

## Assessing Roof Fall Hazards for Underground Stone Mines: A Proposed Methodology

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### Abstract

The potential for roof falls in underground mines remains a clear and present danger for mine workers. An investigation of ground conditions in nearly 50% of the nation's underground stone mines found that the state of roof stability is primarily determined in a limited and subjective manner. These large opening mines, with roof heights typically of 7 m or more, make physical observation difficult. Although some mines use monitoring techniques to gain additional information on roof stability, this practice is usually short-term and localized to address ground conditions in a particular section or part of the mine.

A methodology to assess the risk for a roof fall is proposed in a preliminary fashion based on engineering judgment acquired from extensive underground stone mine experience and examination of related literature. The proposed method utilizes an observational technique to identify the risk of roof falls in three categories. Case study scenarios provide a realistic picture of model implementation. Providing the mine level decision maker with an accurate assessment tool to ascertain the level of risk related to ground conditions is expected to reduce mine worker injuries and fatalities. Moreover, the presences of danger can be overcome with a clear picture of quantified ground conditions.

### Introduction

Mining has been identified as one of four sectors with injury rates that are consistently higher than all other industries within the United States [US] (Anon, 2004). Fatal occupational injury rates in 2002 were highest in mining (23.5 per 100,000 workers), followed by agriculture, forestry, and fishing (22.7), construction (12.2), and transportation and public utilities (11.3). Within the underground mining sector, falls of ground comprised about 28% of the fatal and 16% of the lost-workday injuries in the years from 2000 to 2004 (Anon, 2005). The National Institute for Occupational Safety and Health (NIOSH) has a focused research program to enhance the recognition of hazardous conditions and practices, and then to develop engineering interventions that mitigate conditions most often associated with fall-of-ground injuries. Many of the hazardous conditions present in the underground mining environment are caused by a combination of geologic and mining induced factors. Recognizing and assessing the different stability conditions of mine roof strata is a fundamental part of a proactive effort to address falls-of-ground injuries. The implementation of this process allows decision makers at all levels to determine the potential for a roof fall, a fundamental component of methods to assess risk. This paper proposes a preliminary qualitative method to determine a roof fall risk index, or RFRI, as one possible method to assess the ground fall hazards associated with underground mining.

### Background

Methods aimed at improving the quantitative nature of roof stability assessment have been proposed. In the early 1990s, the United Kingdom (UK) developed a code of practice (now Industry Guidance) for rockbolt use as roadway supports that included geotechnical assessment, initial design, design verification, and routine monitoring (Arthur, Waite and Altounyan, 1998). Cartwright and

Bowler (1999) provided a UK example of a procedure to assess the risk associated with potential failure or overloading of rockbolt support systems. In the mid 1990s, South African mines developed codes of practice to combat rock fall and rock burst accidents, as required by its 1996 Mine Health and Safety Act (Gudmanz, 1998). Swart and Joughin (1998) discussed the importance of rock engineering in developing this code of practice. Van Wijk, et al. (2002) developed a risk rating system for use in South African coal mines. This risk rating system aimed to optimize resources and ensure that focus is placed on the areas where it is most required. Lind (2005) demonstrated an integrated risk management approach that required a basic assessment of physical parameters such as coal seam characteristics, depth below surface, and mining conditions. In the U.S., Duzgun and Einstein (2004) used a statistical analysis of available roof fall data from mines in the Appalachian Basin to assess the roof fall risks associated with underground coal mining. In India, Rahaman, et al. (2004) discussed the using of microseismic monitoring systems to assess the risk of roof falls. All of these reports either demonstrate or postulate the use of geotechnical parameters to determine the mining system's potential for failure, a fundamental step towards managing the risk associated with fall-of-ground hazards. In many underground U.S. stone mines, especially those with large openings (widths >10 m and <17 m wide) and high roofs (>7 m), the state of roof stability is primarily determined in a limited and subjective manner. Therefore, the development of accepted procedures to help determine potential areas of unstable roof will inevitably lead to lower miner exposure to hazardous environments and a measurable reduction in falls of ground injuries.

### A Technique to Determine a Roof Fall Risk Index (RFRI)

The purpose of this paper is to present a qualitative method for determining the RFRI. This method is specifically aimed at underground stone mines where the strata defects that comprise hazardous conditions are difficult to see and the on-site assessment techniques are typically limited and subjective in nature. The assumptions made in this analysis are that the typical underground stone mine has wide openings (>10m and <17m), 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 use of this RFRI is relevant only to this experience base and is solely intended to assist in developing a quantitative method to determine roof fall risk for this mining sector. The target population is 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 past experience and engineering assessments during examination of more than 50 different underground stone mines. Ten measurable and observable categories are proposed, representing a significant range of defects found at these mines.

An assessment value from 1 to 5 is assigned within each category. Increasing values represent higher potential for failure. The assessment value of 3 is also used when information on a parameter is unknown. The 10 defect categories fall into four broad groups: geologic factors, mining induced failures, roof profile, and moisture factors (Table 1, see Appendix A).

## Geologic Factors

The following are the geologic conditions that most often result in increased instabilities in underground stone mines: 1) large angular discontinuities, 2) joint frequency, and 3) roof layer thickness and bedding contact strength. Parameters used in assigning an assessment value are identified in table 1.

**Large Angular Discontinuities** - Large angular discontinuities include faults, slips, and any other significant geologic structures (figure 1, see Appendix B). They can act to weaken competent roof rock and are often zones where deformations are initiated (mobilized). The influence of angular discontinuities on roof strata stability is well documented (Lagather, 1979; Moebs, 1977). If these parameters are non-existent, then a value of 1 is assigned. A value of 5 is assigned to roof strata with multiple angular discontinuities and associated weak (low strength) contacts, implying a high potential for instability from this category. 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. If the occurrence of angular discontinuities is unknown, the assessment value is 3.

**Joint Frequency** - Joint frequency has been identified as an important factor influencing roof stability (Krausse, et al., 1980). Joints refer to the steeply inclined (nearly vertical) fractures that often naturally occur in rock formations (figure 1). Joint frequency is comprised of several parameters that help to 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).

**Roof Layer Thickness and Bedding Contact(s) Strength** - Roof layer thickness and bedding contact strength have long been recognized as important factors in determining strata stability (Moebs, 1977, Hylbert, 1980, Iannacchione and Prosser, 1998). It is the interaction of these two characteristics that controls the development of separate roof beams and partially controls how they deform (figure 1). Massive strata, void of distinct geologic layers, tend to have few continuous, horizontal bedding plane structures, making for stable strata conditions. These strata have an assessment value of 1. Almost without exception, 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, raising the probability of failure. Layers less than 0.25 m thick have often been observed as unstable and present a high probability for excessive roof beam sag, especially when they are bounded by weak contacts. In this case, an assessment value of 5 is assigned. The parameters in this category could easily be modified to match local mining experiences.

## Mining Induced Failures

Mining induced failures are a direct reflection of strata defects produced as a result of mining. There are four important categories of mining induced failures in underground stone mines: 1) shear rupture surfaces, 2) joint separation, 3) lateral strata shifting, and 4) vertical strata separation.

**Shear Rupture Surfaces** - Shear rupture surfaces are typically found in association with buckling of roof layers less than 1m thick. This buckling failure is caused by excessive levels of horizontal stress, producing a low angle shear rupture surface with a sharp contact and covered with a powder-like rock dust residue (figure 1). If the occurrence of angular discontinuities is unknown, the assessment value is 5. When the immediate roof layer buckles, the relatively straight shear rupture surface is observable.

**Joint Separations** - Joint separations occur when nearly vertical fractures begin to expand or open up (figure 1). This can signal a potentially unstable condition, confirming that strata extension is occurring and the strata have lost considerable strength. Because most underground stone mine roofs have some level of vertical jointing

and horizontal bedding plane contacts, most roofs are comprised of blocks of varying sizes that are supported by the confining stresses in the immediate roof beam. When strata extension occurs, the roof blocks are no longer confined and are prone to fall to the ground under the forces of gravity. If no joint separation is observed, then the assessment value is 1. Because the parameters used to define separation are limited, any noticeable or measurable separation of a vertical joint is assigned a value of 5.

**Lateral Strata Shifting** - Lateral strata shifting is a condition caused when roof layers move in different directions along bedding contacts (figure 1). While it is difficult to directly link this category with roof falls, it is commonly recognized as a hazardous condition (Zhang and Peng, 2001). In some mines, lateral strata shifting is associated with large-scale movement along a fault plane or a large angular discontinuity. 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 occurs, then the assessment value is 1. If less than 2 cm of offset is observed where the surface intercepts the mine roof or rib, then the assessment value is 3. If the offset is > 2cm, the assessment value 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 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).

**Vertical Strata Separation** - Vertical strata separation is a condition caused when roof layers separate from one another and sag into the mine entry (figure 1). 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 vertical 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 borescope, or a roof deflection monitor. If no separations exist in the immediate roof, then the assessment value is 1. If the separation is barely detectable or open, then the value is 3. If the separation is easily detectable (>0.5 cm), then the value is 5.

## Roof Profile

The profile of the roof provides a good indication of what damage has occurred to the roof and potentially what damage will occur based upon its shape. This damage can be inherent to the rock or it can be induced by blasting or scaling. The two categories that help to define the roof profile are the roof rock debris on the floor, and roof shape.

**Roof Rock Debris on the Floor** - If an entry is being or has been damaged by existing defects or by blasting or scaling, evidence of this damage is typically found deposited on the mine floor (figure 1). 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 no record is made of it, then this valuable piece of information will be lost. One has to make sure that debris from blasting and scaling the roof and ribs is not confused with roof rocks that have fallen without this man-induced assistance. If no roof rock debris is observed, then the assessment value is 1. Increasing amounts of debris produce higher assessment values. A value of 5 is typically associated with a significant pile of broken rocks that covers a portion of the mine's entry.

**Roof Shape** - It has been established that the shape of the roof can provide some indication of the future performance of the roof (Iannacchione and Prosser, 1998). In general, a smooth roof is desirable in underground stone mining and typically represents a stable state (figure 1). In this case, the assessment value is 1. Conversely, if the roof is highly irregular with pronounced swales and troughs, the potential for unstable conditions increases and the assessment value is 5. Sometimes this condition is caused by inherent weakness within the roof rocks. Other times the rougher looking roof is a result of roof rocks damaged by blasting or scaling.

## Moisture Factors

In mining, the physicochemical effects of water can act to reduce the strength of a mine roof (Unrug, 1997). Also water pressure in fractures may be strong enough to cause roof instabilities. This condition is particularly acute in shallow, large-opening stone mines where extreme humidity conditions, especially in the summer months, reduce roof rock strength. Additionally, the closeness of the mine to the surface places the mines above drainage. This condition promotes the development of weathered joints with variable water flow conditions. Standing or flowing water in prominent fracture systems can exert considerable destabilizing forces within the roof.

**Moisture/Ground Water Inflow** - The assessment values for moisture/ground water inflow characteristics are the following: the roof is dry and no water is observed, the assessment value is 1; if the roof is damp, the value is 2; if dripping occurs, the value is 4; and if the flow of water from the roof is steady, the value is 5.

## Monitoring Data and Its Impact on Assessment Values

To this point, parameter characteristics of the proposed method to assess roof fall hazards have been determined with information readily available at any mine site with a means of accessing and drilling the roof. Because underground stone mines are all drill-and-blast operations, every mine in the U.S. has the basic ability to access and drill the roof. However, if this were the only information that was available to decision makers, then our ability to more accurately assess stability conditions would be limited. In fact, some mines use advanced monitoring techniques to gain additional valuable information about roof stability. This practice has developed, in part, because of difficulties in accurately observing roof conditions when room heights exceed 7 m. Another reason is the need to assess roof rock behavior above the immediate roof, which is entirely out of the decision maker's view. As a result, a diverse range of roof deflection monitoring devices and some geophysical techniques have been or are being used to detect roof rock defects.

## Roof Deflection Measurements

Roof deflection monitoring techniques have long been employed in underground mining to monitor roof behavior (Parker, 1973; Maleki and McVey, 1988; Kaiser, 1981). Typically, these are mechanical or electro-mechanical devices that allow for the measurement of displacement between two or more known points within a roof borehole or between the mine's roof and floor. Sometimes they are simply tools, such as a scratch tool, that allow the operator to remotely feel or detect the crack or separation within a roof borehole.

**Vertical Strata Separation Adjustment** - Because roof-to-floor convergence and roof beam sag monitoring instruments provide an opportunity to collect measurable values of roof deflection, these data can be used to either reduce or increase assessment values for Category 7 - Vertical Strata Separation (table 1). Three general conditions are characterized when measuring roof deflection. The first condition is no measurable roof deflection, indicating the strata is or has become stable. If this occurs, the assessment value for this category is 1.

The second condition is when a measurable level of roof deflection persists for longer than a few days. 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 may not be on a path to a roof fall. In many ways, this condition represents a semi-stable state (Iannacchione et al., 2004). There are many examples where roofs with this kind of deflection have subsequently stabilized, and, in some cases, for long periods of time. If this condition occurs, the assessment value is multiplied by 2. It should be noted that when roof-deflection is measured, it is 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. This

condition suggests the roof is in an unstable state. If this occurs, the assessment value is multiplied by 4.

## Microseismic Emissions

Numerous geophysical techniques exist for detecting zones of potential roof instability, including cross-hole seismic tomography, ground penetrating radar, and the monitoring of microseismic emissions. Maleki, et al. (1992), detected the development of mine roof fractures up to 15 m into the mine roof. Also, Molinda, et al. (1996) used ground penetrating radar to image a known geologic discontinuity at NIOSH's underground Lake Lynn Laboratory. The use of microseismic emissions information has been discussed to assess risk for South African deep hard rock mine stability (Stewart and Spottiswoode, 1996) and Indian coal mine roof falls (Rahaman et al., 2004). Recently, microseismic emissions have been used to identify zones of roof rock instability at an operating stone mine in Pennsylvania (Iannacchione et al., 2001 and 2004).

**Shear Rupture Surfaces Adjustment** - Microseismic emissions have been shown to be particularly good at characterizing the parameters in Category 4 - Shear Rupture Surfaces. As a result, Category 4's assessment value can either be reduced or increased based on the level and clustering characteristics of these emissions (table 1). Emissions that are equivalent to background levels have been found to represent stable conditions, effectively reducing the assessment value to 1. Elevated emissions that cluster in well-defined locations have been associated with roof falls, resulting in an increased assessment by a multiple of 3.

**Lateral Strata Shifting Adjustment** - Monitoring microseismic emissions has the added benefit of identifying large scale bedding plane shears (Gale et al., 2001), albeit to less of a degree than shear rupture surfaces. When emissions increase and cluster, they represent a reasonably good opportunity to further characterize the parameters in Category 6 - Lateral Strata Shifting (table 1). Emissions that are equivalent to background levels have been found to represent stable conditions, while elevated emissions that cluster in well-defined locations have been associated with roof falls.

## Determining the Relative Probability of Roof Falls

The risk of roof falls can be characterized as a risk index. A mathematical expression can be used to calculate the roof fall risk index (RFRI) and is defined as:

$$RFRI = \frac{\sum (AV * W)}{\sum (MAV * W)}, \quad (1)$$

Where:

- AV = the assessment value for each defect category
- MAV = the maximum of assessment value of each category or 6
- W = the weighting of each category

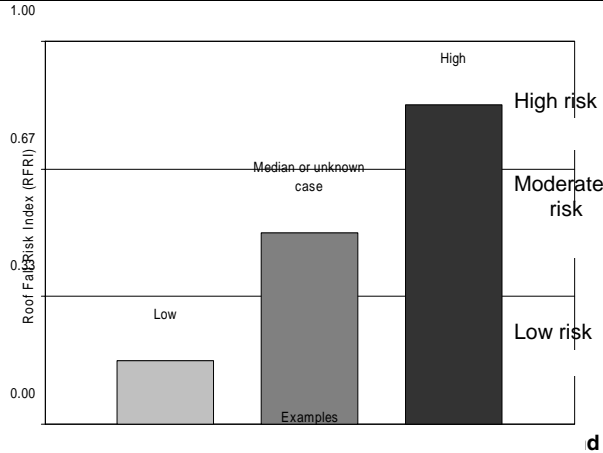
Because the defect categories affect the performance of underground stone mine entries to different degrees, it is necessary to independently weight each of the ten categories (table 2). The defect categories more detrimental to entry performance are 4, 5, 6, 7, and 8 and were assigned a weight of 2. 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 weighted at 1.

The RFRI for the mathematical expression shown in equation 1 produces a distribution where RFRI values approaching 0 would represent a very stable condition and those near 1 a very unstable condition. The minimum and maximum RFRI values without adjustment factors range between 0.17 and 0.83 (figure 2). If the maximum adjustment factors are applied to Categories 4, 6, and 7, an RFRI value of 1.46 is possible. It is also possible to calculate the RFRI if nothing is known about any of the defect categories. This produces a RFRI equal to 0.5, or equally between the stable and unstable conditions. This is a desired outcome of the mathematical expression.

A logical outcome of these three conditions is to divide the RFRI into three risk categories: low, medium, and high (Figure 2). It is important to note that the objective of this paper is to develop a method of ranking hazardous conditions, and it is, therefore, inappropriate at this time to equate the proposed risk categories with a prescribed action.

**Table 2. Weightings of defect categories.**

Category number	Category description	Weighting
1	Large angular discontinuities	1
2	Joint frequency	1
3	Roof layer thickness and bedding	1
	contact strength	
4	Shear rupture surfaces	2
5	Joint separation	2
6	Lateral strata shifting	2
7	Vertical strata separation	2
8	Roof rock debris on floor	2
9	Roof shape	1
10	Moisture/ground water inflow	1



low risk categories.

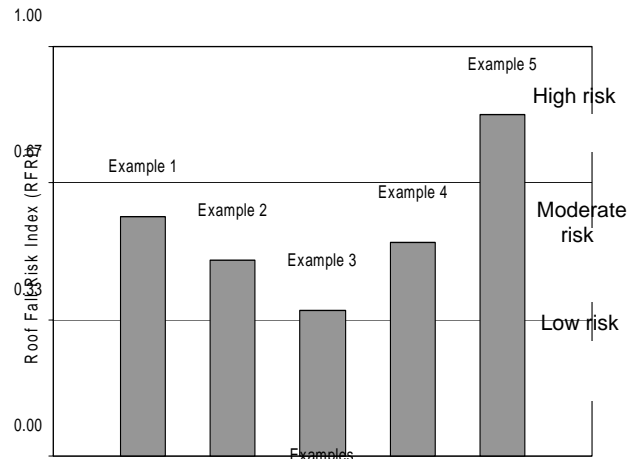
**Hypothetical Case Studies**

Two case studies of the use of the proposed methodology to assess roof fall risk are given below. These cases are meant to demonstrate the use of the method through realistic scenarios. Engineering judgment, based on extensive underground stone mine investigations and related studies found within the literature, was used to identify: 1) the number and kind of defect categories, 2) the parameters used to determine an assessment value for each category, 3) the weightings of categories, and 4) the adjustments for monitoring activities.

**Case 1: Shear Rupture Surfaces with Rock Debris on the Floor**

One ground condition that adversely affects approximately 20% of U.S. underground stone mines is the occurrence of roof falls in conjunction with excessive levels of high horizontal stresses (Iannacchione, 2003). Mines with this problem often have a shear rupture surface in the immediate roof (first 2m of strata), propagating in a direction perpendicular to the principal stress direction (Emery, 1964; Parker, 1966). The shear rupture surface is typically comprised of multiple surfaces that fracture the roof, forming a cutter or gutter type structure in the roof. As the rock fails, it falls to the ground below the shear rupture surface and begins to form a debris pile. The size of the pile depends on the size and shape of the shear rupture surface.

Case No. 1 assumes that the decision makers at the mine have no knowledge of the defect categories discussed above with the following exceptions: 1) the entry has a large shear rupture surface (>1 m in length), and 2) a continuous pile of rock debris has accumulated on the floor beneath the shear rupture surface. This first example produces an assessment value of 5 for defect categories 4 and 8 and assessment value of 3 for all other categories with a RFRI of 0.58 (No. 1, table 3, see Appendix A). This is within the moderate risk zone for a roof fall (No. 1, figure 3).



**Figure 3. Five potential examples of the RFRI for roof strata that contain shear rupture surfaces with rock debris on the floor and their impact on risk assessment (Case No.1).**

Adding information about site conditions provides additional examples, to help explain the proposed methodology and test the method against the author's experience. As more favorable characteristics about the site are obtained, such as favorable geologic conditions, smooth roof profile, dry roof conditions (No. 2, table 3 and figure 3), and when drill holes show no lateral or vertical movement (No. 3, table 3 and figure 3), the RFRI falls to a low of 0.35. This is close to the low risk zone. Indeed if all the additional information indicates the site has stabilized for the current time interval, then a lower risk is apparent.

Conversely, when additional information about the site conditions provides less favorable characteristics, such as drill holes showing lateral strata separation and measurable vertical strata movement (No. 4, table 3 and figure 3), and elevated and clustered microseismic emissions (No. 5, table 3 and figure 3), the RFRI rises to a high of 0.83. This is within the high risk zone for a roof fall.

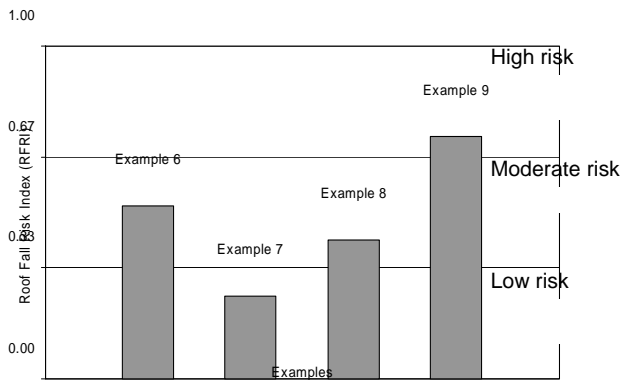
**Case 2: Thinly Bedded Strata with Weak Bedding Contacts**

The impact of thinly bedded strata on roof rock stability is well documented (Hebblewhite and Lu, 2004). Add to this the wide room spans (>15 m) and non-uniform use or rock reinforcement and it is easy to see why this condition has been linked to many underground stone mine roof falls. Euler's formula provides general performance parameters for bedded stone roof beams where the critical stress defining the onset of beam buckling is highly dependent on beam thickness (Iannacchione et al., 1998).

Case No. 2 assumes that the decision maker has no knowledge of local defect categories with only one exception – the site is known to have thinly bedded strata with weak bedding contacts. This condition gives an assessment value of 5 for defect category 3 and assessment values of 3 for all other categories with a RFRI of 0.52 (No. 6, table 3 and figure 4). This is within the moderate risk zone.

A more favorable characterization of the site, where categories 1, 4, 5, 6, 7, 8, and 9 are all 1, and categories 2 and 10 are 3 (No. 7, table 3 and figure 4), produces a RFRI of 0.25. This is within the low risk zone. However, by simply observing some lateral and vertical strata separation (No. 8, table 3 and figure 4) or by actually measuring an accelerating rate of roof deflection within the site (No. 9, table 3 and

figure 4), the RFRI can rise to 0.42 and 0.73, respectively. This is well within the high risk zone.



**Figure 4. Four potential examples of the RFRI for roof strata that contain thin layers with weak bedding contact strength and their impact on risk assessment (Case No.2).**

### Summary and Conclusions

This study proposes a roof fall hazard assessment method for underground stone mines that can be used to help manage miner exposure to unstable roof rock conditions so that roof fall related injuries can be reduced. The underground stone mining industry has an acute need for this capability because current roof stability assessment techniques are limited by difficulties with assessing conditions in high roofs (>7 m).

The proposed roof fall hazard assessment methodology is comprised of ten defect categories that cover a range of geologic, mining induced, roof profile and moisture factors. Each category has a set of parameters that allow for the estimation of an assessment value between 1 and 5. These parameters are based on experience gained from visiting more than 50 different operating mines and from an investigation of relevant topics in the literature.

Important geologic factors affecting roof stability include large angular discontinuities, joint frequencies, and roof layer thickness and bedding plane contact strength. In addition to these naturally occurring strata defects, roof stability is directly impacted by a range of mining induced failures, which include shear rupture surfaces, joint separations, lateral strata shifting, and vertical strata separation. A fundamental assessment of roof stability is also made by examining the profile of the roof where its shape and the amount of fallen material provide evidence of what damage has occurred and, potentially, what damage will occur. Lastly, the influence of moisture on roof stability is determined by observing wetness and ground water inflow conditions. These factors are determined with information readily available at any mine site with a means of accessing and drilling the roof.

In practice, much more information about the character and performance of a mine's roof can be made with monitoring data. These data are generally obtained from roof deflection monitoring devices and some geophysical techniques, all of which help to detect and assess hazardous roof rock defects. In this roof fall hazard assessment methodology, monitoring data are used to adjust assessment values. If monitoring information supports a more stable assessment of roof fall potential, then the RFRI is decreased. Conversely, information that indicates a less stable condition yields a higher RFRI. In this way, decision makers who know more about their site ground conditions are better able to make a more accurate hazard assessment.

The proposed method for roof fall hazard assessment involves calculating a RFRI. Very stable conditions produce RFRI values approaching 0, while unstable conditions produce RFRI values approaching 1. In some cases, where significant adjustments are made, the RFRI may be in excess of 1. Three logical risk categories are defined as low, medium, and high, based upon the RFRI values. Determining the particular risk for a specific underground stone entry will allow decision makers to respond in a proactive and measured

fashion to hazardous roof rock conditions, thereby lowering the potential for fall-of-ground injuries.

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## Appendix A

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

Grouping	Category	Parameter	Assessment Value
Geologic factors	1	Large angular discontinuities	
		None	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
		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	
	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	
	Shear rupture surfaces		
	Mining induced failures	4	None
Small shear (cutter < 1m)			3
Large shear (cutter > 1m)			5
Unknown			3
Microseismic emission at background level			Reduce to 1
Microseismic emission elevated and clustered			Multiply by 3
Joint separation			
5		None	1
		Noticeable or measurable	5
		Unknown	3
Lateral strata shifting			
6		None	1
		< 2cm of offset or partial vertical drill hole offset	3
		> 2cm of offset or complete vertical drill hole offset	5
		Unknown	3
		Microseismic emissions at background level	Reduce to 1
		Microseismic emissions elevated and clustered	Multiply by 2
Vertical strata separation			
7		None	1
		Slight (barely detectable)	3
		Significant (>0.5cm)	5
		Unknown	3
		No roof deflection	Reduce to 1
		Measurable roof deflection	Multiply by 2
	Accelerating roof deflection	Multiply by 4	
Roof rock debris on floor			
Roof profile	8	None	1
		Slight (widely spaced)	2
		Moderate	4
		Significant (continuous)	5
		Unknown	3
	Roof shape		
	9	Smooth	1
		Intermediate	3
		Rough	5
		Unknown	3
Moisture/ground water inflow			
Moisture factors	10	None	1
		Damp roof	2
		Drippers	4
		Steady flow	5
		Unknown	3

**Appendix A (cont'd)**

**Table 3. Assessment values and RFRI for two Case Studies.**

Category	Case 1					Case 2			
	1	2	3	4	5	6	7	8	9
Large angular discontinuities	3	1	1	1	1	3	1	1	1
Joint frequency	3	1	1	1	1	3	3	3	3
Roof layer thickness and bedding contact strength	3	3	3	3	3	5	5	5	5
Shear rupture surface	5	5	5	5	15*	3	1	1	1
Joint separation	3	3	1	1	1	3	1	1	1
Strata shifting (lateral movement)	3	3	1	5	10*	3	1	5	5
Strata separation (vertical movement)	3	3	1	5	5	3	1	5	20*
Roof rock debris on floor	5	5	5	5	5	3	1	1	1
Roof profile	3	1	1	1	1	3	1	1	1
Moisture/ground water inflow	3	1	1	1	1	3	3	3	3
RFRI	0.58	0.48	0.35	0.52	0.83	0.52	0.25	0.42	0.73
* - adjustment factors applied									



## Appendix B

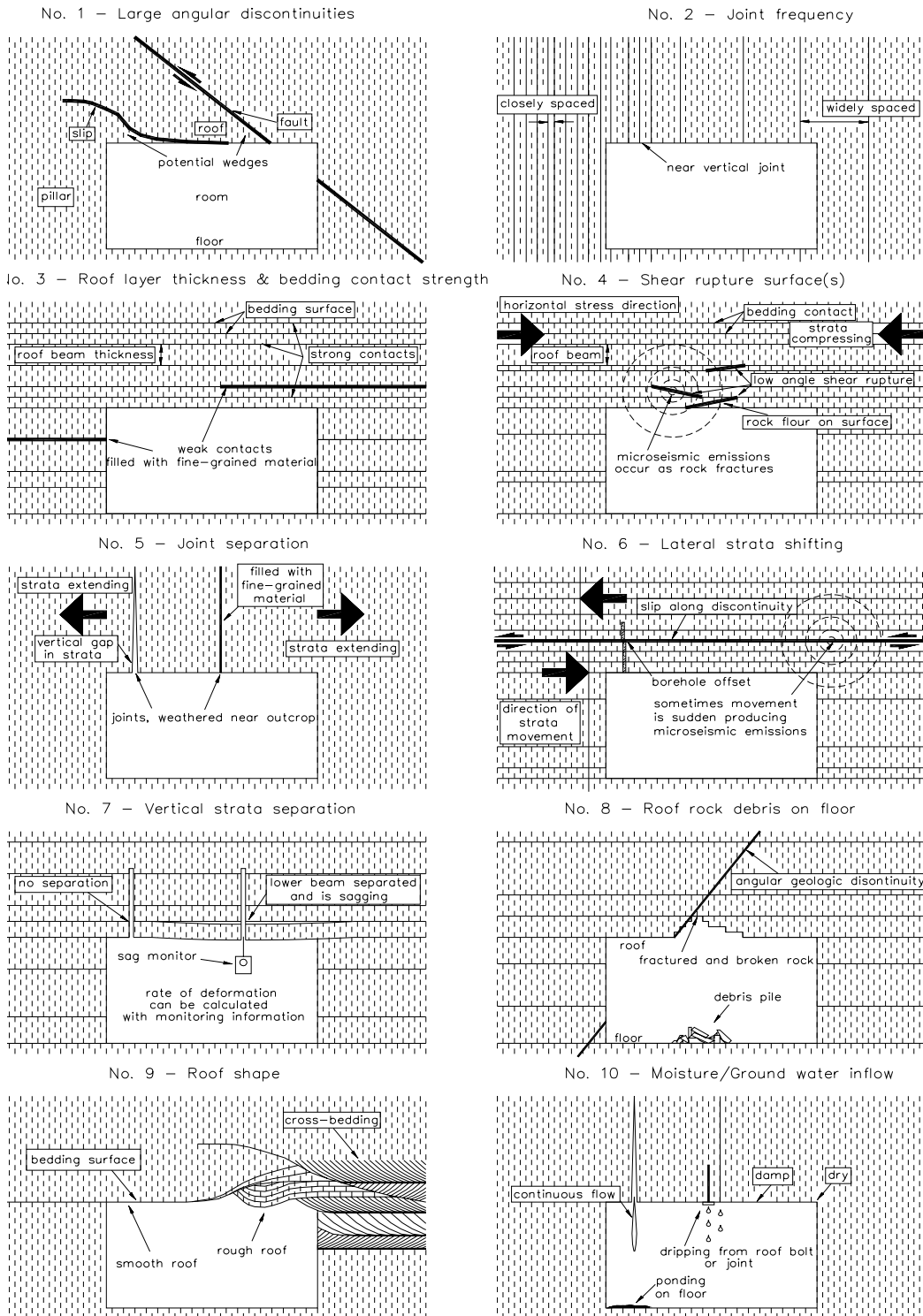


Figure 1. Sketch of parameters associated with ten defect categories.