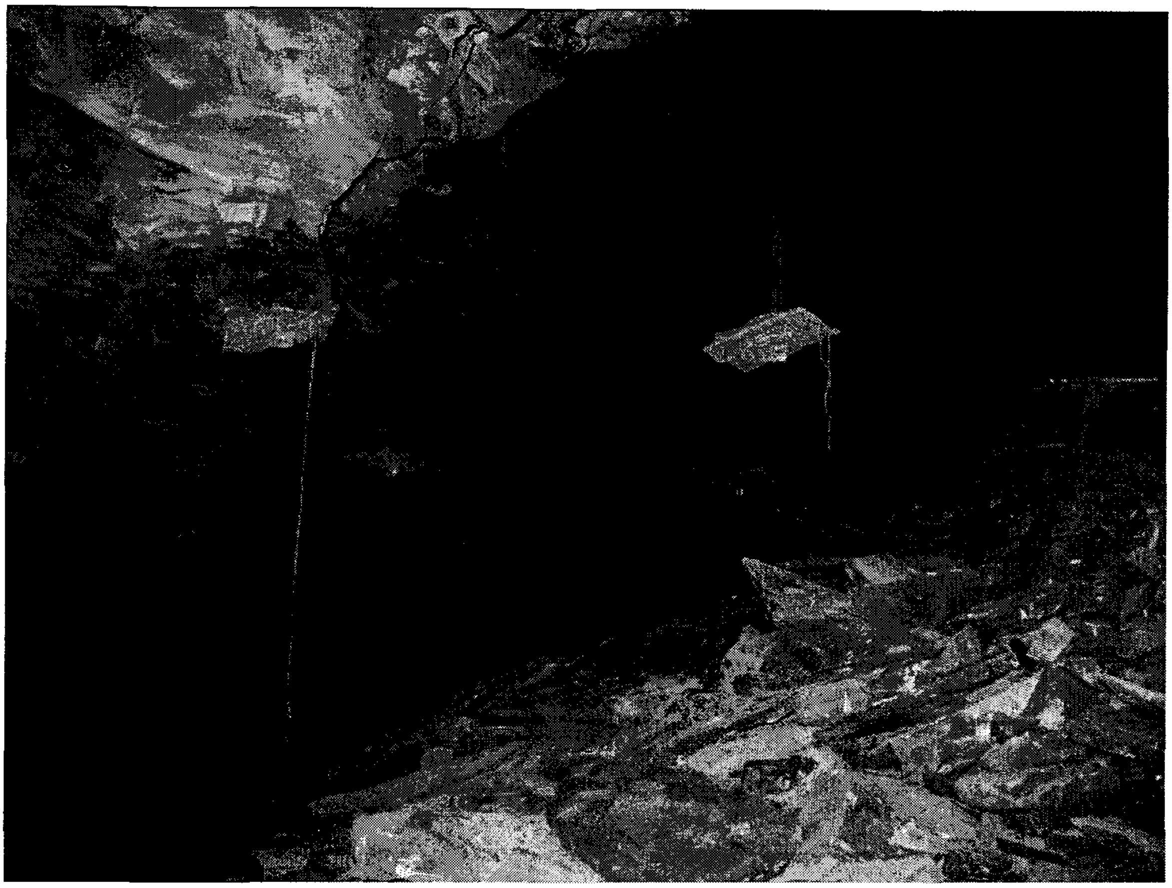

Figure 10 – Photograph showing how moisture-sensitive rock unraveled between bolts and fell to the ground.

If these moisture-sensitive shales can be identified prior to significant roof damage, ground control measures can be implemented to prolong the inevitable deterioration of the mine roof. Mine openings in a highly moisture-sensitive shale will not survive unless an appropriate support design has been implemented. To address this need, NIOSH has adopted a laboratory test that measures the water reactivity and susceptibility to time-dependent roof falls of moisture-sensitive rocks. In the test, the rock samples are subjected to a cycle of immersion in water for one hour then dried for six hours, and the process is repeated three times (Unrug, 1997; Molinda et al., 2006). The wet/dry cycles in the laboratory test simulate the exposure of roof rocks to the seasonal humidity changes in mine ventilation air. Results from the database of testing showed that rocks with disturbed bedding were the most water-sensitive and disintegrated easiest. Shale rocks that were not moisture-sensitive were attributed to the inclusion of a high percentage of unreactive silt-sized quartz. The test has been able to identify and correlate roof falls to rocks susceptible to deterioration (Molinda and Klemetti, 2008). A case study conducted in a Western Kentucky mine showed significant roof deterioration over the 12-year life of the mine, as represented in Figure 11 (Molinda and Mark, 2010). At the time the study began, the water reactivity measurement was not available and it was believed that it could have been used to anticipate the potential roof deterioration over time.

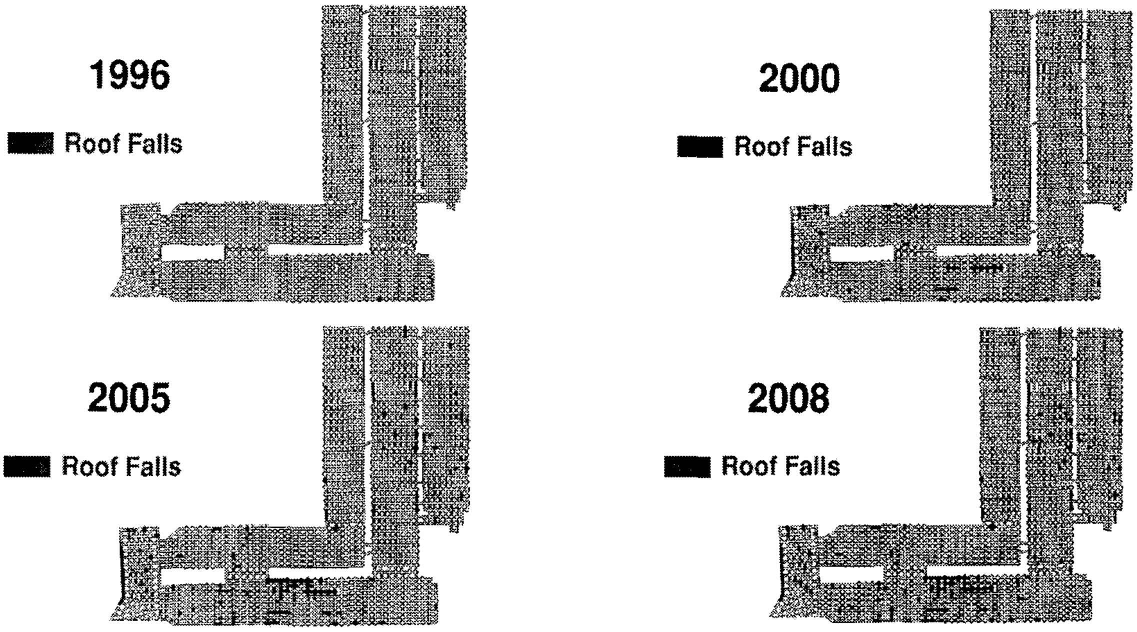

Figure 11 – Progressive roof falls over 12 years at a Western Kentucky mine with a moisture-sensitive shale roof (from Molinda and Mark, 2010).

Control Measures for Moisture-Sensitive Shale

In order to control moisture-sensitive shale in the roof, skin type support needs to be installed. Skin support, such as roof screen, helps contain the broken rock and prevents further deterioration from progressing vertically above the bolted horizon (Gadde et al., 2006). Roof screen can provide sufficient confinement to fractured shale to help support the deteriorated roof rock and slow the process of progressive unraveling between bolts. A photograph displaying the use of roof screen to control deteriorated roof at an Illinois mine is shown in Figure 12. At the same mine, since the inception of roof screening in 1994, injuries due to roof falls have diminished, as seen in the data represented in Figure 13 (Molinda and Klemetti, 2008). Areas that were not screened showed a roof fall rate 5 times higher than the areas that had screen installed.

Figure 12 – Example of roof screen used to control deteriorated roof.

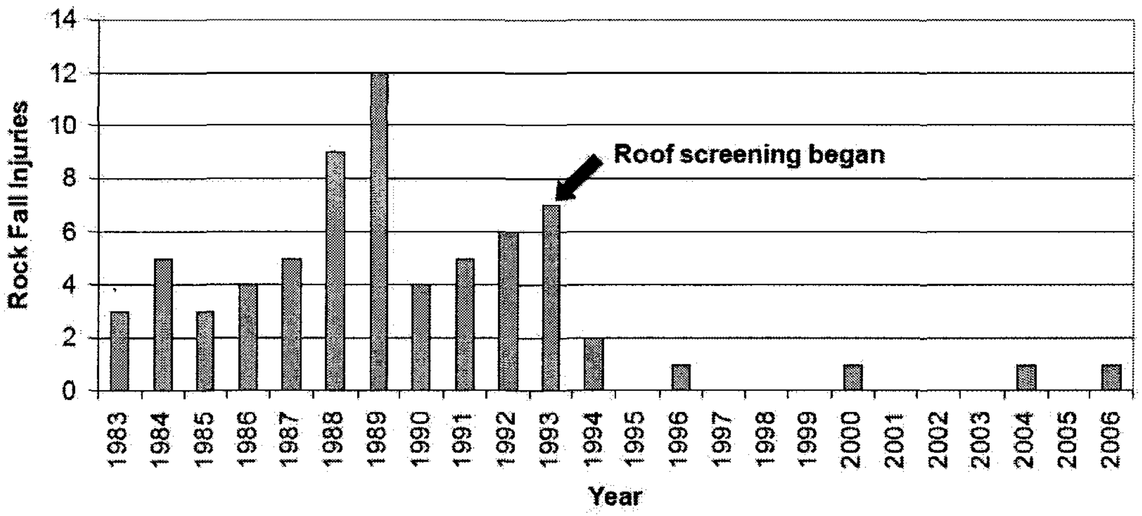

Figure 13 – Graph showing how rock fall injuries have diminished since the first installation of roof screen at an Illinois mine (from Molinda and Klemetti, 2008).

An additional control measure for moisture-sensitive shale is the use of sealants to mitigate moisture sensitivity. A coal mine in West Virginia used gunite on the roof as a solution for very poor roof conditions. In the roof that had been gunited, three roof falls were experienced over the span of 24 crosscuts. In the adjacent entry, the roof had not been gunited and 13 major roof falls occurred over a 6-year period (Mark et al., 2004). In a separate study, a spray-on polymer sealant was found to successfully reduce the amount of measured rock fall into the coal mine entry compared to areas with an unsprayed roof (Klemetti et al., 2009). While the polymer sealant has no strength, it can form a barrier to moisture and is good for short-term applications.

FUTURE CONSIDERATIONS FOR SHALE ROCK MECHANICS

In order to create a successful ground control plan, a mining engineer must characterize the coal mine roof appropriately in order to apply the necessary control measures for a safe and working environment. A civil engineer can construct a bridge successfully because the strengths and properties of the steel and concrete are known ahead of time. However, for a mining engineer, rock failure is a naturally occurring phenomenon and subject to rapid and unpredictable material property changes. Both the strength and thicknesses of highly bedded, moisture-sensitive shale can change rapidly throughout the mine. A drawback for current testing methods is that mechanical properties are difficult to obtain for these weak, moisture-sensitive shales because they cannot be prepared for laboratory testing. Also, cores obtained from surface drill logs are often miles apart and do not give a good indication of the various anomalies and changes in rock strengths that can occur throughout the mine.

New technologies are being developed by utilizing drilling information to better characterize weak shale. By using drilling data, information on roof type and thicknesses of weaker zones can be obtained in real time as mining progresses. Previous research had focused on using drilling information for detection of voids and joints. However, a recent study specifically focuses on using drilling information to estimate rock type by instrumenting roof bolters with vibration and acoustic sensors (Bahrampour et al., 2013). Preliminary measurements showed good results from algorithms used to estimate the different rock types from the drilling data (Bahrampour et al., 2014). It is hoped this technology can be developed and give the mining engineer a quantitative real-time estimate of weak zone locations in the roof so that the correct control measures can be implemented.

Numerical models have been implemented that utilize the strength reduction method (Zienkiewicz et al. 1975) to assist in designing support around weak roof conditions (Esterhuizen, 2012). This method can be utilized once the roof has been characterized and basic rock property parameters have been estimated. The strength reduction method makes use of numerical models to provide an evaluation of the likely stability of a supported entry for given geotechnical conditions and support layout. The mining engineer can compare alternative support scenarios under varying ground conditions, in order to evaluate the impact of future or unknown mining conditions. The contribution of each support component on excavation stability can be evaluated and the impact of various geological layers on stability can also be assessed. If calibrated to field instrumentation sites, the strength reduction method can give insight to the complex failure mechanisms that occur within a weak, bedded material. A previous research study used the strength reduction method to evaluate support designs with and without cable bolts in a variety of geological conditions. The study gave confirmation to the importance of a strong, competent layer of rock that gives anchorage support to the bolts (Murphy and Esterhuizen, 2013). Another study using the method evaluated the effects of depth of cover, bolt length, and horizontal stress (Esterhuizen et al., 2013). The study provided similar predictions of entry stability as previous empirically developed approaches.

The focus of the strength reduction method is to prevent roof falls that occur above the bolted horizon and not smaller skin falls that occur between supports. Also, the method only considers the initial response of the mine roof as a result of coal extraction. This means that roof falls that occur as a result of time-dependent moisture-sensitive shale unraveling between bolts, progressing vertically above the bolts, and causing a massive collapse, are not considered. Available data on the time-dependent failure properties of rock, especially moisture-sensitive shale, or techniques to model time-dependent behavior are not adequate at this time to create a calibrated numerical model. If the time-dependency behavior of shale could be better characterized, perhaps the large variability of time between moisture-sensitive roof falls could be explained and better planned for in the future.

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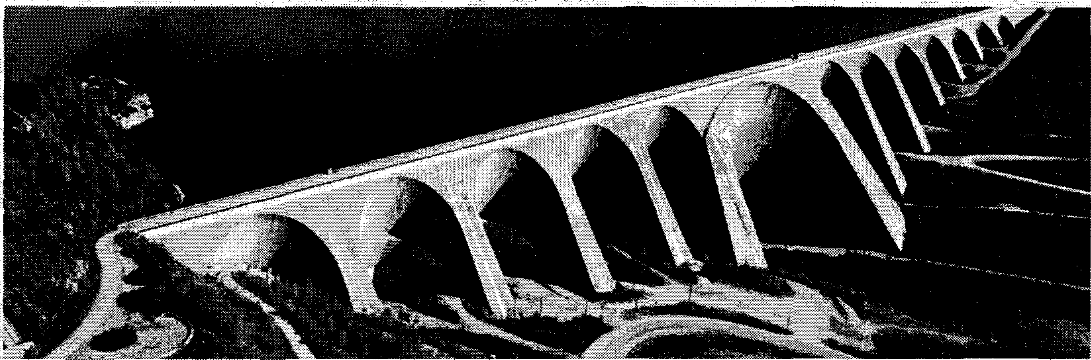

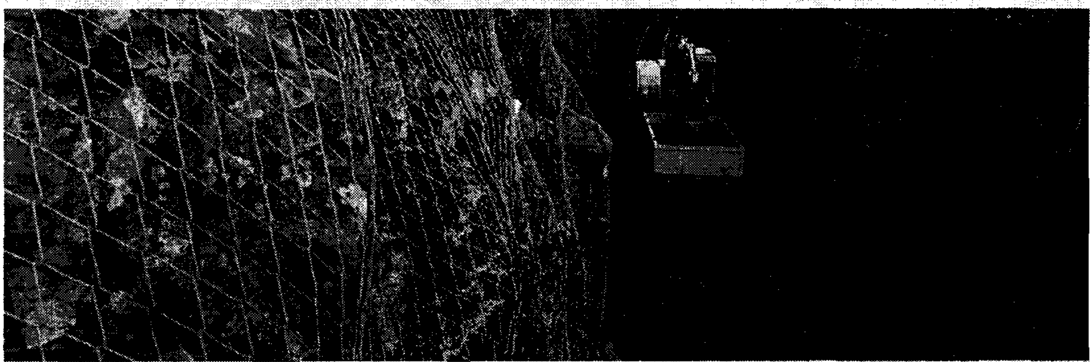

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