Stability Mapping to Examine Ground Failure Risk: A Field Study at a Limestone Mine

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ABSTRACT

As the surface reserves are being depleted, more and more stone operators are seeking underground mining options. Stability of underground openings is a major concern for the safety and productivity. This paper relates to a field study conducted at a large underground limestone mine in Central Pennsylvania. Identification of hazards leading to ground failures and assessment of roof fall risks are important in mitigating injuries. Field observations at this mine were integrated with Roof Fall Risk Index (RFRI) mapping software recently developed by West Virginia University. The system is designed to combine field study data related to geologic factors, mining-induced damages, roof profile, and ground water influx to generate RFRI maps. The mine has adopted a proactive ground control program consisting of comprehensive examination of drilling and bolting logs; precision surveying of roof and rib; accurate mapping of cutters, falls, and geologic structures; and installation of extensometers and microseismic monitoring systems. Investment of time and resources has eliminated fatalities and lost-time injuries due to ground fall. This paper presents the geologic settings, mining conditions, ground control issues along with risk management and control techniques adopted at the study mine.

INTRODUCTION

One of the major hazards of mining is premature ground failure resulting in injuries and fatalities. Falls of roof and rib accounted for over nine thousand injuries in the underground mining sector from 1996 to 2008. Figure 1 shows the incidence rate (number of injuries per 200,000 employee-hours) of roof fall injuries in stone mines during this period (MSHA, 2009). As the surface reserves are being depleted, more and more stone operators are seeking underground options. Entry stability is a major concern for the safety and productivity of underground operations. Entry heights in many stone mines range from 6.1 to 18.3 m (20 to 60 ft) and such entry heights make it difficult to quickly recognize unstable roof conditions. Identification of hazards leading to ground failures and assessment of roof fall risks are important in mitigating injuries and fatalities in the underground stone sector. Many of the roof instabilities are caused by sudden change in geologic structures, the presence of fault zones or major discontinuities, and mining induced damages. Other causative factors include high horizontal stress, influx of ground water, inadequate ground control, improper support design, and incorrect support installation. Failure to recognize geotechnical risks and implement remedial actions could expose miners to rockfall hazards. Reducing the number of ground failure injuries and fatalities is one of the goals of the National Institute for Occupational Safety and Health (NIOSH).

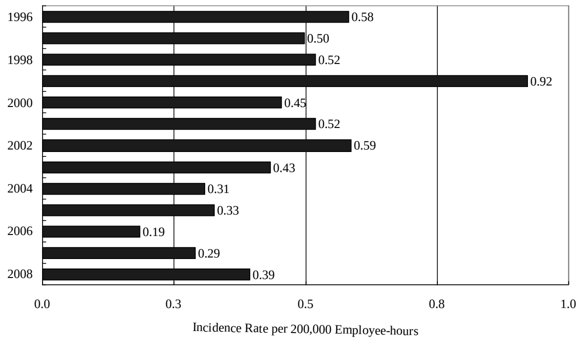

Figure 1. Incidence rate of roof fall injuries in stone mines, 1996 – 2008 (after Pappas, 2009).

The average incidence rate (figure 1) of roof fall injuries is 0.46 injuries per 200,000 work-hours with a standard deviation of 0.13. The incidence rate has shown an upward trend in 2007 and 2008 compared to that of 2006. There is a need for further improvement by using the techniques of risk management and control. The general downward trends in Australian underground mining fatality rates are, in part, attributed to the introduction and acceptance of risk-based management systems (Iannacchione et al., 2009). Major Hazard Risk Assessment (MHRA) in the geotechnical area has been used as a tool to improve miner safety (Potvin and Nedin, 2003). The Mine Safety Technology and Training Commission recommended application of risk-based systems and techniques to enhance worker safety and reduce injuries and fatalities (Grayson et al., 2006). This paper presents a description of geologic settings, mining conditions, rockmass characterization with geotechnical risk assessment, analysis, mapping, and control techniques used at an underground stone mine in Central Pennsylvania.

GEOLOGIC SETTING AND MINING CONDITIONS

The mine is extracting limestone using the room-and-pillar method from the Valentine member of the Linden Hall formation belonging to the Lower Middle Ordovician Limestones (Rones, 1969). The Valentine member is about 21.3 m (70 ft) thick in this area and comprises rocks of two closely related lithologic types. The upper 15.2 m (50 ft) comprises unlaminated, light-gray calcilutites ranging from 0.9 to 1.5 m (3 to 5 ft) in thickness (Rones, 1969). The lower 6.1 m (20 ft) is well laminated with thickness ranging from 0.3 to 0.9 m (1 to 3 ft) with thin clay or fine bentonite partings. The Valentine Limestone comprising light-gray, chemically pure limestone lies above the dark-gray 12.8-m (42-ft)-thick Valley View member of the Linden Hall formation. About 9.1 m (30 ft) of the dark-gray and thinly-bedded section of Centre Hall member of the Nealmont formation lies above the Valentine Limestone. The Valentine Limestone generally dips at 15 degrees and the strike direction runs approximately at N60°E (Rones, 1969).

The southward advance of mining is projected to extend to a depth of about 549 m (1,800 ft). The uniaxial compressive strength of Valentine Limestone ranges from 100 to 145 MPa (14,500 to 21,000 psi) and the maximum horizontal stress in the area ranges from 14.9 to 29.6 MPa (2,170 to 4,300 psi) in the N80°E direction (Esterhuizen and Iannacchione, 2004). A stress control mine design plan has been implemented to alleviate the effects of high horizontal stress and improve ground stability. Pillars are rectangular having their long axis oriented parallel to the maximum horizontal stress direction. Pillar size is approximately 46 x 20 m (150 x 65 ft). Crosscuts are staggered to develop three-way intersections. During development, rooms are driven to 15.2 m (50 ft) wide by 7 m (23 ft) high. Subsequently, an additional 11.3 m (37 ft) of rock is extracted by floor benching. Presently, the overburden thickness ranges from outcrop to approximately 304.8 m (1,000 ft). Roof sag monitors and multi-point extensometers are routinely used to monitor roof movement. Additionally, a surface-based microseismic system has been installed to monitor microseismic emissions associated with strata fracturing.

The dark-gray, thin-bedded Centre Hall Limestone immediately above the Valentine is often laminated, and considered undesirable to constitute the immediate roof beam. On the other hand, the top 1.8 m (6 ft) of Valentine Limestone is massive and competent to constitute a stable roof beam. In areas where the mining depth exceeds 274.3 m (900 ft), a layer of Valentine Limestone of thickness 1.8 m (6 ft) is left at the top of the entry to act as an immediate roof beam. In addition, a stable roof profile is maintained, where possible, by implementing precision blasting. A significant outcome is enhanced ground stability, reduction of guttering, and diminution of roof fractures and roof failures.

GEOTECHNICAL ISSUES

Geotechnical issues related to underground stone mines require careful consideration for ensuring safety of the workforce and stability of the openings. Roof falls ranging from minor local skin failures to entire pillar failures have been experienced by the underground stone mining community. A limited few of these ground failures resulted in injury. Ground control may be described as the ability to predict and influence the behavior of rock in a mining environment to ensure safety of the workforce and serviceability of the mine openings (MOSHAB, 1997). Ground control in limestone mines can be complex because the entries are fairly wide and have large heights. Rocks falling from a high roof have significant injury potential. During a survey of roof stability issues in underground stone mines in the Eastern and Midwestern U.S., Esterhuizen et al. (2007) observed that roof instabilities were primarily related to excessive horizontal stress or unfavorable geologic structures that caused block fallout or beam failure of the bedded roof rocks. Roof falls larger than 0.91 m (3 ft) in length, typically consisting of multiple fragments, were primarily associated with the followings:

- Block failure – large discontinuities and joints associated with fall,
- Beam failure – bedded layers in the roof failed under gravity loading,
- Stress related failure – shearing and buckling due to horizontal stress,
- Caving failure – progressive spalling of blocky roof or weak strata.

Esterhuizen et al. (2008) reported a pillar design methodology based on a study of pillar performance issues in stone mines. Three essential components of an effective ground control program are: (1) systematic coordination of geologic structures and stress parameters, (2) state-of-the-art entry and pillar design consideration, and (3) sound plan of ground support and reinforcement action (MOSHAB, 1997). Loading a pillar beyond its peak resistance often results in load shedding, yielding, shearing, or collapse.

Rockmass Characterization for Excavation Stability

Structural geology greatly influences entry stability in underground mines. Moebs (1977) and Hylbert (1978) investigated the role of structural features on the stability of coal mine roof rocks. Rockmass classification and support design progressed a long way from the traditional tunnel support design of Terzaghi (1946). The Rock Quality Designation (RQD) has been used to provide a quantitative assessment of rockmass quality (Deere and Deere, 1988). This was followed by Rock Structure Rating by Wickham et al. (1972). Bieniawski (1989) published a Geomechanics Classification system, also known as the Rock Mass Rating (RMR) system. Articles related to extensions of the Bieniawski classification system for new applications were published by Laubscher (1990) and Kendorski et al., (1983). The Coal Mine Roof Rating System (CMRR) by Molinda and Mark (1994) has been extensively used for roof rock characterization. The Norwegian Geotechnical Institute (Barton et al., 1974) proposed a Tunneling Quality Index (Q) based on a large number of field data. A significant rationale of rock characterization relates to examining stability and determining support requirements to increase the life and serviceability of underground openings. Many of the earlier attempts to characterize ground stability and prevent premature roof failures were based on rockmass characterization, entry size, support design, and ground water influx. In stone mines, the thickness of the immediate roof beam and the entry width greatly influence roof stability.

GEOTECHNICAL RISK MANAGEMENT

Risk management and control techniques have long been used in many industries including nuclear, petro-chemical, environmental, manufacturing, and aerospace. There is a rich collection of literature including national standards (MIL-STD-882D, 2000; CAN/CSA Q850-97, 1997: AS/NZS 4360, 2004) and industry publications (Potvin and Nedin, 2003; MOSHAB, 1997; MOSHAB, 1999; and DME, 2003). A structured risk management process typically accepts risk levels to as-low-as reasonably achievable (ALARA) or as-low-as reasonably practicable (ALARP) as an integral part of day-to-day operation. The concept of roof fall risk management is important for the underground mining sector. Iannacchione et al. (2009) examined risk management techniques to mitigate injuries and fatalities for mining applications. Several codes of practice to mitigate roof fall risk in the mining industry are available.

The Mine Safety Technology and Training Commission recommended application of risk-based systems and techniques to enhance safety and reduce injuries and fatalities (Grayson et al., 2006). Considerable national expertise is available for the application of risk management techniques in the mining sector (Iannacchione et al., 2009). The Mine safety and Health administration (MSHA) has articulated an informal risk analysis concept consisting of Stop, Look, Analyze, and Manage (SLAM). SLAM requires mine operators, supervisors, miners, and contractors to take proper precautions before performing any task. The goal is to prevent accidents by conducting an informal risk assessment before starting new tasks and by controlling the hazards related to each task. Hazard is defined as *a source of potential harm or a situation with a potential to cause loss*. Risk is defined as *the chance of something happening that will have an adverse impact upon objectives; it is measured in terms of consequences and likelihood* (Potvin and Nedin, 2003 and NSWDPI, 1997). Generally, risk is calculated by multiplying the *probability of occurrence* of an event likely to cause injury by its *consequences* (Iannacchione et al., 2009). Roof falls from a 7-m- (23-ft) high entry usually have serious consequences (Iannacchione et al., 2007b).

Evolution of Geotechnical Risk Management for Mining Applications

The Australian mining industry became interested in the application of structured risk-based management and control techniques to alleviate the risk of rockfall injury and progressed considerably in the transition from prescriptive health and safety standards to proactive, duty-of-care concept (DOCEP, 2006). The regulatory agencies provided guidelines and formulated procedures to help the industry (AS/NZS 4360, 2004; NSWDPI, 1997; QDME, 1999; and QMC, 1999). Australian regulations require mines to use risk management techniques on a regular basis to mitigate injuries and fatalities. The Mineral Industry Safety and Health Center (MISHC) at the University of Queensland (Joy, 1999 and 2006) developed a model and framework for Mineral Industry Risk Management (MIRM). The Mineral Industry Risk Management Gateway (MIRMGATE) at http://www.mirmgate.com/is maintained by MISHC. A host of tools were made available for assessment, analysis, control, and mitigation of risk (NSWDPI, 1997; Potvin and Nedin, 2003; and Joy, 2006).

The South African mining community also accepted risk-based procedures for mitigating rockfall injuries (Swart and Joughin, 1998; Van Wijk et al., 2002; and Lind, 2005). Mining sectors in Canada, United Kingdom, and USA became interested in using risk-based procedures in mitigating rockfall hazards and injuries. Figure 2 shows the basic structure of rockfall risk management process (MOSHAB, 1999). The process, listed below, begins with a sound planning followed by a detailed hazard identification, risk analysis and assessment, and finally risk management and control.

Figure 2. Risk management process to mitigate roof fall injury (after MOSHAB, 1999).

- Planning – identify team members, collect geotechnical information, and establish acceptable risk levels in consultation with subject matter experts, relevant employee groups, and management.
- Hazard Identification – classify geotechnical parameters and conditions that could cause or have a potential to cause roof fall injury. Potvin and Nedin, (2003) identified a host of parameters that could influence rockfall probability including rockmass quality, structural geology (joints, faults, angular discontinuities, etc.), mining-induced stress, blast damage, size and shape of excavation, and influx of ground water.
- Risk Analysis and Assessment – determine the likelihood of roof fall injury due to each defect condition, determine the degree or severity of injury, and rank all risks with appropriate weighting factors.
- Risk Management and Control – implement strategies to reduce risk to an acceptable level, eliminate exposure to high risk activities, install instrumentation for monitoring risk, and implement audit and review process.

Table 1 is a simplified version of generic risk matrix for geotechnical hazard analysis. The roof fall probabilities are low, medium, and high and the severity of consequences are also low, medium, and high. This is a 3 x 3 matrix resulting in nine possible risk rankings.

RISK ASSESSMENT, MANAGEMENT, AND CONTROL AT THE STUDY MINE

Hazards leading to potential roof failures and possible injuries were carefully examined during this field study. Accessible underground areas including production faces were visited during the data collection phase. Field measurements were limited to the areas where miners usually work or travel.

Table 1. Generic risk matrix for geotechnical hazard analysis.

Severity of Consequences	**Probability of occurrence of mishap (roof fall)**		
	Low (Possible)	**Medium (Likely)**	**High (Very likely)**
High (Critical)	M	S	H
Medium (Marginal)	L	M	S
Low (Negligible)	L	L	M
L: Low mishap category - operation with (SLAM). M: Medium mishap category - time limited operation with approval from safety director. S: Serious mishap category - essential to suppress risk to an acceptable lower level, use monitoring and control. H: High mishap category - must treat and mitigate risk to an acceptable lower level			

Roof Fall Risk Index (RFRI)

Iannacchione et al. (2007a) developed a procedure for determining RFRI based on the observed values of defect categories (figure 3) and their respective weights. The major groupings for computing RFRI were (a) geologic factors, (b) mining-induced failures, (c) roof profile, and (d) ground water influx. The geologic factors were (a) angular discontinuity, (b) joint frequency, and (c) strata strength. The mining-induced failure parameters were (a) shear rupture surface, (b) joint separation, (c) lateral strata shift, and (d) strata separation. The roof profile parameters were (a) rock debris on the floor and (b) roof shape. Parameters for water influx were damp roof, drippers, and steady flow. The study area was divided into small measurement areas where risk ranking parameters were considered uniform. The size of measurement areas ranged from 15.2 x 15.2 m (50 x 50 ft) at the intersections to 15.2 x 68.6 m (50 x 225 ft) in the entries.

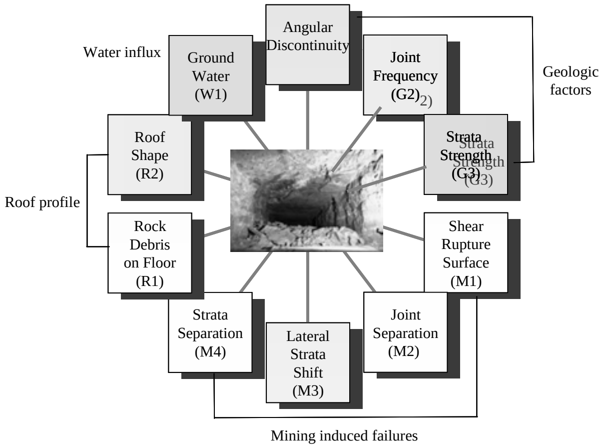

Figure 3. Parameters for evaluating roof fall risk at the study mine (after Iannacchione et al., 2007a).

The roof fall probability of a measurement area was assigned low (1), medium (2), or high (3) based on its RFRI value. RFRI values below 30 were assigned low (1) probability and higher than 40 were assigned high (3) probability. RFRI values ranging between ≥ 30 and ≤ 40 were assigned medium (2) probability (Iannacchione et al., 2007b). Areas representing medium (2), or high (3) probability were routinely bermed off to prevent unauthorized entry. Only roof remediation activity under the supervision and guidance of geotechnical experts were allowed in such areas.

Roof Fall Hazard Exposure

A qualitative risk rank of a measurement area could be estimated by combining its RFRI value with the miner exposure. Miner exposure may be represented by the duration of time miners are expected to occupy different work locations. Miner exposure could be grouped as Continuous, Intermittent, Rare, or Non-existent. A continuous exposure rating is appropriate for production face areas and main haulage routes where miners are present during most of their working shift. An intermittent exposure rating is appropriate for areas occasionally visited by miners during the work shift. The secondary haulage routes and non-production development faces could represent such areas. Parts of the mine rarely visited by miners could be assigned rare exposure rating. Bermed-off areas, considered off-limits to the miners, represent non-existent exposure rating.

RFRI Mapping Software

The RFRI mapping software developed by Prof. Heasley (Heasley and Wang, 2005), conveniently plots color-coded risk levels on a mine map. RFRI mapping, an application program, was created as a run time extension for the PC-based AutoCAD[1] drafting program. This application program has been integrated with the LaModel boundary element software package (Hardy and Heasley, 2006). The process of creating a RFRI map involves the following steps:

- Open the AutoCAD file containing the mine map and load the stability application program. Laptop computers may be conveniently used if analysis is desired while collecting data in underground locations.
- Create a new layer and draw the boundary of each measurement area. After several steps of running the program, a data entry screen similar to that shown in figure 4 will be available to help identifying parameters in each defect category.
- A drop down menu will appear for each defect category. Select the desired parameter in each defect category (figure 4). The system will assign the required category values to compute the RFRI. Table 2 is an example of defect categories and typical assessment values for few measurement areas.

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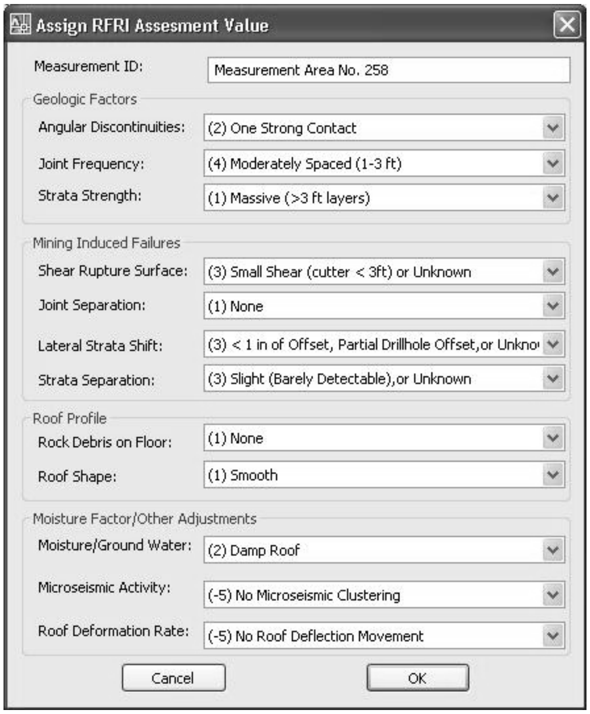
[1] Mention of any company or product does not constitute endorsement by the National Institute for Occupational Safety and Health.

Table 2. Typical assessment values used in figure 4 for computing RFRI.

CATEGORY	RFRI MEASUREMENT AREA NO.								
	A25	**A27**	**A29**	**A43**	**C19**	**C25**	**C29**	**C37**	**C42**
Angular discontinuity (G1)	1	1	1	1	1	1	1	1	1
Joint frequency (G2)	3	2	2	3	3	2	3	2	2
Strata strength (G3)	3	2	2	2	3	2	2	2	2
Shear rupture surface (M1)	1	1	2	1	4	3	1	2	1
Joint separation (M2)	1	4	5	4	4	1	1	1	1
Lateral strata shift (M3)	1	1	1	1	1	1	1	1	1
Strata separation (M4)	1	1	1	1	1	1	1	1	1
Rock debris on floor (R1)	4	2	2	2	6	4	2	4	4
Roof shape (R2)	3	1	2	2	3	2	1	2	2
Ground water	1	2	4	1	1	1	1	1	1
RFRI	26	27	34	28	41	27	20	24	22



Measurement ID: Measurement Area No. 258

Geologic Factors

Angular Discontinuities: (2) One Strong Contact

Joint Frequency: (4) Moderately Spaced (1-3 ft)

Strata Strength: (1) Massive (>3 ft layers)

Mining Induced Failures

Shear Rupture Surface: (3) Small Shear (cutter < 3ft) or Unknown

Joint Separation: (1) None

Lateral Strata Shift: (3) < 1 in of Offset, Partial Drillhole Offset,or Unkno

Strata Separation: (3) Slight (Barely Detectable),or Unknown

Roof Profile

Rock Debris on Floor: (1) None

Roof Shape: (1) Smooth

Moisture Factor/Other Adjustments

Moisture/Ground Water: (2) Damp Roof

Microseismic Activity: (-5) No Microseismic Clustering

Roof Deformation Rate: (-5) No Roof Deflection Movement

Figure 4. Data input format in AutoCAD.

- Based on the assessment values, the program computes the RFRI. It also assigns a color code for each measurement area in the AutoCAD map (figure 5).

Roof Fall Risk Management and Control

The mine has implemented a procedure for routinely inspecting underground work stations and berming off areas of potential roof fall risk. A RFRI rating of 30 or more signifies potential roof fall risk. The purpose of berming off is to prevent unauthorized entry during the roof remediation process. Roof remediation is carried out under the supervision of experienced personnel. Subsequently, such areas are inspected to ensure compliance with safety and legal requirements. Investment of time and resources to enhance safety had a positive impact and the mine has not experienced any lost-time injuries or fatalities due to ground failure since 2001.

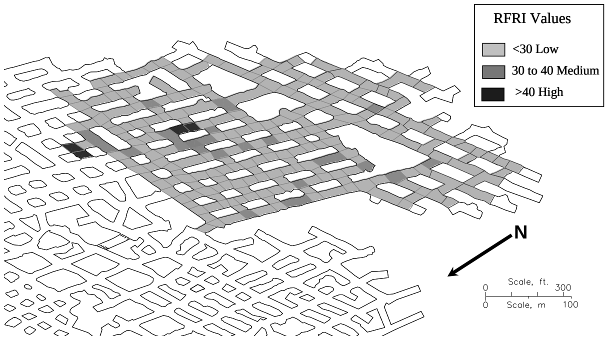


Figure 5. RFRI plot of a study area (after Iannacchione et al., 2007a).

Miners, contractors, and supervisors are allowed to work and travel in areas having low (<30) RFRI rating. However, all employees and contractors are required to observe MSHA's concept of Stop, Look, Analyze, and Manage (SLAM) (http://www.msha.gov). The goal is careful observation of work areas and implementation of safety measures before starting any new task.

Underground mining is associated with certain inherent geotechnical hazards that cannot be totally eliminated, and must be controlled and managed during the life of mining (Hebblewhite, 2003). Roof fall is considered an inherent geotechnical hazard (table 3). The study mine adopted a proactive approach to identify and mitigate roof fall risks. A microseismic monitoring system and a host of roof deformation sensors were installed for early detection of symptoms leading to roof failure. Also, potential unstable areas were bermed off to prevent entry and eliminate miner exposure. This practice proved helpful in mitigating rockfall injuries. Appendix A provides brief information about management, control, and audit of geotechnical risks at this mine.

Table 3. Inherent geotechnical hazards associated with room-and-pillar mining.

Hazard	Consequences
Room or intersection failure	Operator safety, equipment damage, loss of access, and production disruption.
Local pillar collapse	Production disruption, employee safety, loss of access.
Regional pillar failure (pillar run)	Loss of reserves, production disruption, potential worker safety issues, and possible subsidence consequences.
Regional closure (creep)	

SUMMARY AND CONCLUSIONS

Underground mining is associated with inherent roof fall hazards that cannot be totally eliminated and must be controlled and managed during the life of mining. This paper relates to application of an integrated RFRI mapping technique that provides a convenient way of plotting comprehensive color-coded RFRI maps. RFRI maps help to identify areas of potential roof instability. The major groupings for computing RFRI are geologic factors, mining induced failures, roof profile, and ground water influx. The geologic factors are angular discontinuity, joint frequency, and strata strength. The mining induced failure parameters are shear rupture surface, joint separation, lateral strata shift, and strata separation. The roof profile parameters are rock debris on the floor and roof shape. Parameters for ground water influx are damp roof, drippers, and steady flow.

Stability of underground openings is a major issue for the safety and productivity at the study mine. The mine had implemented a proactive roof fall risk management, control, and audit plan outlined in Appendix A. The plan proved helpful in eliminating lost-time injuries and fatalities related to ground failure. In summary, the results of this study are encouraging for further exploration toward implementing a comprehensive ground control plan in underground stone mining.

DISCLAIMER

The findings and conclusions in this report have not been formally disseminated by the National Institute for Occupational Safety and Health and should not be construed to represent agency determination or policy.

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APPENDIX A

Risk Management, Control, and Audit

Work areas: Inspect face, roof, and rib areas in each heading where miners are working or scheduled to work. Communicate observations to miners and foreman. Pay particular attention to any changes in lithology, bedding planes, joint systems, faults, and secondary minerals. Communicate all information to the next shift and engineering. Follow the written procedures for all roof inspection, monitoring, support, and repair works.

Drilling, blasting, and mechanical scaling: Record all observations in the drilling, blasting, and scaling logs. Pay particular attention to geology. Surface sounding and scaling report must be communicated to the next shift and engineering.

Haulage, escapeways, portals, and work stations: Inspect regularly haulage, escapeways, portals, and all underground work stations. Record observations and communicate information to the next shift and engineering.

Roof wedges, spalls, and dribbles: Paint roof wedges, spalls, and dribbles. Install additional lighting (stationary or portable) in the area. Communicate information to the next shift and engineering.

Roof bolting: Observe for drill speed, dust, and water consumption. Use scratch tool to detect fractures in roof holes, and record crack location (depth) and extent of strata separation. Communicate information to the next shift and engineering.

Extensometers: Install extensometers or roof sag monitors to measure roof deflection. Record observations related to roof deformations. Communicate information to the next shift and engineering.

Roof falls, gutters, and changes in strike or dip: Roof falls, roof gutters, and any changes in the strike or dip (direction or magnitude) must be located and shown on the mine map. Their effect on ground stability should be evaluated.

Microseismic monitoring: The mine has installed a monitoring system to detect microseismic emissions associated with rock fracturing. Unusually high level of microseismic activity is routinely investigated.

Mining plan modifications: The mine emphasizes the concept of mitigating roof fall risk by design changes and has modified mining plan to alleviate the effects of horizontal stress at a deeper section of the mine.