Roof Stability Issues in Underground Limestone Mines in the United States

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ABSTRACT

The room-and-pillar mining method is used extensively in underground limestone mines in the Eastern and Midwestern U.S. The rock mass is typically a near-horizontal, bedded deposit at relatively shallow depth. A survey of 34 mines was conducted in which data on roof spans, rock mass properties and support practices were collected as part of a National Institute for Occupational Safety and Health research project into ground control in limestone mines. The average room width is 13.5 m (44 ft), accommodating large mechanized equipment. The results show that the immediate roof beam can consist of many individual layers and can contain several near-vertical joints. In spite of the room widths, the roof is naturally stable in many mines. Observed roof instabilities can generally be related to excessive horizontal stresses or unfavorable geological structures that cause block fallout or beam failure of the bedded roof rocks. The survey showed that the rock mass quality of the limestone does not vary significantly throughout the Eastern and Midwestern U.S. Roof conditions and the need for support were found to be closely related to the thickness and competence of the first layer of limestone in the roof. The findings highlight the need to identify local geological structures and the roof beam characteristics so that support alternatives can be evaluated. Monitoring and observational technologies that are available for identifying potentially unstable roof are presented, which include: roof characterization using the Rock Fall Risk Index, automated logging of roofbolt hole drilling, microseismic monitoring and displacement monitoring.

INTRODUCTION

Underground extraction of the relatively flat-lying limestone deposits in the Eastern and Midwestern U.S. is carried out by the room-and-pillar method. High productivity and low mining costs are achieved by utilizing large mechanized equipment in rooms that have an average width of 13.5 m (44 ft). The immediate roof is typically a strong limestone bed that may be reinforced by rock bolts. In about one third of the mines, limestone in the floor is extracted by benching in-between the pillars, which requires the roof to remain stable during this secondary extraction phase. Falls of ground from the roof and pillar ribs can be a significant safety hazard, which is exacerbated by the height of the workings. The National Institute for Occupational Safety and Health (NIOSH) is investigating roof stability in limestone mines with the objective to develop guidelines for designing stable roof spans. This paper summarizes and evaluates the results of a survey of rock mass and roof conditions that were carried out in 34 underground limestone mining operations in the Eastern and Midwestern U.S. Methods of assessing potentially unstable roof conditions are discussed.

SURVEY OF GEOTECHNICAL PARAMETERS AND ROOF CONDITIONS

Data Collection

Data were collected on rock strength, jointing and other geological structures, room and pillar dimensions, roof stability and pillar performance. Categorizing roof stability is a challenge, because roof conditions can only be subjectively assessed. In bedded strata, it is relatively easy to identify small-scale instabilities if the roof horizon is formed by a smooth bedding plane, because the voids left by rock fragments that fell out will be readily visible. When the roof line is formed by blasting through intact rock or by a rough natural surface, it is not a simple matter to identify potential or past instabilities. In addition, evidence that a rock fragment dislodged from the roof does not necessarily imply that the fragment posed a safety hazard; it may have been removed during blasting or subsequent scaling operations. Between two and five data sets were collected at various locations at each mine site. A data set describes the stability of the roof and pillars in an area of approximately 100 by 100 m (300 x 300 ft). The following information was recorded:

1. Rock mass data was collected in accordance with the requirements of the Rock Mass Rating (RMR) system of rock mass classification (Bieniawski, 1989). This included rock strength, joint frequency, joint conditions and groundwater information. Since drill core was not available at any of the sites, the rock quality designation (RQD) could not be obtained. The joint frequency approach, proposed by Laubscher (1990), was used to obtain the combined joint spacing and RQD rating. The joint frequency was measured in two orthogonal windows, each 3 m (10 ft) wide by 1.8 m (6 ft) high. Rock strength was based on uniaxial

compressive strength (UCS) tests conducted in the laboratory on samples collected at the mine sites.

2. It was observed that large discontinuities that extend across a room can have a significant effect on roof stability. These discontinuities are often widely spaced and may not be well represented in the 3 m (10 ft) wide mapping windows used in this study. Large, widely spaced discontinuities were therefore identified and described separately.

3. Information on the roof composition was obtained from the mine personnel. These data included aspects such as the type and thickness of the roof beds, the location of prominent bedding planes and any other factors that impact roof stability under operational conditions.

4. The condition of the roof was visually assessed. Observed roof instabilities were categorized by their size and are called *rock falls* or *roof falls*. Rock falls are smaller than about 1 m (3 ft) in length and typically fall out of the roof as single fragments. Roof falls can extend across the full width of a room and usually consist of multiple rock fragments. Table 1 shows the sub-categories used to describe rock falls and roof falls. These sub-categories are related to the causes of the failures. It is recognized that a roof fall can be the culmination of several factors, however, in most cases it is possible to identify a dominant factor that contributed to the roof failure.

5. Pillar and room dimensions were measured and information on the depth of cover, blasting procedures, roof support type and spacing, and other mining parameters were collected.

Table 1. Types of roof instabilities.

Type	Description
Rock Falls	**Isolated rock fragments less than about 1 m (3 ft) in length.**
Slabs -	Thin slabs caused by weathering or stress spalling, less than about 30 cm (1 ft) in length and about 25 mm (1 inch) thick.
Blocks -	Blocky rock fragments caused by the intersection of joint planes, blasting factures, bedding or stress fractures.
Beams -	Stepped roof or brow formed by fall propagating to bedding plane.
Roof Falls	**Falls larger than about 1 m (3 ft) in length typically consisting of multiple rock fragments.**
Blocks -	Large discontinuities and joints associated with fall.
Beams -	Bedded layers in the roof fail under gravity loading.
Stress -	Horizontal stress-related shearing and buckling of roof beds.
Caving -	Fall caused by progressive spalling or blocky roof or weathering of weak strata.

Geological Setting

The limestone mines included in this study are concentrated in the Interior Plains and the Appalachian Highlands physiographic regions (U.S. Geological Survey, 2007). Twenty four of the mines fell within the Interior Plains region and are located in Illinois, Iowa, Kentucky, Missouri and Indiana. The Appalachian Highlands region includes the remaining ten mines in this study which are located in Pennsylvania, Maryland, West Virginia, Virginia and Tennessee.

Limestone deposits included in the study that are located in the Interior Plains region are generally flat-lying or only gently dipping and include rocks ranging across most of the Paleozoic Era Ordovician Age (5 x 10^8 years) to the Pennsylvanian Age (2.7 x 10^8 years). The Ordovician Age in this region includes the economic horizons of the Camp Nelson and the Tyrone limestones. The Mississippian Age includes the very silicieous and cross bedded Loyalhanna as well as the Greenbrier and the Monteagle. The Monteagle is a gently dipping Upper Mississippian limestone which is mined on more than one horizon (Brann and Freas, 2003). In the Pennsylvanian Age, the Vanport member of the Allegheny Group is mined (Iannacchione and Coyle, 2002).

Overall, the limestone rocks encountered in the Appalachian Highlands region are similar in age to those found in the Interior Plains region. They differ in that they have been transformed through mountain building processes to consist of elongated belts of folded and faulted sedimentary rocks. Mines that were visited operate in the Middle Ordovician Five Oaks formation, the Vanport and Loyalhanna mentioned earlier, and the steeper dipping Monteagle formation which is mined at dips of up to 35 degrees.

Horizontal Stress Field

Stress measurements and field observations have shown that the horizontal stresses in the Appalachian Highlands and Interior Plains regions can be much higher than the overburden stress. Horizontal stresses have been measured in limestone mines (Iannacchione et al., 2003) and in many of the area's coal mines (Mark and Mucho, 1994). Research has shown that the horizontal stress may be explained by the effect of plate tectonics (Dolinar, 2003; Iannacchione et al., 2002). Tectonic loading is related to the movement of the North American plate as it is pushed away from the Mid-Atlantic ridge. A constant strain field of between 0.45 and 0.90 millistrains is associated with the tectonic loading, which induces higher horizontal stresses in the stiff limestone strata. The induced stress magnitude is not necessarily related to the cover depth for depths encountered in limestone mining operations, but rather to the stiffness of the strata. Horizontal stresses are not necessarily present in all the limestone formations because local features such as outcropping and folding may have relieved the stresses over geological time (Iannacchione et al., 2003; Iannacchione and Coyle, 2002).

A review of horizontal stress measurements in limestone and dolomite formations in the Eastern and Midwestern U.S. and Eastern Canada has shown that the maximum horizontal stress can vary between 7.6 MPa (1,100 psi) and 26 MPa (3,800 psi) up to depths of 300 m (1,000 ft). Limited information is available at greater depths. The orientation of the maximum horizontal stress is between N60°E and N90°E in 80% of the sites. This agrees with the regional tectonic stress orientation as indicated by the World Stress Map Project (2007). The minimum horizontal stress is approximately equal to the vertical stress.

The horizontal stress can cause beams within the roof to buckle and fail in shear (Iannacchione et al., 2003). Failure can initiate as guttering in one corner of an excavation, called "cutter roof" in coal mines, and propagate to a large-scale roof fall (Esterhuizen and Iannacchione, 2004). Falls related to horizontal stress typically line up in the direction perpendicular to the regional maximum

Figure 1. Typical oval shaped roof fall associated with horizontal stress in the roof.

horizontal stress and are oval shaped when seen in plan view, see figure 1. Careful observation of the roof falls and other signs of excessive stress can assist in identifying the orientation of the maximum horizontal stress (Mark and Mucho, 1994).

ROCK MASS CHARACTERISTICS

Uniaxial Compressive Strength

Cores were drilled from rock samples collected at 20 of the mines visited and tested in the laboratory for uniaxial compressive strength and elastic properties. The average rock strength was computed for each mine site. The results show that 68% of the average rock strength values lie in the range of 120 to 180 MPa (17,400 to 26,100 psi), with minimum and maximum values of 70 and 302 MPa, respectively (10,100 and 43,800 psi). The highest strengths were found in the siliceous Loyalhanna and the Tyrone formations, while the lowest strength was found in the Monteagle formation in the Interior Plains region.

Jointing and Bedding

Discontinuities within the limestone formations were subdivided into bedding related discontinuities and joints. All the sites visited contained one or more sets of joints. The average joint spacing was 0.4 m (15 in) and the trace length typically in the range of 1 to 3 m (3.3 to 10.8 ft). Joints are typically rough with no infilling or weathering. Isolated cases containing soft calcitic or clayey infill were observed. Large joints that extend from roof to floor or across the width of an excavation were observed in about 40% of the locations visited. These are discussed in greater detail below.

Bedding layers do not always form a discontinuity in the limestone. It was found that the trace length of bedding discontinuities was greater than that of the joint sets. Bedding discontinuities typically had very rough surfaces. Isolated cases of bedding joints with calcite infill were observed. The average spacing of bedding discontinuities is 0.9 m (3 ft) with trace lengths typically in the 3 to 10 m (10 to 30 ft) range with about 30% of the cases extending greater than 30 m (100 ft). Bedding discontinuities are often used to establish a stable roof line. It was found that 36% of the underground locations visited made use of a local bedding plane as the roof line.

Occasionally, bedding discontinuities were observed within the pillar ribs that extend over several hundred meters with relatively thick weak clayey or calcite infill. Such bedding discontinuities are expected to have a significant effect on roof stability if they occur within the immediate roof of an excavation. Since such discontinuities are not visible when they are above the roof line, data on their presence is limited. Further investigation and analysis of the effect of such weak layers in the roof is underway.

Large Joints

It was found that large widely-spaced joints exist at about 43% of the underground sites visited. The average spacing of the large joints was 12 m (40 ft) with a minimum of 1 m (3 ft) and maximum of about 100 m (330 ft). The data collection approach used in this study did not identify spacings of larger than 100 m (330 ft). The dip of these discontinuities typically fell in the range of 70 – 90 degrees, with isolated cases in the range of 30 – 70 degrees. Large discontinuities dipping shallower than 30 degrees were categorized as bedding related features. The large discontinuities can contain soft infill materials but the fill material is seldom more than 5 mm (0.2 in) in thickness.

Rock Mass Rating

In all cases the data collection for rock mass rating was carried out approximately 2 m (6 ft) from the floor of the mining horizon. The rating results therefore do not describe the detail of the rock layer in the immediate roof, but rather represent the typical rock mass conditions at the site. The rock mass rating is presented in terms of the RMR, which classifies the rock mass on a scale of 0 to 100, with higher numbers indicating stronger rock masses. The RMR values were found to fall in a narrow range, and the ratings for the immediate roof are not expected to be significantly different from the remainder of the formation. Figure 2 shows the distribution of RMR values obtained. It can be seen that the values range between 60 and 90, which lays within the “Good” to “Very Good” quality categories.

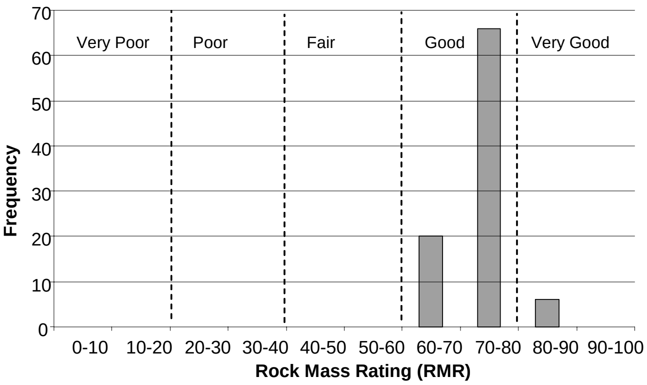

Figure 2. Distribution of Rock Mass Rating (RMR) values in underground limestone mines.

EXCAVATION STABILITY

Mining Dimensions and Roof Reinforcement

Measurements were made of the room width and the diagonal span across four-way intersections. In addition, other dimensions describing the room and pillar layout were taken. Table 2 provides a summary of the results. It can be seen that room widths vary between 9.1 m (30 ft) and 16.8 m (55 ft). Sixty eight percent of the room widths fall in the 12-15 m (40-50 ft) range. The diagonal span measured at four-way intersections averaged 21.7 m (70 ft).

Table 2. Summary of mining dimensions.

Dimension	Average, m (ft)	Minimum, m (ft)	Maximum, m (ft)
Mining height	11.6 (38.1)	4.8 (15.7)	38.0 (124.7)
Room width	13.5 (44.3)	9.1 (29.9)	16.8 (55.1)
Intersection diagonal	21.7 (71.2)	29.6 (97.1)	16.1 (52.8)
Pillar width	13.8 (45.3)	4.6 (15.1)	28.6 (93.8)

Roof reinforcement is carried out through the use of rock bolts of various types. Regular reinforcement by pattern bolting or irregularly spaced bolts was observed at 46% of the locations visited. The remaining 54% of sites were naturally stable or occasionally used roof bolts to support the roof in isolated areas. Fully-grouted bolts are most commonly used, with friction bolts and mechanical anchor bolts being less prevalent. Bolt lengths vary from 0.9 m (3 ft) to 2.4 m (8 ft) with 1.8 and 2.4 m (6 and 8 ft) long bolts making up 67% of the bolts in use. Bolt spacing of 1.5 m (5 ft) and 1.8 m (6 ft) are the two most commonly observed spacings, and the maximum bolt spacing was 2.4 m (8 ft). In extreme situations, cable bolts and sealant injection have been used to stabilize the roof. These are considered special applications and were not included in the study.

Roof Instabilities

All but four of the 34 mines visited had experienced some form of small-scale rock falls or larger roof falls. The results of the survey of roof conditions are presented below, in accordance with the categories shown in table 1. The frequency of smaller scale *rock falls* was as follows:

1. Slabs: 11% of the total roof area observed.
2. Blocks: 6% of the total roof area observed.
3. Beams: 11% of the total roof area observed.

In the remaining 72% of roof area observed, the roof was stable with no sign of current or past instability, which includes the roof at the four mines that did not show any signs of instability. Figure 3 shows an example of a 13-m-wide, naturally stable excavation with excellent roof conditions. Most of the above listed instabilities are addressed by scaling, rockbolting or screen installation as part of the normal support and rehabilitation activities.

In addition to small scale rock falls, large *roof falls* were observed at 19 of the 30 mines that experienced small scale roof instability. The large falls made up a very small percentage of the exposed roof in the mines; many of the mines only had a single instance of a large roof fall. Roof falls were categorized by identifying the most significant factor contributing to each fall, as shown in table 1. A summary of these factors and the relative frequency of occurrence of each are presented below:

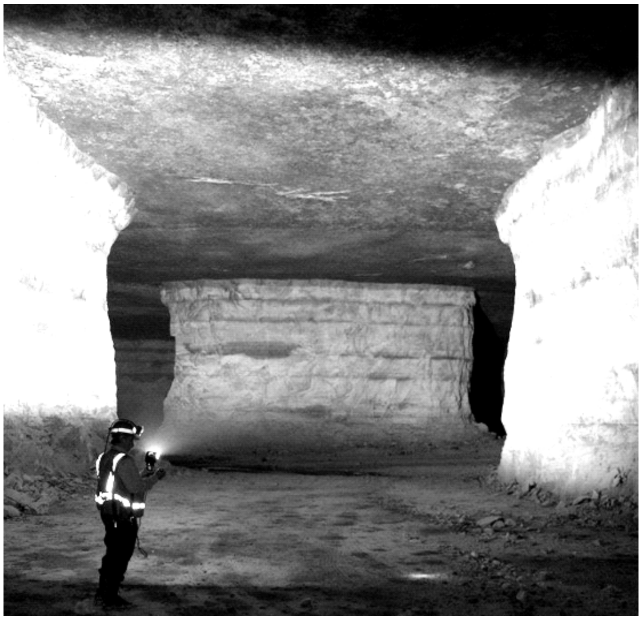

Figure 3. Naturally stable 13 m (44 ft) wide roof spans in a limestone mine in the Central Plains region.

1. Stress: Horizontal stress was assessed to be the main contributing factor in 36% of all roof falls observed. These falls are equally likely to occur in shallow or deep cover. A roof fall related to stress-induced damage was observed at a depth of as little as 50 m (150 ft) in one case.
2. Beams: The beam of limestone between the roof line and some overlying weak band or parting plane failed in 28% of all roof falls observed.
3. Blocks: Large discontinuities extending across the full width of a room contributed to 21% of the roof falls.
4. Caving: The remaining 15% of the roof falls was attributed to collapse of weak shale exposed in erosion channels or progressive failure of weak roof rocks.

Although the large roof falls only make up a small percentage of the total roof exposure, their potential impact on safety and mine operations can be very significant. Most cases of large roof falls required barricading-off or abandonment of the affected entry. When large roof falls occur in critical excavation areas, the repair can be very costly. Figure 4 shows a case where extensive support was required to rehabilitate a large roof fall.

Roof Beam Stability

The stability of excavations in bedded deposits is closely tied to the composition of the first beam of rock in the roof. An assessment of the data collected showed that 25 of 34 mines were attempting to maintain a specific thickness of limestone beam in the immediate roof. A constant thickness of roof beam is achieved either by probe drilling to determine the thickness of the roof beam or by following a known parting plane or marker horizon.

Figure 4. Repair of a large roof fall in which horizontal stress is thought to have contributed to the failure.

The average roof beam thickness in mines that were able to mine without regular support was 2.25 m (7.4 ft), while the average beam thickness in the mines that were using regular roof support was 1.3 m (4.3 ft). Several of the mines that used regular support do so to alleviate the effects of horizontal stress, which is not related to beam thickness. If these mines are removed from the data, the average beam thickness in mines that use regular support drops to 0.8 m (2.6 ft). These results seem to indicate that mines with a relatively thin beam of limestone in the immediate roof are more likely to encounter unstable roof and regular roof bolting becomes necessary.

The beam thickness is obviously not the only factor to consider when deciding on roof reinforcement. Other aspects such as roof jointing, bedding breaks, blast damage, groundwater and horizontal stress can contribute to roof instability resulting in the need for rock bolt support.

Horizontal Stress Issues

This study showed that horizontal-stress-related roof instability can occur at any depth of cover. This is not unexpected, given that the horizontal stresses are caused by tectonic compression of the limestone layers, which is not related to the depth of typical limestone mines. Observations show that the tectonic stresses in limestone formations that outcrop may have been released over geologic time by relaxation towards the outcrop (Iannacchione et al., 2002). Consequently, outcropping mines can have highly variable horizontal stress magnitudes which depends on the amount of relaxation that occurred and the distance from the outcrop.

Operations that experience horizontal-stress-related roof instability can consider changing their layouts so that they are favorably oriented relative to the maximum horizontal stress. This can be achieved by laying out the main development direction parallel to the maximum horizontal stress and minimizing the amount of cross-cut development (Parker, 1973). The direction of the maximum horizontal stress can be determined by various stress measurement techniques or can be inferred from stress-related roof failures (Mark and Mucho, 1994). Modifying a layout in this manner will not necessarily eradicate all stress-related problems, but has been shown to considerably reduce these problems (Kuhnhein and Ramer, 2004).

Rock Mass Classification and Roof Stability

The RMR rock mass classification carried out as part of this study showed poor correlation to the roof spans used in the various mining operations. In addition, the rock classification could not discriminate between cases of stable and unstable roof spans. Application of other classification methods such as Barton's Q-system (Barton et al.,1976) and the Modified Matthews Stability Graph method (Potvin, 1988 and Nickson, 1992) also showed poor correlation. This can be explained as follows:

1. The limestone rock mass is relatively strong and the rock mass strength does not dictate excavation spans. In addition, the rock mass classification values and excavation spans both fall in a narrow range, which precludes the identification of a trend.
2. The stability of the roof in bedded limestone rocks is closely tied to the characteristics of the immediate roof beam. Beam stability considerations are not well represented in the rock mass classification methods assessed.

It is evident that an alternative roof classification method is required for limestone mines. The method should clearly differentiate between potentially stable and unstable roof conditions. The results of the survey indicate that such a method should be focused on the immediate roof beam and consider its thickness and composition, horizontal stress and the presence of large joints.

Comparison of the Physiographic Regions

An evaluation was made of the collected data to determine whether differences exist in rock conditions and roof stability between the Appalachian Highlands and Interior Plains physiographic regions. The evaluation showed that the regions are very similar in terms of rock mass strength as expressed by the RMR values. The average uniaxial compressive strength of the rocks in the Appalachian Highlands region appears to be slightly higher, but insufficient data is available to determine the level of statistical significance. The average room width in the Appalachian Highlands is 13.7 m (45.0 ft) and in the Interior Plains it is 13.5 m (44.2 ft), which indicates that the rock conditions must be similar, allowing similar excavation dimensions to be developed. Roof bolting is used in about 50% of the mines in both regions, again confirming that rock conditions are similar. Roof bolt spacing and lengths were not significantly different in the two regions. Horizontal-stress-related roof stability issues were also equally prevalent in the two regions.

ROOF ASSESSMENT AND MONITORING ALTERNATIVES

Ground control in limestone mines is complicated by the fact that excavations are large and small rock falls can have significant consequences. Changes in the rock mass, such as the thickness and competence of the immediate roof beam, the presence of large discontinuities and horizontal stress can all contribute to instability. Many of these important factors are not readily observable during routine examinations. NIOSH therefore advocates a systematic approach to identifying and mitigating potential roof instability through a program of assessment and monitoring.

Roof assessment techniques that are well established include roof sounding during scaling operations, borescope inspection of holes drilled into the roof, using a scratch tool for locating voids in the roof and observation of geological anomalies. Three technologies that can supplement these techniques are: a) roof fall hazard assessment through the Roof Fall Risk Index (RFRI), b) automated drill recording, and c) roof displacement monitoring. These technologies can provide the information necessary to develop a significant component of a comprehensive ground control plan.

Roof Fall Hazard Assessment

NIOSH developed the Roof Fall Risk Index (RFRI) as a tool for systematically identifying roof fall hazards in operating mines (Iannacchione et al., 2007). The RFRI focuses on the character and intensity of defects caused by a wide range of local geologic, mining and stress factors and is 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. The total rating varies from 0 to 100, with values approaching 0 representing 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 and communication tool. This technique requires that roof fall hazards be mapped and the spatial distribution within the underground workplace determined. The RFRI strives to assess roof conditions over large, continuous areas, with fewer time-consuming measurements than are used in many existing rock mass classification systems. This produces a more comprehensive assessment of changing roof conditions than was previously possible. Examples of the application of this technique are available in Iannacchione et al. (2006).

Automated Drill Recording

Characterization of the immediate roof through automated drill recording is a recent development introduced by J.H. Fletcher and Co.[1] located in Huntington, WV. Measurements of force, velocity and operational characteristics during roof or face drilling are used to determine geotechnical properties of the rock mass. Of particular interest to underground stone mines is the presence and location within the roof rock of bedding separations, weak beds, or fracture systems. Knowing the presence and location of these discontinuities allows for the development of a roof support strategy that considers a proper bolting system such as bolt length and bolting horizon.

Collins et al. (2004) reported on a field test of the automated drill recording system in an underground limestone mine. For this test, five holes were drilled at various locations in the mine. The holes were subsequently bore-scoped with a video camera for comparison purposes. In each test hole, the voids identified by the roof mapping system closely resembled the information obtained from the bore-scoped data.

During the past few years, the system has been improved and upgraded. The accuracy of this roof characterization technology was assessed at 3 underground limestone mines in 2007 with J. H. Fletcher and Co. providing the roof mapping data and NIOSH conducting the bore-scoping of the same holes. At each mine, 5 to 8 holes were used in the comparisons. In all cases, large strata separations or weak beds were readily shown with the mapping system and were clearly visible on the bore-scoped video.

Roof Displacement Monitoring

Roof displacement monitors used in conjunction with a comprehensive ground control plan can be an effective tool in providing essential information on a mine's roof stability. Monitoring in most cases should be considered a long-term activity to be most productive and effective. Prior to monitoring, locations of highest concern should be identified based on observation regarding geologic conditions using a system such as the above mentioned RFRI. In addition, mine areas of constant exposure to the mine worker, such as main travel ways, maintenance and repair areas and underground crusher stations are locations suited for proactive monitoring (Prosser et al., 2003).

The NIOSH experience with roof monitors encompassed the installation of more than 100 Roof Safety Monitoring System (RMSS) units at 21 underground limestone mines (Marshall et al., 2000). At 85% of the monitor sites no roof movement was reported or recorded. In four of the mines, roof movement or instability was recorded that resulted in timely responses to potentially unstable roof. At one mine with excessive horizontal stress, approximately 33% of the monitoring sites, showed roof movement, with some cases showing more than 10 cm (4 in) of roof deflection, which aided in decisions concerning ground control and worker safety.

One U.S. company, that appears to have monitors suited for underground limestone applications is Simplified Mine Instruments, located in Iron River, MI. Four different types of instruments are available which provide increasing capability to measure roof movement depending on conditions and circumstances: a) the basic or "watchdog" model drops a reflective rod into view when a pre-set amount of movement has occurred; b) the "Miner's Helper" can be used to measure the roof movement directly; c) the "Remote Miner's Helper" adds the ability to measure at a distance from the monitoring station if the location is difficult to access and allows for readings to be taken electronically; and d) a three-point extensometer is available to measure movement at 3 locations within a single borehole.

Microseismic Monitoring

Rock under stress emits audible microseismic emissions at a rate which increases with increasing stress level. The rate of emission generally increases prior to and during major fracturing of the rock. If sufficient fracturing occurs in the rocks in the roof of an excavation, the rock begins to deflect into the opening. Microseismic monitoring system can detect the microseismic events and calculate the source of the event. Early research by the U.S. Bureau of Mines (Obert, 1945) identified the potential for using microseismicity as an indicator of mine stability. NIOSH research (Iannacchione et al., 2004a) examined the relationship between microseismic activity and the corresponding roof deflection associated with two large roof falls in a limestone mine. The results showed a connection between roof rock instabilities and trends in microseismic activity. In addition, microseismic activity was sometimes shown to occur prior to roof deflection, demonstrating that rock fracturing precedes roof deflection. The results suggest that microseismic monitoring combined with roof

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[1] Reference to a specific product does not imply endorsement by NIOSH.

deflection monitoring could be used to better determine the relative stability of local roof rock conditions. Application of this technology can form the basis for assessing roof stability and planning appropriate ground control strategies (Iannacchione et al., 2004b).

SUMMARY AND CONCLUSIONS

The study of roof conditions in limestone mines in the Eastern and Midwestern U.S. has shown that:

- Rock mass conditions in the limestone formations are relatively uniform throughout the Appalachian and Interior Plains regions. Mining dimensions, roof support practices and roof instabilities do not vary significantly between the regions.
- Roof stability is closely related to the thickness and composition of the layer of rock in the immediate roof of the workings. Mines that did not use roof reinforcement generally had thicker limestone beds in the immediate roof.
- Large roof falls were observed at 19 of 34 mines visited, in many cases at just a single location.
- The main factors contributing to large roof falls are: horizontal stress, large joints and insufficient thickness of the immediate roof beam.
- Horizontal-stress-related roof instability can occur at any depth of cover.
- The reviewed rock mass classification schemes do not sufficiently characterize the immediate roof beam to be useful for roof span or support design in limestone mines.
- Technologies such as the RFRI method of roof hazard assessment, automated drill recording, displacement monitoring and microseismic monitoring can assist mine personnel in identifying and monitoring roof conditions as part of a comprehensive ground control management plan.

The results presented in this paper forms part of a NIOSH research project aimed at providing roof span and pillar design guidelines for limestone mines. The authors wish to thank the staff of the various mining operations visited for their willingness to share their experiences and their time to accompany us during the underground examinations.

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