FIELD VERIFICATION OF THE ROOF FALL RISK INDEX: A METHOD TO ASSESS STRATA CONDITIONS

Anthony T. Iannacchione, Acting Geotechnical Engineering Section Chief
Gabriel Esterhuizen, Senior Service Fellow
NIOSH-Pittsburgh Research Laboratory
Pittsburgh, PA, USA

Scott Schilling, Engineering Geologist
Graymont (PA), Inc.
Pleasant Gap, PA USA

Tom Goodwin, Mine Foremen
Hanson Aggregates North America,
Connellsville, PA USA

ABSTRACT

The Roof Fall Risk Index (RFRI) is a new method introduced by the National Institute for Occupational Safety and Health (NIOSH) to assist the underground stone mine operator in 1) assessing defects the mine strata and 2) rating the relative roof fall risk these defects pose. The RFRI utilizes observational techniques to identify defects in the roof strata caused by local geologic, stress, and mining conditions. Assessment values for ten defined defect categories provides the foundation for estimating a range of risk conditions between 0 and 100 that define the potential for a roof fall. This paper examines how the defect information is collected using two field verification sites and proposes methods to analyze the RFRI data. These examples provide information on how well the method replicates observed conditions and how it might be applied in practice.

INTRODUCTION

Many of the hazardous conditions present in the underground mining environment are caused by a combination of geologic and in-situ stress factors which can be further affected by local mining activity. Recognizing and assessing roof stability conditions is a fundamental part of any proactive effort to address falls-of-ground injuries. The implementation of this process allows decision makers at all levels to estimate the potential for a roof fall. The RFRI was previously introduced at the 2006 SME Annual Meeting in St. Louis (Iannacchione et al., 2006). Methods to assess roof fall risk in underground mines were examined and the role of the RFRI was outlined; however, site-specific examples were not provided. In its current revised form, the RFRI varies from 0 to 100, higher numbers indicating a greater potential for a roof fall. This paper provides field evidence to demonstrate how this method works and how it may be used to assess the roof conditions.

The RFRI is for use in underground stone mines where the defects that result in unstable strata conditions are difficult to see and current assessment techniques are typically limited and subjective in nature. The assumptions used in this analysis are that the underground stone mine has wide openings (> 10m), high roofs or back (> 7m), relatively flat lying strata, and uses blasting techniques to break the rock, scaling to remove loose rocks and, on occasion, some form of rock reinforcement and roof monitoring. The current use of the RFRI is relevant only to this experience base.

This method is applicable to the 70 to 90 underground, relatively flat lying, limestone room-and-pillar mines in the central and eastern portion of the U.S. The criteria used to rate strata defects are based on twenty years of ground control experience and engineering assessments from examination of more than 50 underground stone mines.

OBSERVING AND ASSESSING STRATA DEFECTS

Ten measurable and observable categories are proposed that represent a significant range of defects found at underground stone mines (table 1). An assessment value (AV) from 1 to 5 is assigned within each defect category. Increasing values represent more severe defects. The assessment value of 3 is also used when information on a parameter is unknown. The ten categories and the parameters used for assigning individual AVs are:

- Category 1 (Large Angular Discontinuities) notes the occurrence of significant geologic structures such as faults and slips that cut the roof rock at angles from 10 to 70 degrees from horizontal (Figure 1, No.1). These discontinuities act to weaken competent roof rock and can be zones where displacements are initiated (mobilized). The influence of angular discontinuities on roof strata stability is documented by Lagather (1977) and Moebs (1977). If these parameters are non-existent, then an AV of 1 is assigned. An AV of 5 is assigned to roof strata with a significant angular discontinuity, containing weak (low strength) contact. Typically strong contacts are comprised of sharp surfaces with relatively rough profiles while weak contacts are comprised of smooth surfaces that are either polished or filled with fine grained material.

- Category 2 (Joint Frequency) focuses on the importance of joint frequency on roof stability (Krausse et al., 1980). Joints refer to the steeply inclined (nearly vertical) fractures that often naturally occur in rock formations (Figure 1, No.2). Joint frequency is comprised of several parameters that help define the frequency or spacing of joints. Typically, the joints will occur in preferential orientations that can cluster in one or more groupings. It is recommended that the cluster with the lowest average distance between joints be used to evaluate this parameter (table 1). Widely spaced joints yield an AV of 2, while closely spaced joints have an AV of 5.

- Category 3 (Roof Layer Thickness and Bedding Contact(s) Strength) evaluates roof layer thickness and bedding contact strength. Past experience has demonstrated how these geologic conditions interact to affect individual roof beam conditions and the potential for separations between these same layers (Moebs, 1977, Hylbert, 1980, Iannacchione and Prosser, 1998). Massive strata, void of distinct geologic layers, tend to have few continuous, horizontal bedding plane contacts, resulting in few defects (Figure 1, No.3). These strata have an AV of 1. By necessity, mine roofs with wide spans are comprised of relatively strong layers. Layers greater than 1 m in thickness are often observed as stable. If these layers are bonded by weak bedding contacts, then the strata are typically less stable. As the roof layers incrementally thin below 1 m in thickness, the associated beam deformation or sag can increase. Layers less than 0.25 m thick have often been observed as sagging and present a high probability for eventual roof beam failure, especially when they are bounded by weak contacts. In this case, an AV of 5 is assigned.

- Category 4 (Shear Rupture Surfaces) considers the influence of shear rupture surfaces, typically caused by buckling of roof layers less than 1 m thick (Figure 1, No.4). When excessive levels of horizontal stress are present, a roof layer can buckle, producing a low angle shear rupture surface with a powder-like residue (Gale et al., 2001; Iannacchione el al. 2003). The shear failure or roof cutters are typically comprised of a concentrated zone of defects. They are typically assigned an AV of 5 but if present in very small lengths (< 1 m) are given an AV of 3.

- Category 5 (Joint Separations) takes into account the separation of vertical fractures or joints. This type of defect occurs only when the strata loses compression in the direction perpendicular to the joint orientation (Figure 1, No.5). Joint separation signals that strata extension has occurred. Because most underground stone mine roofs have some level of vertical jointing and horizontal bedding plane contacts, most roofs are comprised of block segments of varying size that are supported by the confining stresses in the immediate roof beam. When strata extension occurs, the roof blocks are no longer confined and can fall to the ground under the forces of gravity. If no joint separation is observed, then the AV is 1. Because separation is a severe defect, any noticeable or measurable separation of a vertical joint is assigned an AV of 5

- Category 6 (Lateral Strata Shifting) examines defects associated with lateral strata shifting where roof layers move in opposing directions along bedding contacts (Figure 1, No.6). While it is difficult to directly link this category with roof falls, it is commonly recognized as an unstable condition (Zhang and Peng, 2001). In some mines, lateral strata shifting are associated with large-scale movement along a fault plane or a large angular discontinuity (Iannacchione et al., 1981). The level of strata offset on either side of the shifting surface can be an indication of the magnitude of movement. If no lateral strata shifting occur, then the AV is 1. If less than 2cm of offset is observed where the surface intercepts the mine roof or rib, then the AV is 3. If the offset is greater than 2cm, the AV is 5. Many of these lateral offsets do not intercept the mine roof or rib and can be hidden from view within the immediate roof. A proven technique to detect these surfaces is to drill vertical boreholes into the roof on a regularly spaced pattern. This technique has been used in coal mining to successfully determine the magnitude and direction of strata shifting (Mucho and Mark, 1994).

- Category 7 (Strata Separation) encompasses the vertical strata separation caused when roof layers separate from one another and sag into the mine entry (Figure 1, No.7). The association of roof layer deflection with roof falls is well established and has been a subject of many investigations (Parker, 1973; Maleki and McVey, 1988; Iannacchione and Prosser, 1998). While strata separation can be determined by many methods, a basic requirement is a vertical borehole drilled into the roof and some means to observe and locate separations and determine their magnitude. Often, this is accomplished with devices such as a simple scratch tool, a bore scope, or a roof deflection monitor. If no separations exist in the immediate roof, then the AV is 1. If the separation is barely detectable or open, then the AV is 3. If the separation is easily detectable (>0.5cm), then the AV is 5.

- Category 8 (Roof Rock Debris on the Floor) assesses the amount of defects in the roof strata by estimating the amount of roof rock deposited on the mine floor (Figure 1, No.8). It is vitally important that this information be retained by the mining operation in some manner. If the floor is cleaned after debris has fallen from the roof and not recorded, then this information needs to be inferred. Debris from blasting and scaling the roof and ribs must be differentiated from roof rocks that have fallen. If no roof rock debris is observed, then the AV is 1. Increasing amounts of debris produce a higher AV. An AV of 5 is typically associated with a pile of broken rocks that obstructs or hinders walking in that portion of that mine entry.

- Category 9 (Roof Shape) uses the shape of the roof profile to estimate the concentration of defects in the roof strata (Iannacchione and Prosser, 1998). In general, a smooth roof is desirable in underground stone mining and typically represents a roof that has not been damaged by blasting or scaling (Figure 1, No.9). Smooth roof is given an AV of 1. Conversely, if the roof is highly irregular with pronounced swales and troughs, the potential for increased amounts of defects increases the AV to 5. Sometimes this condition is caused by inherent weakness within the roof rocks. Other times the rough looking roof is a result of roof rocks damaged by blasting, scaling or excessive stress conditions.

- Category 10 (Moisture/Ground Water Inflow) appraises the amount of defect damage by moisture/ground water inflow characteristics (Figure 1, No.10). Different AV's are assigned as the conditions change from dry (AV=1), to damp (AV=2), to dripping (AV=4), and finally to the steady flow of water from the roof (AV=5).

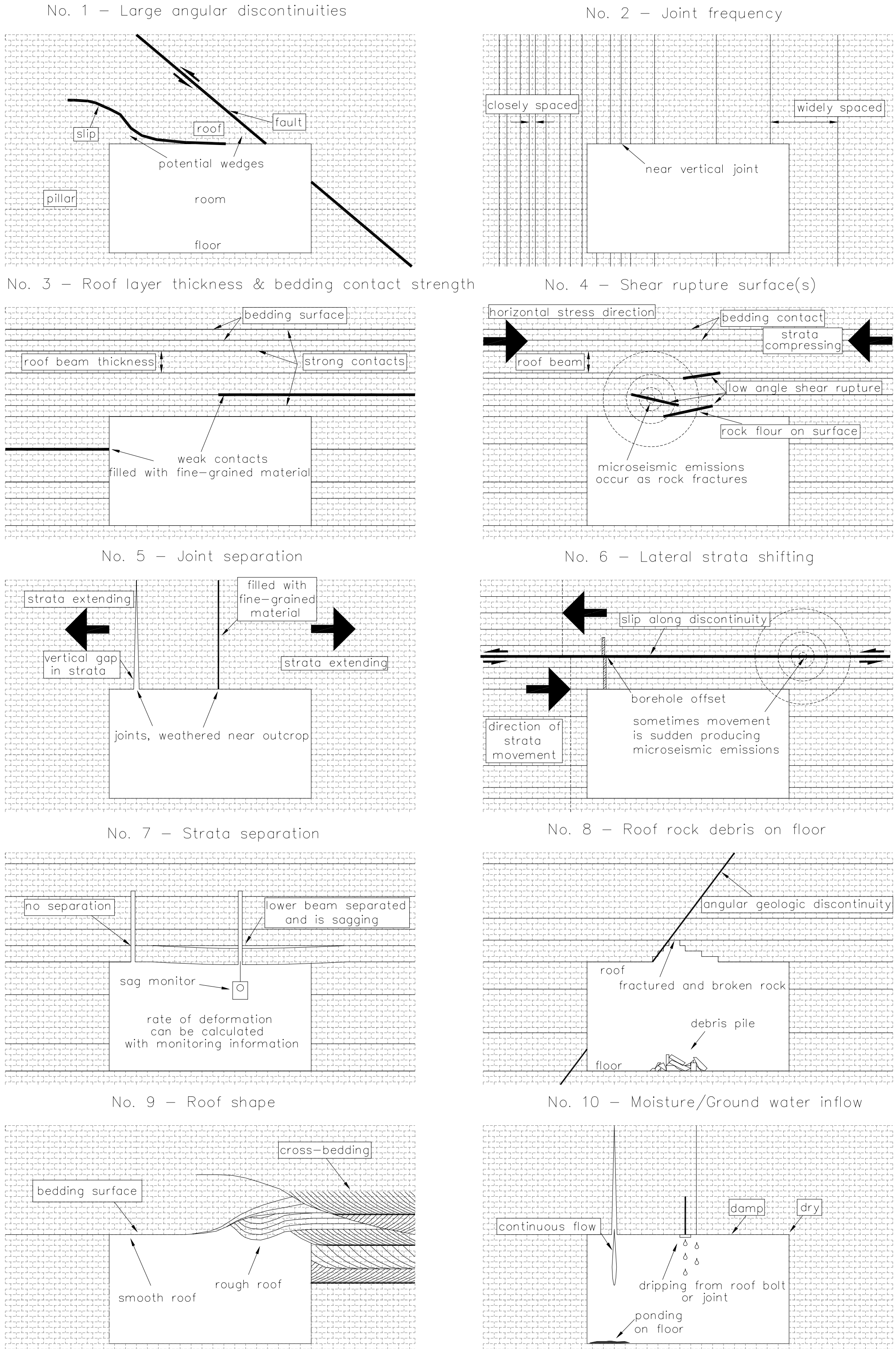

Figure 1. Sketch of parameters associated with the ten defect categories.

Table 1 - Defect categories for determining the RFRI in underground stone mines

Grouping	Category	Parameter	Assessment Value	Weight	Category Value
Geologic factors	1 - Large angular discontinuities	*None*	*1*	*1*	
		One, strong contact	*2*		
		One, weak contact	*3*		
		More than one, strong contact	*4*		
		More than one, weak contact	*5*		
		Unknown	*3*		
	2 - Joint frequency	*None*	*1*	*1*	
		Widely spaced (>1m)	*2*		
		Moderately spaced (0.25 to 1m)	*4*		
		Closely spaced (<0.25m)	*5*		
		Unknown	*3*		
	3 - Roof layer thickness and bedding contact strength	*Massive (>1m layers)*	*1*	*1*	
		Strong bedding contacts in immediate roof (0 to 3m)	*2*		
		Weak bedding contact(s) in immediate roof (0 to 3m)	*3*		
		Rock layers 0.25 to 1m with weak bedding contact(s)	*4*		
		Thin layers (<0.25m) with strong bedding contact(s)	*4*		
		Thin layers (<0.25m) with weak bedding contact(s)	*5*		
		Unknown	*3*		
Mining induced failures	4 - Shear rupture surfaces	*None*	*1*	*2*	
		Small shear (cutter < 1m)	*3*		
		Large shear (cutter > 1m)	*5*		
		Unknown	*3*		
	5 - Joint separ-ation	*None*	*1*	*2*	
		Noticeable or measurable	*5*		
		Unknown	*3*		
	6 - Lateral strata shifting	*None*	*1*	*2*	
		< 2cm of offset or partial vertical drill hole offset	*3*		
		> 2cm of offset or complete vertical drill hole offset	*5*		
		Unknown	*3*		
	7 - Strata separ-ation	*None*	*1*	*2*	
		Slight (barely detectable)	*3*		
		Significant (>0.5cm)	*5*		
		Unknown	*3*		
Roof profile	8 - Roof rock debris on floor	*None*	*1*	*2*	
		Slight (widely spaced)	*2*		
		Moderate	*4*		
		Significant (continuous)	*5*		
		Unknown	*3*		
	9 - Roof shape	*Smooth*	*1*	*1*	
		Intermediate	*3*		
		Rough	*5*		
		Unknown	*3*		
Moisture factors	10 - Moisture/ ground water inflow	*None*	*1*	*1*	
		Damp roof	*2*		
		Drippers	*4*		
		Steady flow	*5*		
		Unknown	*3*		
Sum all category values					
Multiplied by 1.11					
Microseismic activity adjustment: *no microseismic clustering subtract 5; clustering add 25; 0 if unknown*					
Roof deformation rate adjustment: *no roof deflection movement subtract 5; constant deflection add 15; accelerating deflection add 30; 0 if unknown*					
RFRI					

CALCULATING THE RFRI

A fairly simple and straight forward mathematical expression is used to calculate the RFRI and is defined as:

$$RFRI = [\Sigma (AV * W) / \Sigma (SV * W)] * 100 \tag{1}$$

Where: AV = the assessment value for each defect category
SV = the scaling value (SV = 6.0)
W = the weighting of each category

Because the individual defect categories reflect the ground stability of underground mine entries to different degrees, it is necessary to weight (W) each of the ten categories (Table 1). The defect categories viewed as more detrimental to roof conditions are 4, 5, 6, 7, and 8 and were assigned a W of 2. The other categories, i.e., roof shape (9), moisture/water inflow (10), and all of the geologic related factors (1, 2, and 3), were each assigned a W of 1.

A scaling value (SV) of 6.0 is assigned for the current defect categories and associated W. The SV = 6.0 was selected so that AV of 3 for all ten defect categories will result in an RFRI of 50. The SV can be modified if the W or defect categories are modified in future versions of the RFRI, to maintain this relationship. When these SV's and W's are used, the RFRI can be calculated with the following equation:

$$RFRI = \Sigma (AV * W) * 1.11 \tag{2}$$

For the SV and W used above, the RFRI distribution ranges between 17 and 83. Adjustments can alter this range (see below), but the RFRI should never be greater than 100. When RFRI values approach 0, very low concentrations of defects are measured and roof conditions are potentially stable. When RFRI values approach 100, very high concentrations of defects are measured and roof conditions are potentially unstable.

ASSESSMENT VALUES ADJUSTMENTS

Two factors make it necessary to develop ways to adjust RFRI values: 1) all underground mines have conditions that are unique, and 2) additional information about local strata conditions is sometimes available. As additional experience is added, it maybe necessary to append the list of defect categories, adjust category W or change category AV. This first factor is beyond the scope of this paper, but should be addressed in the future. Today, many mines collect additional observational and monitoring information on the character and behavior of their strata, often through drill holes in the roof. Monitoring instruments are typically deformation sensors, either of the roof sag or roof-to-floor convergence variety, but can also include a range of geophysical techniques including microseismic monitoring. Two RFRI adjustments are presented below, but others may be added to help address the unique characteristics at every operating mine.

Microseismic Activity Adjustment

Microseismic emissions are known to be particularly good at characterizing shear rupture surfaces (Iannacchione et al., 2004). It follows that an adjustment to the RFRI value can be made if adequate microseismic monitoring information exists. Clustering of microseismic events in time, and within a relatively well-defined area of the mine, can signal that rock fracturing is occurring and that the strata may be unstable. Clustering in time is defined by microseismic activity far in excess of the normal background rate. Clustering in space is defined by the microseismic activity occurring within the same general area. The location accuracy of microseismic events can greatly influence spatial clustering. If microseismic activity does not cluster, the strata are most likely not producing new fracture surfaces. In this case, the RFRI is reduced by 5 (Table 1). If microseismic emissions cluster, then the RFRI is increased by 25 (Table 1).

Roof Deformation Rate Adjustment

Roof deflection measurements are known to produce non-ambiguous assessments of strata separation characteristics. Monitoring roof beam sag and roof-to-floor convergence provides an opportunity to collect values of roof deflection measurements that can be used to adjust the RFRI values. Three general conditions are characterized when measuring roof deflection. If no roof deflection is measured, the strata can be temporarily considered to be stable. In this first condition, the RFRI is reduced by 5 (Table 1). The second condition is when a measurable level of roof deflection persists for a period. The magnitude of this value is site specific in nature and has been found to range between a few tenths of a millimeter to several millimeters per day. This condition suggests the roof is no longer stable but still may not be on a path that will lead to a failure. There are many examples where roofs with this amount of deflection have temporarily stabilized, in some cases for long periods of time. If this condition occurs, the RFRI is increased by 15. It should be noted that when roof deformations occur, it might be advisable to construct some form of notification and/or barrier to limit entry into the area. The third condition is when the rate of deflection increases on some type of regular basis, such as from one-day to the next or perhaps one-week or month to the next. An increasing rate of roof deflection is a well documented precursor of roof failure (Maleki and McVey, 1988). This condition suggests the roof is in an unstable state. If this condition occurs, the RFRI is increased by 30.

FIELD VERIFICATION CASE STUDIES

The RFRI was field tested at two underground stone mines. These field trials consist of three components: 1) collection of defect information from the mine, 2) analysis of RFRI values, and 3) assessment of RFRI performance.

Field Verification Site No. 1: Comparing Roof Stability Conditions

At the first field verification site, the mine was driving a 4-entry system to a nearby outcrop to enhance local mine ventilation. Roof conditions were generally good in this part of the mine, but were expected to become more difficult as mining approached the outcrop. The mine was interested in knowing the general condition of the roof in this area and wanted to examine how conditions changed with time. The principal verification test was to evaluate how well the RFRI characterized actual roof conditions.

<u>Collection of defect information from the mine:</u> During one mine visit, a total of 3 hours was spent mapping the new 4-entry development. The geologic, stress and mining related defects were observed and placed on a mine map (Figure 2a). The mapped region was then divided into 46 measurement areas (Figure 2b). A general summary of the AV for the most important Defect Categories used to determine the RFRI for typical measurement areas at the first site are as follows:

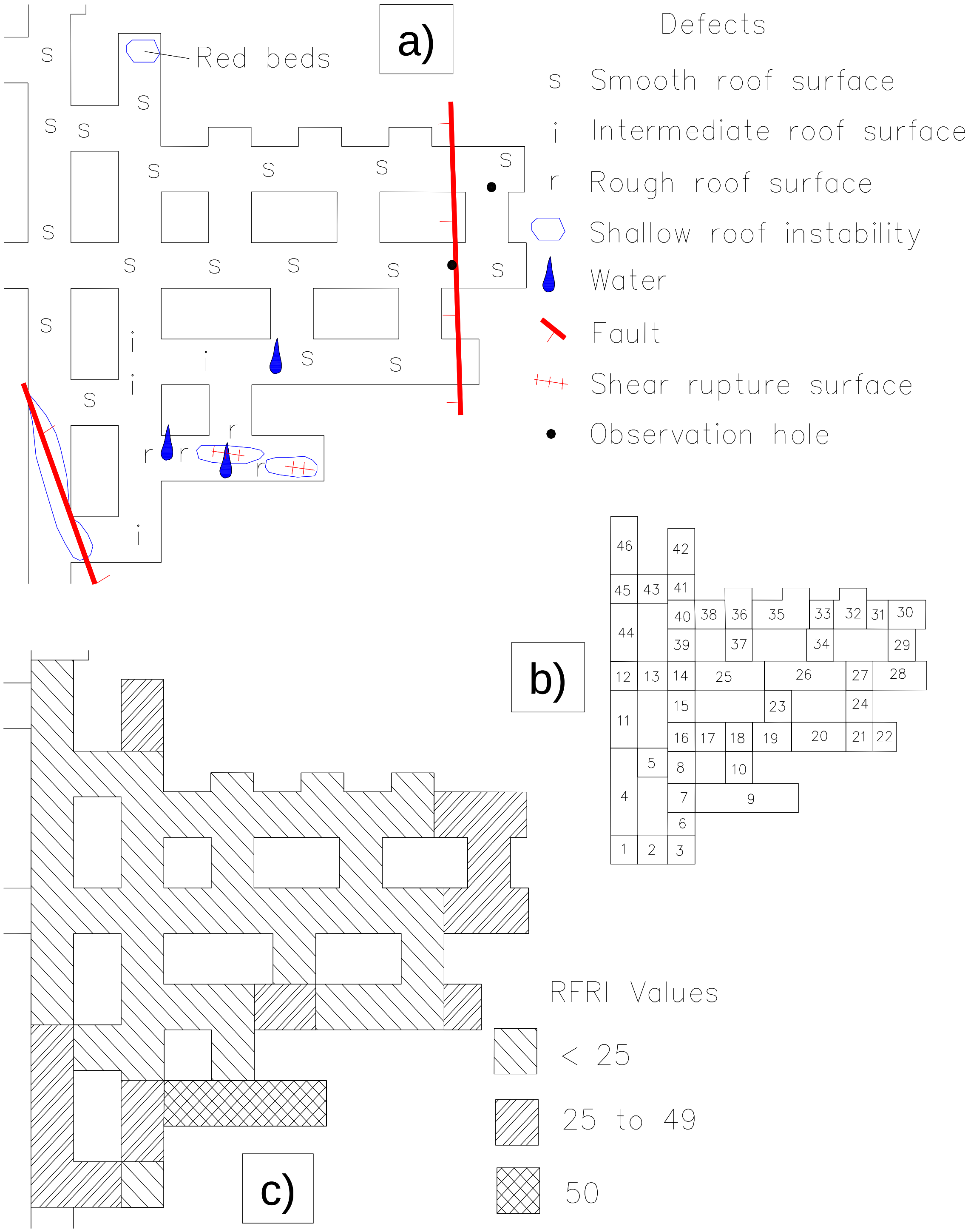

Figure 2. The first field verification site measurement region: a) defects map, b) 46 measurement areas, and c) roof fall risk map displaying the individual RFRI values over the measurement region.

- Category 1 – *Large angular discontinuities*: Several faults intersected the roof strata at dips ranging from 20 to 50 degrees. These faults generally contained clay material and were sources of water infiltration. These large angular discontinuities produced significant defects. The AV was 5 for these fault conditions.
- Category 3 – *Roof layer thickness and bedding contact strength*: An AV was generally 2 indicating strong bedding contacts in the immediate roof. Whenever weak red beds were encountered, an AV of 5 was assigned.

- Category 4 – *Shear rupture surfaces*: The AV ranged between 1 and 5; 1 if no shears were present, 5 when extensive shears were present.
- Category 7 – *Strata separation*: The AV was typically 1; however, higher values were assigned to areas where separations were detected from roof drill holes.
- Category 8 – *Roof rock debris on floor*: AV was 1 if no roof rock spalling occurred and higher if guttering was observed, i.e. common in association with shear ruptures.
- Category 9 – *Roof shape*: Whenever smooth roof was observed an AV of 1 was assigned. Rough roofs were assigned an AV of 5. Typically these roofs contained shear ruptures or multiple brows outlining individual roof layers.
- Category 10 – *Moisture/ground water inflow*: The AV was 1 for dry conditions, 2 for damp areas and 3 to 5 for areas where significant water flow was observed.

Category 1 and 4 had the most pronounced affect on the RFRI followed by 3, 7, 8, 9, and 10.

Analysis of RFRI values: The RFRI values in the measurement region ranged from a low of 19 to a high of 58 (Figure 3). A roof fall risk map was constructed from the 46 RFRI measurements (Figure 2c). The highest percentage of these values occurred at the lowest RFRI indicating that most of the mine's roof in this section had low concentrations of defects. In fact, 591 m or 69 % of the measured mine entries had an RFRI < 25. Approximately 25 % or 220 m had an RFRI between 25 and 50. The main factor for the elevated RFRI values in these areas was faults. Small increases in the percentage of RFRI values from 30 to 35 and 45 to 50 were caused by faults (Figure 3), the latter were faults with some vertical strata separation and rough roof conditions.

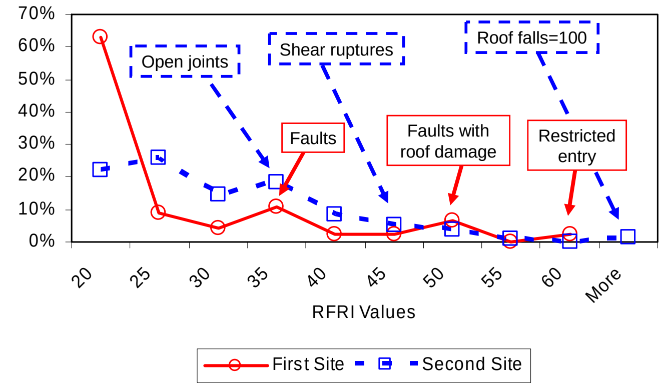

Figure 3. Percentage of RFRI values collected from the two field verification sites.

Comments on the assessment of the RFRI field test: The maximum RFRI value of 58 was calculated for a section of entry 52 m long that contained shear ruptures, rough roof, vertical strata separations and flowing water conditions. The next highest RFRI value was 46. The mine was concerned about the stability of this area and constructed berms to restrict entry into the area. The fact that the mine operator and the RFRI both identified this entry as having an elevated risk for roof failure validates the performance of the RFRI.

Field Verification of Site No. 2: Comparing Mine Design Changes

At the second field verification site, two mine layout designs were implemented to improve roof conditions. The first, Design A, used headings (entry paralleling the main direction of mine development) developed in the S30W direction and crosscuts (entry between headings) developed in the S80W direction (Figure 4).

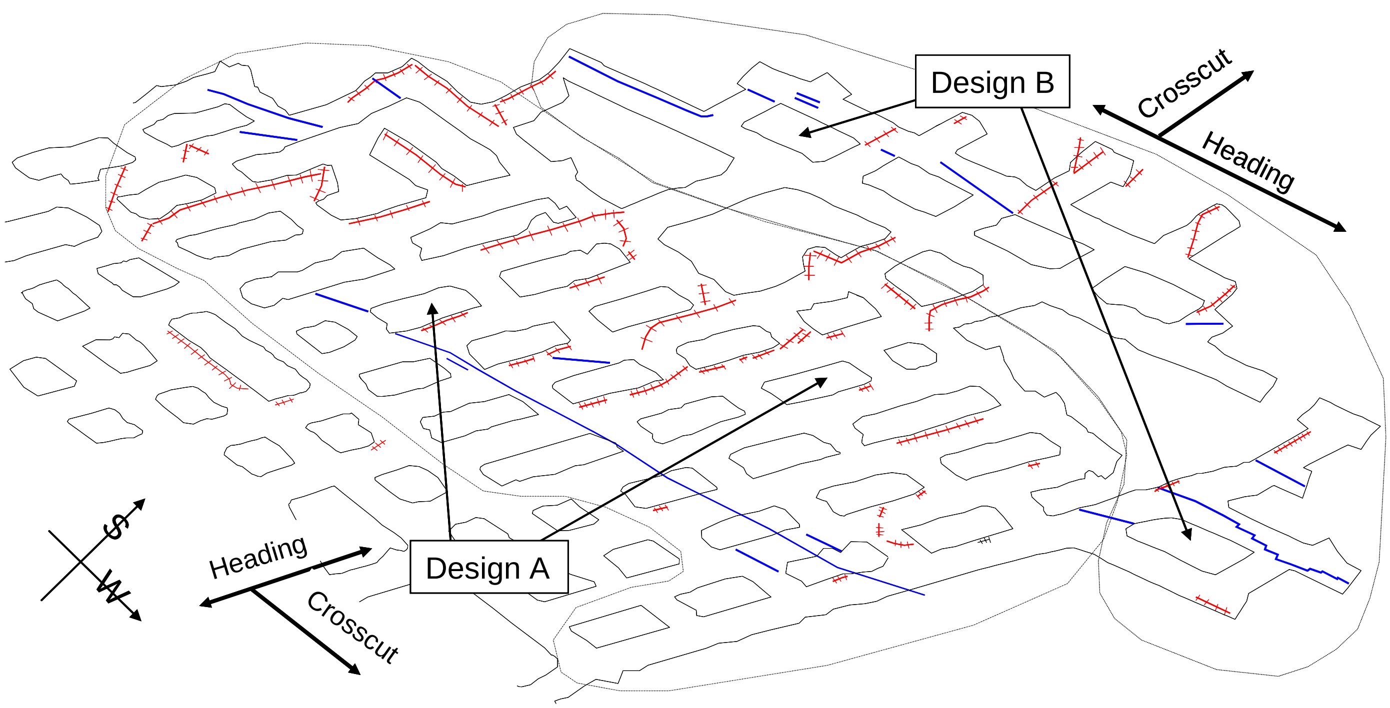

Figure 4. The second field verification site measurement region showing the two mine layout designs. Major defects are also shown where shear ruptures are drawn as tracked features and open joints are drawn as solid lines.

The pillars are rectangular with the long axis oriented parallel to the headings. Because the operator had wanted to eliminate the 4-way intersections, crosscuts were offset, resulting in only 3-way intersections.

Next, Design B was implemented which optimizes the mine layout when developing in excessive horizontal stress conditions (Emery, 1964; Parker, 1966; Shaffer and Petersen, 2000; Iannacchione et al., 2003). This design orients the headings and the associated rectangular pillars parallel to the principal horizontal stress direction. The crosscuts are offset and oriented roughly perpendicular to the headings. The principal verification test was to evaluate how well the RFRI characterized entry performance under these different design conditions.

<u>Collection of defect information from the mine:</u> During two mine visits, 10 hours were spent mapping a portion of the mine that contains parts of the two distinct mine layouts (Figure 4). The geologic, stress and mining related defects were observed and placed on the mine map. The mapped region was then divided into 226 measurement areas. Each measurement area generally encompassed one of three mine entry characteristics: headings, crosscuts and 3-way intersections. The length of these different measurement areas ranged from 12 to 66m. In this study, the measurement areas are equivalent to distinct segments of mine entries. This facilitated analyzing the influence of mine layouts on RFRI. A general summary of the AV for the most important Defect Categories used to determine the RFRI for typical measurement areas at the second site are as follows:

- Category 2 – *Joint frequency*: The AV ranged between 2 and 4 where joint spacing ranged from 0.3 to 1m. Most of the higher AV's (3 and 4) were associated with the major water bearing fracture system that cuts across the measurement region.
- Category 3 – *Roof layer thickness and bedding contact strength*: The AV was generally 2, indicating pronounced bedding contacts in the immediate roof.
- Category 4 – *Shear rupture surfaces*: The AV ranged between 1 and 5: 1 if no shears were present, 5 when extensive shears were present.
- Category 5 – *Joint separation*: The AV ranged between 1 and 5: 1 if the joints were closed, 5 if they were open.
- Category 7 – *Strata separation*: The AV was typically 1, however higher values were used if separation was observed along brows or within drill holes (typically locations were marked on the roof by driller).
- Category 8 – *Roof rock debris on floor*: The AV ranged between 1 and 5: 1 if the floor was clear of debris, 5 if the debris pile was difficult to negotiate.
- Category 9 – *Roof shape*: The AV was 1 for smooth roof and 3 for uneven roof profiles, i.e. associated with guttering, shearing, blasting or fracturing.
- Category 10 – *Moisture/ground water inflow*: The AV was 1 for dry conditions, 2 for damp areas and 3 to 5 for areas where significant water flow was observed.

Category 4 and 5 had the most pronounced affect on the RFRI at this site followed by 7, 8, 9, and 10.

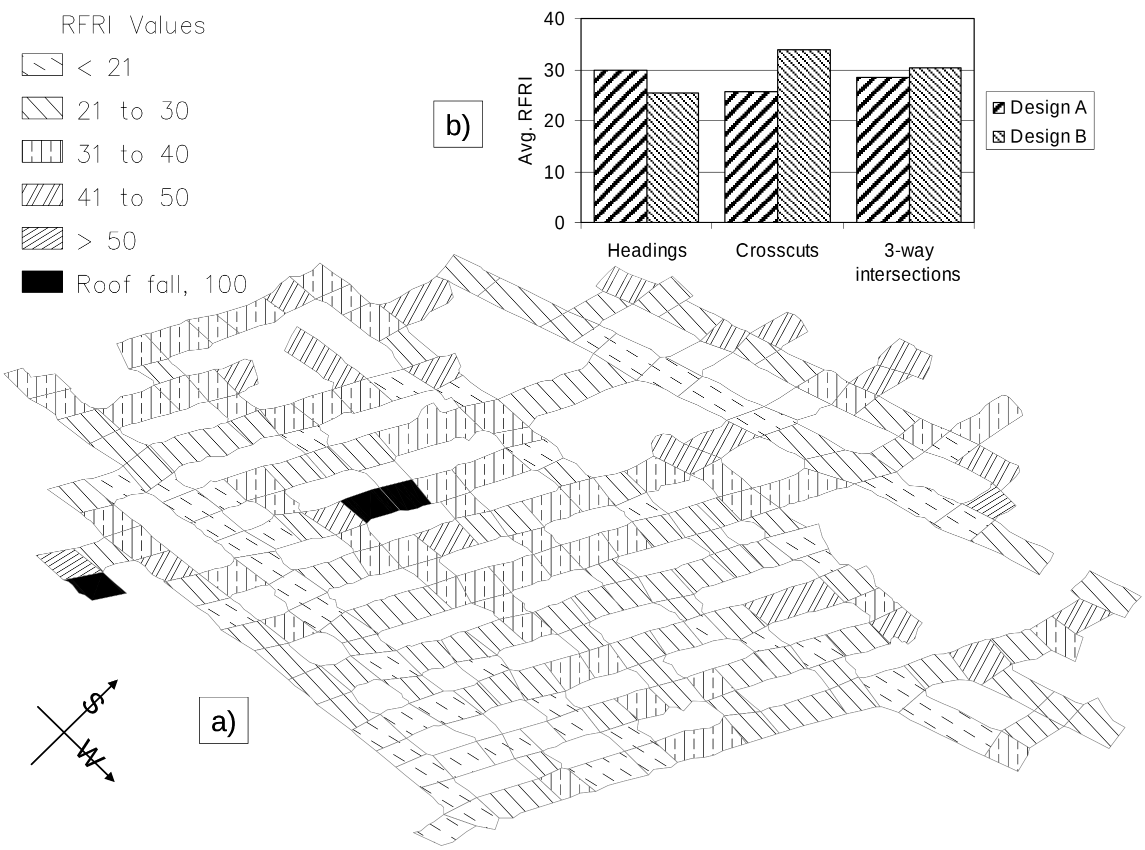

Figure 5. (a) Roof fall risk map displaying the 226 RFRI values over the measurement region. (b) RFRI for different entry characteristics in the Design A and Design B.

Analysis of RFRI values: The distribution of the 226 RFRI values collected from measurement sites is shown in Figure 5. RFRI values ranged from a low of 19 to a high of 53, with the exception of the pre-survey roof fall areas that are assigned an RFRI of 100 (Figure 5a). As would be expected, most of the locations had low RFRI values. For example, 61 % of the measured entry areas had an RFRI less than 30. Twenty-seven percent of the entries had RFRI values between 30 and 40, and were often adversely influenced by open joints and to a leaser extent by shear ruptures and flowing water. Twelve percent of the entries were dominated by shear ruptures.

A roof fall risk map was constructed from the 226 measured RFRI values (Figure 5a). The average RFRI for the different mine designs were calculated and shown in Figure 5b. In general, Designs A and B have similar overall average RFRI (A = 28 and B = 29); however, small, but important, differences are observed when individual entry characteristics are considered. For example, the headings of the Design B had an RFRI of 25 as compared to the 30 for the headings of the Design A. The opposite trend was observed for the crosscuts where Design B had a higher RFRI (26 versus 34). The RFRI for the 3-way intersections was very similar for both designs. This data indicates that Design A had similar concentrations of defects in both the headings and crosscuts, whereas Design B had relative low concentration of defects in the headings and higher concentrations in the crosscuts.

Comments on the assessment of the RFRI field test: When excessive levels of horizontal stress exist, shear ruptures are typically oriented perpendicular to the principal stress direction. This orientation has high compressive stresses and represents the least favorable mining direction. Conversely, orientations parallel to the principal stress direction are typically free of shear ruptures but can often have tensile fractures. This orientation represents the most favorable mining direction. As the horizontal stress field becomes more bi-axial, or less equal, these tension fractures can extend and open, hence open joints can sometimes occur perpendicular to the shear ruptures.

At the second verification field site, these very conditions were observed. Shear ruptures occurred in orientations that cluster around S20E as shown by the tracked pattern on Figure 4. Additionally, a significant number of open fractures exist in the S70W orientation suggesting a highly bi-axial horizontal stress field (see the solid lines on Figure 4). For this reason, the main headings in Design B were laid out along that direction to take advantage of favorable conditions. Conversely, crosscuts were oriented 53 degrees off the S70W bearing (S17W) and offset by rectangular pillars to inhibit the extension of roof cutters in the least favorable mining direction (S20E). The crosscuts at this mine could not be developed in the S20E due to steep dips in that direction. Because the RFRI has produced trends that support the collective knowledge of roof conditions in the mapped region of the study site, this field trial was viewed as a success.

SUMMARY AND CONCLUSIONS

NIOSH's RFRI was developed to help assess the risk of roof falls associated with underground stone mining. This method is centered on an examination of the defects contained in the roof caused by a wide range of local geologic, mining and stress factors. The RFRI is based on observations and should be considered as a part of an overall strategy deployed by mining operations to assess the risk of roof falls. Clearly more information leads to less uncertainty and potentially reduces the risk associated with ever changing mining conditions. NIOSH's aim is to develop a method to help mine safety personnel identify and track changing roof conditions.

The RFRI is an assessment technique that can be used to rate roof fall risk in important parts of a mine or potentially the entire mine property. It should also be viewed as a powerful communication tool that helps to track changes in roof conditions. It can also be used as a training method to help less-experienced miners identify defective rock conditions. Lastly, decision makers can use it to examine changes in mining conditions and to help develop plans for proactive actions during the course of mine development.

The purpose of this paper was to provide field examples that demonstrate how rock defect information is collected and analyzed and to verify that output from the RFRI are meaningful and, at least, partially repeatable. The first field verification test was conducted to examine how well the RFRI assessed roof conditions as a new set of entries was developed. In this case, the RFRI showed that elevated risks were associated with mining under major geologic discontinuities (faults) and that areas identified by the mine operator as the most hazardous also contained the highest RFRI values.

In the second field verification test, a new stress control mine layout was compared with a previous layout to determine what affects these design changes had on roof conditions. In this case, headings developed in a favorable mining direction had lower RFRI values then crosscuts developed in less favorable directions. In both field verification tests, the RFRI was found to perform as designed.

REFERENCES

Emery, C.L. (1964). In Situ Measurements Applied to Mine Design. Proceedings, 6th Symposium on Rock Mechanics, Rolla, MO, pp. 218-230.

Gale, W.J., Heasley, K.A., Iannacchione, A.T., Swanson, P.L., Hatherly, P. and King, A. (2001). A Rock Damage Characterization from Microseismic Monitoring. Proceedings, 38th U.S. Rock Mechanics Symposium, July 7-10, Washington, DC, pp. 1313-1320.

Hylbert, D.K. (1980). Development of Geologic Structural Criteria for Predicting Unstable Mine Roof Rocks. U.S. Department of the Interior, U.S. Bureau of Mines Open File Report 9-78, 249 p.

Iannacchione, A.T., Ulery, J.P., Hyman, D.M. and Chase F.E. (1981). Geologic Factors in Predicting Coal Mine Roof-Rock Stability in the Upper Kittanning Coalbed, Somerset Co., PA, U.S. Department of the Interior, Bureau of Mines RI 8575, 40 pp.

Iannacchione, A.T. and Prosser, L.J. (1998). Roof and Rib Hazards Assessment for Underground Stone Mines. Mining Engineering, February, pp. 76-80.

Iannacchione, A.T., Marshall, T.E., Burke, L.M., Melville, R. and Litsenberger, J. (2003). Safer Mine Layouts for Underground Stone Mines Subjected to Excessive Levels of Horizontal Stress. Mining Engineering, April, pp. 25-31.

Iannacchione, A.T., Coyle, P.R., Prosser, L.J., Marshall, T.E. and Litsenberger, J. (2004). Relationship of Roof Movement and Strata Induced Microseismic Emissions to Roof Falls. Mining Engineering, December, pp. 53-60.

Iannacchione, A.T., Esterhuizen, G.S., Prosser, L.J. and Bajpayee, T.S. (2006). Assessing Roof Fall Hazards for Underground Stone Mines: A Proposed Methodology. SME Preprint 06-59 SME Annual Meeting, St. Louis, MO, March 27-29.

Krausse, H.F., Damberger, H.H., Nelson, W.J., Hunt, S.R., Ledvina, C.T., Treworgy, C.C. and White, W.A. (1980). Engineering Study of Structural Geologic Features of the Herrin (No. 6) Coal and Associated Rock in Illinois. U.S. Department of the Interior, U.S. Bureau of Mines Open File Report 96-80, Vol. 1, 67 p.

Lagather, R.B. (1977). Guide to Geologic Features Affecting Coal Mine Roof. Mine Safety and Health Administration IR 1101, 18 p.

Maleki, H.N and McVey, J.R. (1988). Detection of Roof Instability by Monitoring the Rate of Movement. U.S. Department of the Interior, U.S. Bureau of Mines RI 9170, 12 pp.

Moebs, N.N. (1977). Roof Rock Structures and Related Roof Support Problems in the Pittsburgh Coalbed of Southwestern Pennsylvania. U.S. Department of the Interior, U.S. Bureau of Mines RI 8230, 30 pp.

Mucho, T.P. and Mark, C. (1994). Determining Horizontal Stress Direction Using the Stress Mapping Technique. Proceedings, 13th International Conference on Ground Control in Mining, Morgantown, WV, Aug. 2-4, pp. 277-289.

Parker, J. (1966). Mining in a Lateral Stress Field at White Pine. Canadian Institute of Mining and Metallurgy Transactions, Vol. LXIX, pp. 375-383.

Parker, J. (1973). How to Design Better Mine Openings: Practical Rock Mechanics for Miners. Engineering and Mining Journal, Part 5, December, pp. 76-80.

Shaffer, D and Petersen, G. (2000). Practical Rock Mechanics for Practical Miners. Aggregate Manager 4(10): 26-31.

Zhang, Y. and Peng, S.S. (2001). Effects of Bedding Plane Sliding and Separation and Tensioned Bolt in Layered Roof. Proceedings, 20th International Conference on Ground Control in Mining, Morgantown, WV, Aug. 7-9, pp. 226-234.