Methods for determining roof fall risk in underground mines

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Background

A realistic goal for underground mines trying to reduce the incidence of miner injuries associated with roof falls is to assess the conditions that pose a roof fall risk. If mine operators properly assess roof fall hazards, they can better reduce roof fall risks with appropriate engineering and administrative controls. Any methodology that helps attain this goal can be thought of as a roof fall risk-assessment method. An effective roof fall risk-assessment method includes the ability to observe variable roof conditions and assess how much these conditions represent the potential for a roof fall capable of injuring miners. This methodology should rank the risks associated with varying conditions, should be reasonably reproducible and should clearly indicate roof fall risk to all mine personnel responsible for the design, approval or installation of controls that either stabilize the roof or lessen the exposure to roof falls. This paper focuses on the risk-assessment issues, leaving the roof fall risk-management process, where controls are designed and used to reduce risk, to another discussion.

One of the most important safety issues at any mining site is the need to identify the location and nature of roof fall hazards. The mining law requires that roof falls be reported to enforcement agencies by Form 7000-1. Roof fall locations are to be displayed on mine maps and made available to miners or their representatives. The Code of Federal Regulations, Title 30 Part 50 Section 2, defines a reportable roof fall as "an unplanned roof fall at or above the anchorage horizon in active workings where roof bolts are in use" or as "an unplanned roof or rib fall in inactive workings that impairs ventilation or impedes passage" (Anon, 2005). In general, roof fall reporting requirements consist of time and date, location information, mining method involved, equipment involved and a narrative that fully describes the conditions contributing to the roof fall and that also quantifies the damage. The standard also requires the operator to take steps to prevent a recurrence. The mining law, however, does not specifically require that information about hazards that could cause roof falls be displayed on mine maps or communicated to mine workers.

Abstract

Reducing the number of roof fall injuries is a goal of the NIOSH mine safety research program. Central to this effort is the development of assessment techniques to help identify the nature of the risks associated with working under potentially hazardous roof conditions. This paper discusses a method to determine the roof fall risk using a qualitative risk-analysis technique. The ability to determine roof fall risk has been a long-standing goal of safety professionals and could provide the kind of information needed by on-site personnel responsible for worker safety to mitigate roof fall injuries.

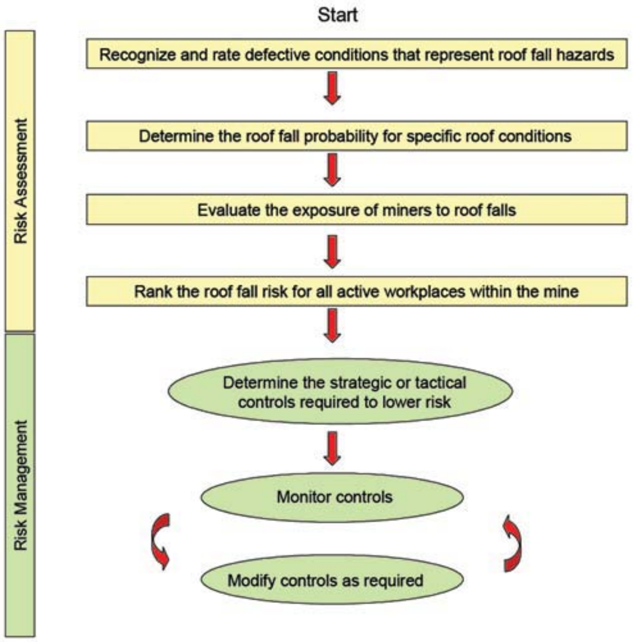
Why is a roof fall risk-assessment method important for improving miner safety?

The potential for roof falls in underground mines is a significant danger for mine workers. In 2006, 10 fatal ground fall injuries occurred (Table 1). Also, during the 10-year period from 1996 through 2005, 7,738 miners were injured from roof falls in underground coal, metal, nonmetal and stone mines (MSHA, 2005). Coal mines had the highest rate, 1.75 roof fall injuries per 200,000 hours worked underground (Table 2). While this rate dropped over this period, there were still 581 recorded roof fall injuries in 2005, with many classified as severe. Fatal injury trends from 1996 to 2005 were equally troubling, with 100 roof fall fatalities. While coal mining had the highest number with 82, metal mining had the highest rate with 0.03 fatalities per 100,000 miners (Table 1). These statistics attest to the seriousness of this safety issue, although roof fall injuries decreased from 1.71 in 1996 to 1.19 in 2005 per 200,000 hours worked (Table 2). Clearly, progress in miner safety has been made, but further improvement is possible. It is imperative that new safety techniques and methodologies continue to be developed, so this downward trend in roof fall injures can be maintained.

Most safety decisions in the U.S. mining industry are guided by company policy and the requirements of state and federal regulations. These decisions have been successful in reducing roof fall injuries (Table 2). For this study, the author's underlying assumption is that incorporating risk-assessment and risk-management methods to the existing decision-making process will help to further reduce miner injury rates.

FIGURE 1

Flow diagram depicting the generalized structure of roof fall risk assessment activities and its relation to risk management activities.



What is the state-of-practice for minerals industry risk assessment?

The International Organization for Standardization (ISO) and the American National Standards Institute (ANSI) produce standards and guidelines that define the use of risk-assessment and risk-management methods. When applied to a particular industry, the issues unique to that industry require special approaches. For example, the environmental and health sciences have long used risk-assessment and risk-management methods to identify the highest environmental and occupational health and safety risks and to develop controls specific to their operational and regulatory environments (National Research Council, 1983, 1994, 2006).

Risk-assessment and risk-management methods for the mining industry are more prevalent in countries with safety standards that emphasize duty-of-care, i.e., Australia, Canada, United Kingdom and South Africa, rather than the prescriptive health and safety regulations, i.e., the United States. Duty-of-care in these countries is defined in legislation that requires employers, suppliers and employees to provide, design for and adhere to reasonable activities that ensure workers are cared for. In Australia, an ISO has been specifically developed (Anon, 2004) to enable organizations to implement environmental management systems (EMS) for continuous improvement in their operations.

In the mid-1990s, Australia's mineral industry became heavily involved in risk-management methods that typically consisting of structured, team-based exercises to review potential problems carefully with new or existing mining methods, new equipment or other operational problems (Joy, 2001). Joy estimates that at least 80 percent of all Australian coal mines have performed some form of structured, team-based risk assessment/risk management. Tools used in these exercises include HAZOP (Hazard and Operability Analyses), FMECA (Failure Modes, Effects and Criticality Analysis), WRAC (Workplace Risk Assessment and Control) and the BTA (Bow Tie Analysis). All of these tools and techniques are defined in a framework by Joy (2006) to explain the management of risk in the minerals industry. Lastly, the Minerals Industry Safety and Health Center (MISHC) Web site is an excellent source for information on Australia's diverse risk-assessment/risk-management approaches (www.mishc.up.edu.au).

Examples of risk assessment applied to ground control issues

In the early 1990s, the United Kingdom (UK) developed a code of practice (now referred to as Industry Guidance) for rock bolt use as roadway supports that included geotechnical assessment, initial design, design verification and routine monitoring (Arthur et al., 1998). Cartwright and Bowler (1999) provided a UK example of a procedure to assess the risk associated with potential failure or overloading of rock-bolt 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-assessment method for use in South African coal mines. This risk-assessment method aims to optimize resources and focuses attention on the areas where it is most required. Lind (2005) demonstrated an integrated risk-management method that required a basic assessment of physical parameters such as coal seam characteristics, depth below surface and mining conditions.

The Minerals Council of Australia (MCA) helped produce a national guideline for the management of roof fall risks in underground metalliferous mines (MOSHAB, 1997). Potvin and Nedin (2003) published a "Reference Manual" in support of the MCA guidelines meant as a collection of techniques and examples

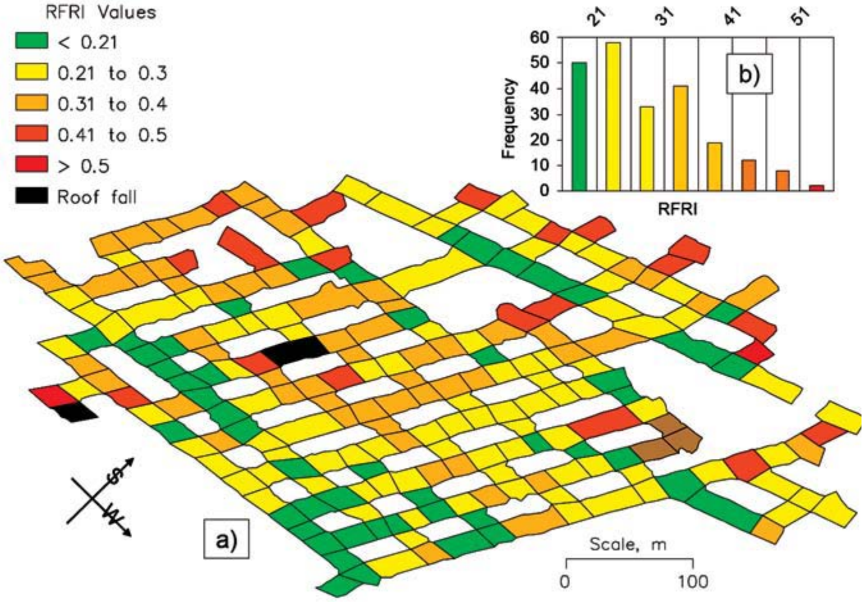
Table 1

Fatal roof fall injuries in underground coal mines during 2006.

Date	Mine	Company	State
1/10/06	#1	Maverick	KY
1/29/06	Aberdeen	Andalex	UT
2/1/06	#18 Tunnel	Long Branch	WV
2/16/06	HZ4-1	Perry County	KY
3/29/06	#4	Jim Walter	AL
4/20/06	#1	Tri Star	KY
10/6/06	#2	D & R	KY
10/12/06	#7	Jim Walter	AL
10/20/06	Whitetail Kittanning	Alpha Natural Resources	WV
12/17/06	Prime #1	Dana Mining	WV

of good roof control practices.

FIGURE 2



(a) RFRI values for the 226 measurement area that comprised the study area and (b) histogram of RFRI frequency.

Roof fall hazard-assessment techniques

Risk-assessment methods provide a systematic approach to identifying and characterizing risks, especially those associated with low-probability, high-consequence events such as roof falls. The first step in utilizing a roof fall risk-assessment method requires identification of the potential roof fall hazards. Because local geologic, stress and mining conditions interact to create varying roof conditions, commodity-specific or activity-based hazard-assessment techniques and associated risk-analysis techniques are needed to locate potential risk within workplaces throughout the mine. Many hazard-assessment techniques generally can be classified into one of the following three groups: hazard maps, rock-mass classification systems and monitoring data. While all three techniques are useful in hazard assessment, they have had only limited application when applied to roof fall risk assessment.

To help improve the link between hazard assessment and risk assessment, NIOSH developed a tool called the roof fall risk index (RFRI) to systematically identify roof fall hazards. The RFRI is specifically developed for underground stone mine and is mentioned here as an example that could be adapted to mining conditions. The RFRI focuses on the character and intensity of defects associated with specific roof conditions and attempts to incorporate some of the characteristics discussed in the other hazard assessment techniques (Iannacchione et al., 2006; Iannacchione et al., 2007). The defects measured within the RFRI can be caused by a wide range of local geologic, mining and stress factors and are equated directly to changing roof conditions causing roof fall hazards. A significant range of defects found at underground stone mines are classified into 10 categories (known as defect categories), each of which is assigned an assessment value ranging from 1 to 5, with the numerical value increasing with the severity of the defects. To calculate the RFRI, one must determine the assessment value for each defect category, multiply by an assigned weight (either 1 or 2), add all category values together and multiply by 1.11. Ideally, values approaching zero represent safer roof conditions, while an RFRI approaching 100 represents a serious roof fall hazard.

The RFRI is a hazard-assessment technique that can be used as both a training tool and a communication tool. This technique requires that roof fall hazards be mapped and the spatial distribution within the un-

Table 2

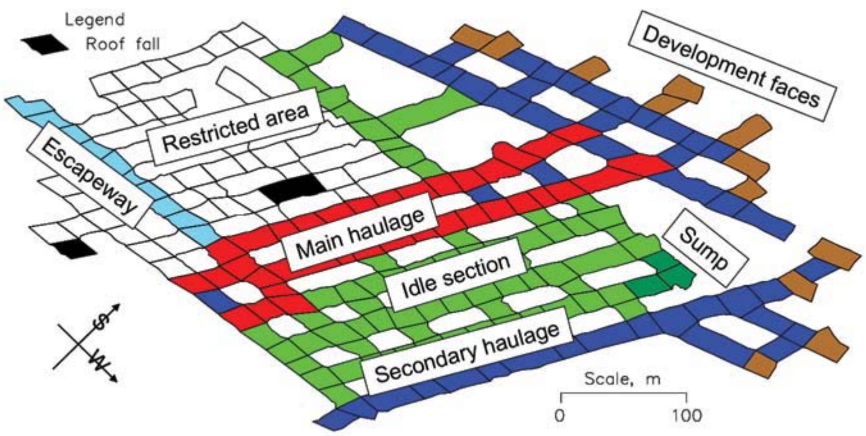
Roof fall injury and fatality rates over then 10-year period from 1996 to 2005 for underground mines.

	Coal		**Metal**		**Nonmetal**			**Stone**		**Total**
Year	**Injury rate**	**Fatal rate**	**Injury rate**	**Fatal rate**	**Injury rate**	**Fatal rate**	**Injury rate**	**Fatal rate**	**Injury rate**	**Fata rate**
1996	1.8	0.029	2.08	0.016	0.36	0.0	0.58	0.116	1.71	0.028
1997	1.9	0.02	2.12	0.032	0.43	0.0	0.5	0.055	1.8	0.022
1998	2.03	0.033	2.07	0.052	0.44	0.0	0.52	0.0	1.89	0.032
1999	1.89	0.031	1.82	0.061	0.59	0.0	0.92	0.051	1.77	0.033
2000	1.98	0.011	1.63	0.023	0.4	0.0	0.45	0.0	1.79	0.011
2001	1.79	0.03	1.01	0.09	0.31	0.0	0.52	0.0	1.58	0.032
2002	1.75	0.011	0.94	0.0	0.31	0.0	0.59	0.0	1.55	0.009
2003	1.51	0.009	0.86	0.0	0.3	0.0	0.43	0.0	1.34	0.007
2004	1.5	0.008	0.68	0.0	0.25	0.0	0.31	0.0	1.31	0.007
2005	1.34	0.023	0.81	0.0	0.33	0.0	0.24	0.0	1.19	0.019
Total	**1.75**	**0.021**	**1.51**	**0.03**	**0.38**	**0.0**	**0.5**	**0.021**	**1.6**	**0.021**

Injury rate = Roof fall injuries (Degree of Incident, Class 1-6) per 200,000 hours worked underground.
Fatal rate = Roof fall fatalities per 100,000 miners.

FIGURE 3

Miner activity (fictional example) and related miner exposure for the 226 measurement areas.



derground workplace determined. The RFRI strives to assess roof conditions over large, continuous areas, producing a comprehensive assessment of changing roof conditions than was previously possible.

Moving from hazard assessment to risk assessment

Hazard assessment in conjunction with the mine's individual roof control plans can be thought of as an implicit form of risk assessment. Ideally, a hazard-assessment technique should be capable of ranking the various hazards and communicating these hazards to the persons or groups in need of this information. The outcome of this process can aid in establishing minimum roof support standards for a mining operation where a general class of hazards is being addressed. The focus of this roof fall risk-assessment approach is on identifying areas of highest risk so that additional controls can be applied. These controls can range from additional monitoring to supplemental roof support.

Identifying areas of highest roof fall risk is accomplished through standard risk-analysis methods, where the probability of occurrence and its consequence are determined using

Risk = Probability of occurrence x Consequence (1)

Of the many different risk-assessment methods discussed in the literature, only a few risk analysis techniques apply to the roof fall problem. For example, when determining the probability of occurrence, two very different approaches are available: qualitative assessment and quantitative assessment. This paper focuses on a qualitative risk-analysis technique using a risk matrix as shown in Table 3.

For a roof fall event, the Probability of occurrence term in Eq. (1) consists of two factors: the probability of a roof fall occurring and the potential for a miner being injured by this roof fall. Roof fall probability in this analysis can be estimated with the RFRI, while injury potential is estimated by the miner's exposure to hazardous roof conditions. Miner exposure is dependent on the frequency of an activity within an area versus the percentage of the workforce involved in that activity (Table 4). The activity frequency can range from many times per shift to once per month, while the percentage of the workforce involved in that activity can range from many (>50 percent) to few (<5 percent). Roof fall probability and miner exposure can be determined for all areas of the mine accessible by the miner.

The consequence term in the risk equation typically refers to the severity of the event. When a miner is injured from a roof fall, some medical attention is required. For example, of the 7,738 miners injured from roof falls between 1996 and 2005, 1.3 percent resulted in a fatality, the rest required medical attention (Table 2). For most of the nonfatal injuries, the rock that struck the miner was probably relatively small. Because it is beyond the author's abilities to forecast the size of a roof fall, it was assumed that any roof fall could seriously injure a miner. Therefore, the consequence should always be considered severe and assigned a unit value of 1. This effectively takes away the consequence term from this analysis. Therefore, a more appropriate definition for roof fall risk is

Roof fall risk = Roof fall probability x Miner exposure to roof falls (2)

Qualitative approach to measure roof fall risk

A qualitative approach allows for estimations of roof fall probability and miner exposure. Roof fall probabil-

Table 3

A generalized risk matrix used in many qualitative risk-analysis techniques.

	Probability of occurrence		
Consquences	High value	Medium value	Low value
High value	High risk		
Medium value		Moderate risk	
Low value			Low risk

Table 4

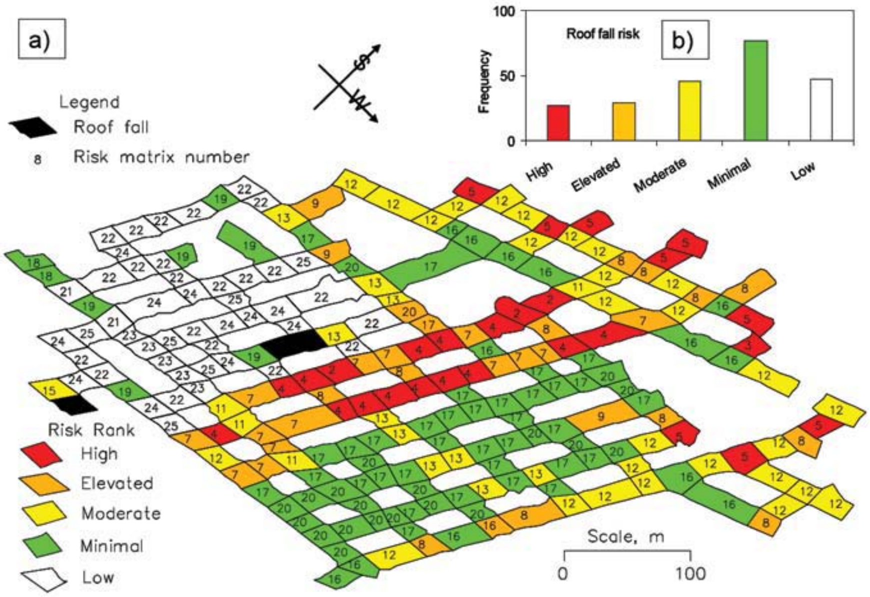
Exposure of miners within a particular work area.

	Frequency			
Percent of workforce	Many times/shift	1/day	1/week	1/month
Most >50%	A	A	B	C
Many – 30%	A	B	C	D
Several – 10%	B	C	D	E
Few <5%	C	D	E	E

ity can be qualified by calculating the RFRI over regions of an underground mine and by grouping RFRI values to appropriate roof fall probability categories that range from very unlikely to very likely. RFRI values approaching 0 represent low defect conditions typically associated with stable roof conditions and imply a very unlikely roof fall probability. Conversely, RFRI values approaching 100 represent excessive defect conditions typically associated with unstable roof conditions, implying a highly likely roof fall probability. Intermediate RFRI values fall into the unlikely, possible and likely roof fall probability category.

The other input for calculating roof fall risk, miner exposure, requires an estimation of miner activity through these same measured areas used in the RFRI analysis. These estimated parameters are used within a risk matrix (Table 5) to assign the relative roof fall risk for any accessible area within a mine. As roof conditions and patterns of miner activity change within a mine, roof fall risk changes accordingly. The ultimate utility of the risk rankings, shown in Table 5, lies in ones ability to identify areas with the highest risk and to design controls that mitigate risk in a logical and thoughtful fashion.

FIGURE 4



(a) Ranked risk for roof fall injuries over the 226 measurement areas comprising the study area and (b) histogram of roof fall risk categories. The study area is a fictional case presented here as an instructional example.

Characteristics of a roof fall risk-assessment method

The process to assess risk and implement controls to manage risks can be thought of as a series of steps (Fig. 1). The first step is to recognize and rank defective roof conditions within active portions of the mine. By doing this, hazards are identified and some attempt can be made to rank these hazards from low to high. The next step uses a wide variety of risk-analysis techniques to determine roof fall probability associated with specific conditions. Miner exposure, a key element in assessing risk, is next determined by estimating the amount of time miners are expected to occupy the different locations within the active underground workings. Combining the probability of roof falls with the estimations of miner exposure yields a series of roof fall risk levels tied to changing roof conditions. Because risk can be ranked throughout the mine, risk-management methods can be used to determine how to mitigate the risk.

Demonstration of a roof fall risk-assessment method

The intention of the following example is to detail a comprehensive risk-analysis method and to apply it to an experience at a mine setting. In a previous paper (Iannacchione et al., 2006), the RFRI values at an active underground stone mine were calculated and placed on a mine map (Fig. 2 (a)). The study area was divided into 226 measurement areas that ranged in size from that of a 15 x 15 m (50 x 50 ft) intersection to the 15- to 30-m- (50 to 100 ft-) long entries between intersections. The RFRI frequency distribution is shown in Fig. 2 (b). Roof fall probability is implied directly from the RFRI values and divided into five categories: very unlikely, unlikely, possible, likely and very likely.

This analysis uses logically assumed miner exposure data that replicated a main haulage route running north-south in the center of the section, a secondary haulage route running along the western portion of the section, active development faces along the southern perimeter of the sec-

Table 5

A risk matrix comparing roof fall probability with miner exposure. The exposure period used for this example could range from one to six months.

	Roof fall probability				
Risk exposure (From Table 5)	Highly likely (RFRI > 50)	Likely (RFRI 41 to 50)	Possible (RFRI 31 to 40)	Unlikely (RFRI 21 to 30)	Very unlikely (RFRI < 21)
A	1	2	4	7	11
B	3	5	8	12	16
C	6	9	13	17	20
D	10	14	18	21	23
E	15	19	22	24	25

tion, an idle section behind the faces and between the haulage routes, and restricted areas to the east (Fig. 3). The main haulage route in a stone mine is the area of highest miner activity, where most of the workforce is in that location many times per shift. Therefore, using Table 4, an exposure value of A is assigned. The secondary haulage route and the development faces are assigned an exposure value of B, because approximately 30 percent of the shift workforce is in these areas at least once per day. Idle sections away from the haulage routes and the development areas are assigned an exposure value of C where approximately 10 percent of the shift workforce is in these areas once per day. The restricted area, and the escapeway that services this section, is assigned the lowest exposure value of E.

Table 6

A potential correlation between a risk ranking and the levels of acceptability of existing and new control measures to mitigate roof fall injuries.

Risk ranking	Risk category	Percentage	Risk management response
1–5	High	12	Unacceptable, additional controls needed
6–10	Elevated	13	Undesirable, additional controls should be examined
11–15	Moderate	20	Acceptable with management review and approval
16–20	Minimal	34	Acceptable with monitoring and auditing
21–25	Low	21	Acceptable

It is now possible to use the 5 x 5 risk matrix shown in Table 5 to estimate the risk associated with each of the 226 measurement areas within the study area. Twenty-five risk rankings are identified ranging from 1, the highest, to 25, the lowest (Table 5). Within these rankings, five risk categories are subjectively assigned, ranging from high to low (Table 6). Seventy-five percent of the study area measurement areas are within the moderate-to-low risk categories. A potential correlation between the risk ranking and the action taken to manage risk are given in Table 6. Clearly, a risk ranking method such as this allows the mine operator to focus attention on high-risk areas in the main haulage and development entries where proactive tactical and strategic controls to mitigate these hazardous conditions can be applied. To ensure effective implementation of these controls, it is necessary that the mine operator strive to:

- understand how roof falls occur,
- decide how to deal with crucial roof fall warning signs,
- develop triggers to action,
- specify what kind of actions are mandatory and who is responsible for taking action and
- put decisions in writing along with reasons.

Summary and conclusions

In practice, unstable roof and the risks it presents within the underground workplace are often only partially known. Because risk-assessment and risk-management methods rely on hazard recognition practices and controls that either reduce the risk of the hazard or lower worker exposure, they have the potential to increase roof fall hazard recognition efforts and make it possible to address the highest risk roof fall hazard. When risks are ranked, mine operators have the opportunity to:

- investigate strategic or tactical controls;
- monitor the performance of the controls; and
- modify them as needed, in an iterative process, thus continually addressing the highest roof fall risk areas.

These methods help to rule out the option of doing nothing by introducing required actions in certain situations through structured decision-making.

There are four basic steps to the roof fall risk-assessment method used in this paper:

- Recognize and rate defective roof conditions that represent roof fall hazards: This is accomplished with the RFRI hazard assessment technique.
- Determine the roof fall probability for specific roof conditions: This is accomplished using qualitative analysis techniques where RFRI values were grouped into logical probability categories.
- Evaluate the exposure of miners to roof falls in the study area.
- Rank the roof fall risk for all active workplaces within the mine using a risk matrix: Rating or ranking roof fall risks helps to identify what areas should be monitored most closely by the mine operators and miners alike. It is also critical for prioritizing the areas where administrative and/or engineering controls are needed most to reduce these risks.

This paper demonstrates how roof fall risk can be assessed by appropriately designed hazard assessment and qualitative risk-analysis techniques. These techniques help to rate hazards, rank roof fall risk over a mine property, provide a means to communicate information with all levels of the mining operation, track changing conditions as the mine develops, train less-experienced miners to recognize hazardous conditions and develop controls/plans that are the hallmark of a proactive approach to mitigate risk to miners.

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