Roof monitoring helps prevent injuries in stone mines

From 1990 to 1996, 16 states reported 92 injuries from falls of roof, rib or face in the more than 90 underground stone mines in the United States (Fig. 1). Missouri, Pennsylvania and Kentucky accounted for 48% of the total number of injuries (Fig. 2). Of this total, 11 miners were killed. Of the 11 fatalities, 10, or 91%, were associated with unrecognized loose or failed rock within the roof beam. Additionally, unrecognized roof beam failures resulted in a majority of the falls of ground injuries occurring in underground US stone mines from 1990 to 1996.

This number is not large in magnitude. But a work force of fewer than 2,000 miners makes for a high fatal-accident rate. The severity of the typical fall-of-ground injury is, in general, very high. About three-fifths of all roof, face and rib fall injuries were designated by the US Mine Safety and Health Administration (MSHA) as some kind of lost time accident. MSHA assigns each accident a severity value from one to six. A one represents a fatality, a two, a permanent disability and three, a lost time accident (Fig. 3).

FIG. 1

Roof, face and rib-fall injuries in the underground stone industry.

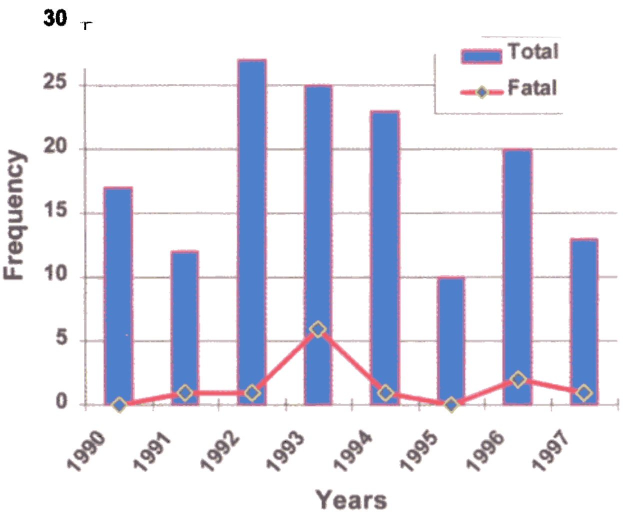
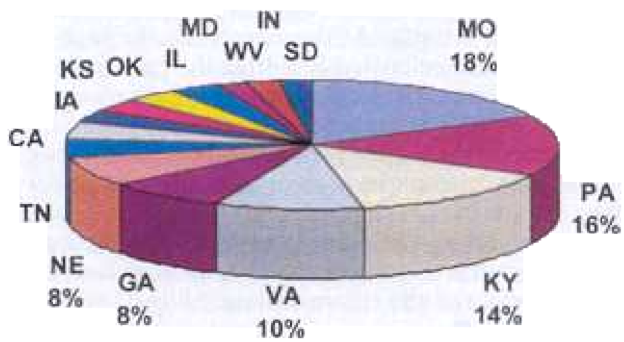


FIG. 2

Underground stone roof, face and rib-fall injuries by state from 1990 to 1996.



Most underground stone mines operate in thick limestone formations. Intact (solid) pieces of limestone are generally strong. They often have compressive strengths of 207 MPa (30,000 psi) and tensile strengths of 14 MPa (2,000 psi). Persistent horizontal bedding planes typically cause limestone roof rock members to separate into beams ranging from 0.15 to 1 m (0.5 to 3 ft) thick that span large rooms, ranging from 6.1 to 18.3 m (20 to 60 ft) and averaging 13.1 m (43 ft) wide (Fig. 4).

The deformation characteristic that affects roof beam stability is excessive deflection (Fig. 5). If deflection, or bending, of the roof beams becomes excessive, roof failure can occur, leading to injuries to miners. However, these beams can contain vertical and subvertical discontinuities (vertical joints or fractures and subvertical cross-bed planes) that sometimes affect local roof-beam strength, producing wedge or prism shaped failures (Fig. 5).

If dangerous roof beam deflection values are known, they can be used as a clear indicator of roof instability (Parker, 1973). There is a potential for roof monitoring to assist mining operations in gathering quantitative and qualitative information. But, for this technology to be implemented, several technical problems must be overcome:

The factors that influence the variability in roof beam deflection and failure must be identified.
A simple, inexpensive method to monitor dangerous levels of roof beam deflection must be produced.
Guidelines for evaluating the output of these monitoring devices must be established.

Current roof-monitoring technology

Observing and monitoring rock deformations provide information for making critical mining decisions. Traditionally, miners have sounded the rock, listening for the drummy sounds that signal loose rock. The act of

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Table 1

Number of mines using observational and monitoring techniques.

Observation or monitor type	Sounding	Observation hole	Wedge	Borescope	Scratch tool	Extensometer	Miners Helper	Guardian Angel	Telltale
Number of mines	9	11	5	6	4	2	7	4	1

drilling exploration, roof bolts or blastholes can provide much information about the rock. If separations are present, the drill will often accelerate through these zones. Dust and water from adjacent fractures or drill holes indicate the occurrence of hidden rock fractures. Borescopes and borehole cameras have been used to observe fracture characteristics and roof lithology. Wedges inserted into angular fractures or horizontal bedding planes along the roof and ribs of the mine have been used to observe the movement of rock masses — if the wedge falls out, the rock mass is moving.

Observational techniques can be extended by regularly monitoring the movement of the mine roof. Monitors can be divided into two basic types: roof-to-floor convergence monitors, and roof and rib extensometer monitors. Most stone mine development rooms average 7.1 m (23 ft) and bench rooms average 16.4 m (54 ft) in height, roof-to-floor. So convergence monitors are difficult to install, maintain and analyze. Roof and rib extcnsometers are more widely used than convergence monitors. However, they are difficult to read because of their location on the roof line or back.

In its simplest form, roof and rib extensometer monitoring can be accomplished with a scratch tool (Fig. 6). This device can detect separations and provide an indication of loose rock layers or roof beam deflection. Information on the location and size of the separation can be marked on the roof and used to assess potential, future roof degradation.

For many years, extensometers permanently installed in drill holes have been used in underground mines to detect ground fall hazards. Sonic probe extensometers have been widely used in the United States, the United Kingdom and Australia. This commercial system allows for 20 permanent anchors up to a 6-m (20-ft) height. The probe is temporarily inserted when measurements are made.

Homemade mechanical extensometers have consisted of a top and bottom anchor, steel wire or rigid tubing, and some kind of micrometer or dial gauge. These devices have been used for decades in metal mines in Michigan, Missouri and Idaho. For example, in the Missouri lead belt district, a deflection rate of 0.17 mm/month (0.007 in./month) is considered a good warning of strata failure. Extensometers have been used as real-time hazard warning devices. Parker (1973) discussed an ingenious method to alert miners of strata movement by adding a warning light to an extensometer.

Some common commercially available mechanical extensometer monitoring devices are the Miners Helper, the Guardian Angel and the Dual Height telltale (reference to a specific product does not imply endorsement by National Institute for Occupational Safety and Health (NIOSH) (Fig. 7). These monitors have one or two anchor points that measure the overall separation of rock layers in the immediate roof. If roof deflection is detected by the Miners Helper and the Guardian Angel, a reflecting flag drops from the roof line, signaling the potential for imminent roof failure. In some cases, this information has been used to indicate a need to add roof support, remove roof rock or danger off affected areas.

Coal mines have used telltales for decades to warn miners of strata movement. The telltale is a rigid bar — possibly a roof bolt — anchored into the roof. A small section of rod protruding from the borehole is covered with three bands of reflective tape. The portion of the bar closest to the roof is generally green, followed downward by yellow and then red. The idea is that, as the roof deflects downward, the roof line can easily be seen to move through the green, yellow and red tape zones.

Recently, Bay Tech has produced an electronic telltale. In the United Kingdom, coal mines use telltales every 20 m (65 ft) with action bands from 0.4 to 2 cm (0.2 to 1 in). Between 1990 and 1995, falls of ground were reduced from 267 to six, partially due to the use of telltales (Altounyan et. al, 1997).

FIG. 3

Severity of roof, face and rib-fall accidents from 1990 to 1996.

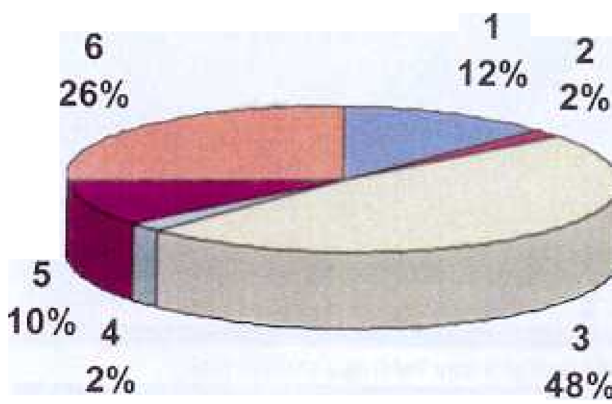


FIG. 4

Histogram of room widths for 65 underground stone mines.

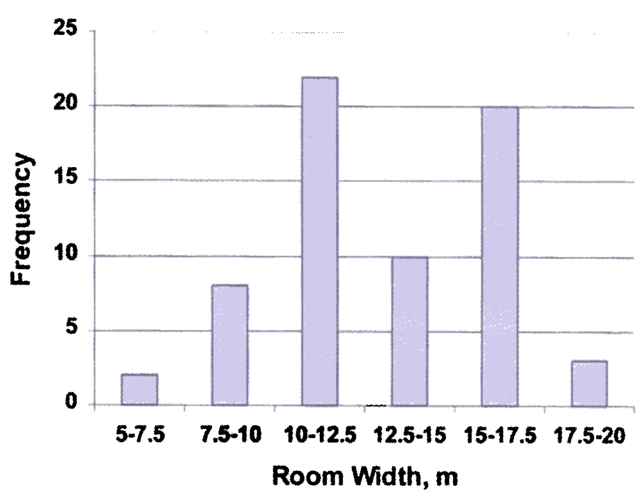


FIG. 5

Two different modes of roof-rock failure that are common in underground stone mines.

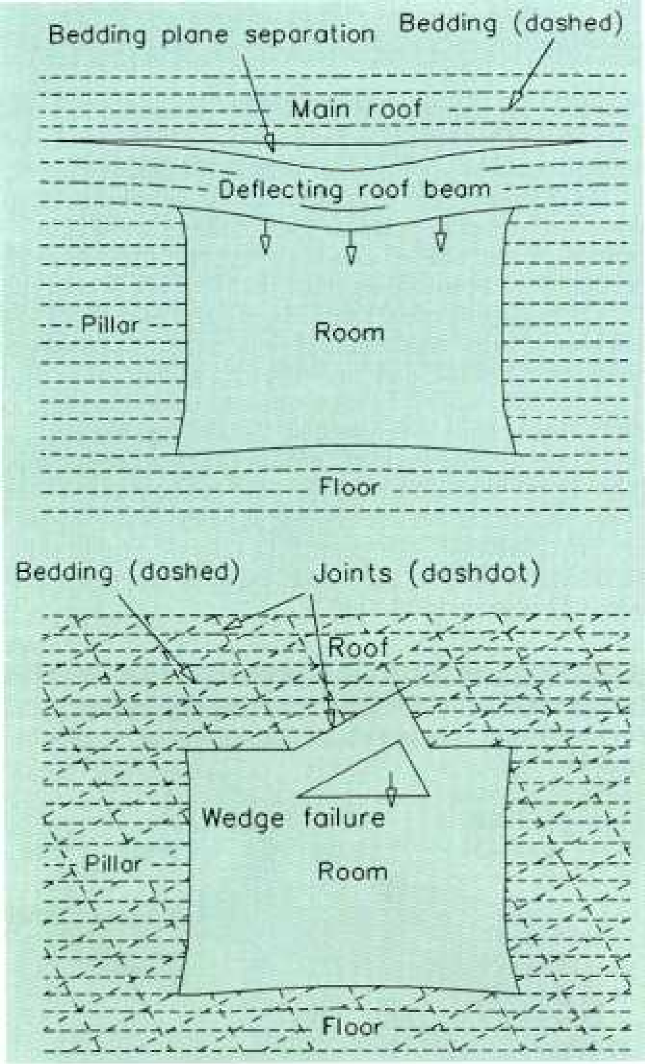


FIG. 6

Photograph of a man holding a scratch tool.

Overview of ground-control planning methods

Generally, underground mines use observational techniques, primarily visual inspection, to determine roof stability. Additional knowledge related to roof stabiliby is gained through blasting, drilling and scaling. For example, a driller preparing to bolt notices a sudden increase in the penetration rate. He realizes that possibly a gap or clay seam was encountered.

Much of this hands-on information provides an overview of the general conditions related to roof stability. However, this base of knowledge can quickly deteriorate if that hands-on experience is lost through changes in employment or other circumstances.

Many mines supplement visual inspections and knowledge gained through hands-on experience with various types of observational and monitoring techniques. Based on observations and discussions with personnel at 48 mines, 49 observational and monitoring techniques beyond basic visual inspections were used at 26 mines (Table 1). This suggests that additional information is beneficial or needed to solve some classes of ground control problems.

To date, observational techniques are used more than monitoring techniques. Observational techniques accounted for 31 of the 48 mines, or 65% of the total. Drilling observational holes to detect conditions in the roof was the most used technique with 11, or 23%, of the 48 mines. The data also show that 11 of the 48 mines used or have available commercial mechanical monitors (Miners Helper or Guardian Angel). This relatively low number of overall usage and the fact that 46% of the mines use no additional monitoring methods suggest apparent limitations to using these methods.

A comprehensive ground-control plan includes the basic visual and hands-on components. But it also uses supplemental observational and monitoring techniques. And it regularly reads, analyzes and displays information gained from these efforts. When this type of information is logged or mapped, it provides a documented history of ground conditions. This information can be analyzed and prepared by consulting firms or with in-house expertise. The availability of this information at the time of a major ground fall or when unstable geologic conditions are encountered is useful in deciding a course of action or alteration of the mining plan. Mines that follow these practices and that promote open communication and participation from everyone at the site are the mines with the most proactive approaches towards ground control safety.

NIOSH's roof-monitoring safety system

There have been considerable advancements in roof monitoring. But existing instruments have several limitations that minimize the impact of this technology on underground stone mining. These limitations include:

Difficulty in taking readings in high roof or back areas.

Exposure to dangerous ground while reading the monitors.

Complexity in making repetitive readings.

Problems with making measurements within multiple roof horizons.

Difficulty in seeing warning devices in the dusty and foggy production face areas.

FIG. 7

Photograph of a commercially available Miners Helper, the Guardian Angel and the RMT's Dual Height Telltale roof mechanical extensometer monitoring devices.

Expense of some commercial monitors.

NIOSH developed a new generation Roof-Monitoring Safety System (RMSS). It improves the existing methods for determining roof stability. This electromechanical roof monitor includes several features.

- It can be fabricated in most standard mine shops.
- It is relatively inexpensive (single-point RMSS costs less than $40/unit to fabricate in-house).
- It reduces potential damage from face blast because of the in-hole positioning (this is true only of the single point RMSS, Fig. 8a).
  It has the capability for monitor reading at ground level (allows the miner to take readings away from potentially unstable roof conditions).
  It can be remotely read with a multimeter or commercial data-logging devices.
  It can accommodate as many as six anchor points (this is true only of the multipoint RMSS, Fig. 8b).

Perhaps the greatest benefit of this new monitor is that the miner does not have to make readings in areas of questionable roof stability. After all, these instruments are most often deployed in areas where roof rock instabilities are suspected. Figure 9 illustrates the advantage of the electromechanical RMSS over other existing techniques.

How do roof monitors assess strata stability?

Every opening made in rock causes a redistribution of stresses in the adjacent strata. In bedded or layered sedimentary rock, the roof beams deflect into the opening immediately after excavation (Fig. 10). A decay in the rate of deflection occurs as the stresses redistribute in response to the opening.

Eventually, the beam deflection stabilizes (Fig. 10). In most strata, this initial deflection takes place quickly. For example, NIOSH researchers have installed monitors in the face area a few days after a production blast and have not been able to detect this period of decelerating deflection.

As time passes, these roof beams are subjected to natural, geologic and mining processes. These include dramatic humidity variations from changing environmental conditions, chemical alterations from strata water, tectonic stresses, additional mining adjacent to the opening and heat from machinery. These processes initiate a period of instability that sometimes continues until failure occurs.

In some mining conditions, the immediate roof beam may fail sometime between the blast and the time when miners first re-enter the face. These beams are found draped over the rubble stonepile produced from the production blast. In other mines, roof beam failure will periodically occur days, months or even years after the excavation has been formed. The time between the decelerating and the accelerating beam-deflection generally represents a period of stable roof conditions.

Roof beam deflection due to gravity loading can be estimated using standard formulas for deflection of

FIGS. 8A AND B

Single-point RMSS with multimeter and multipoint RMSS with data acquisition.

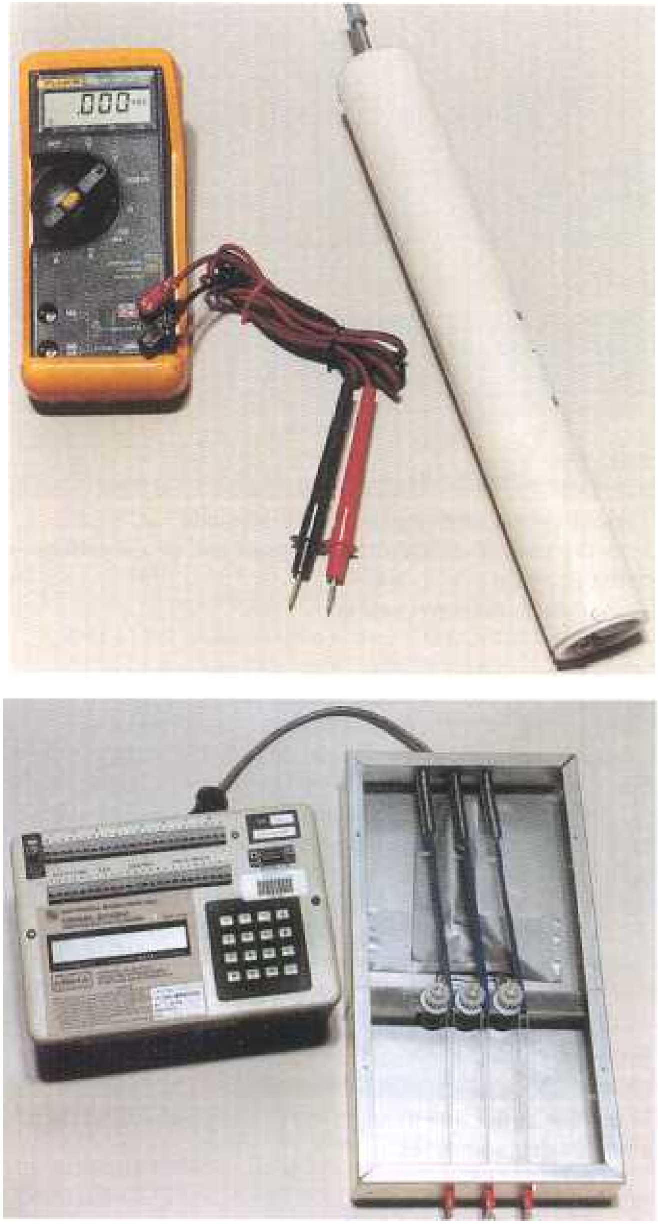


FIG. 9

Comparison of three roof-monitoring techniques.

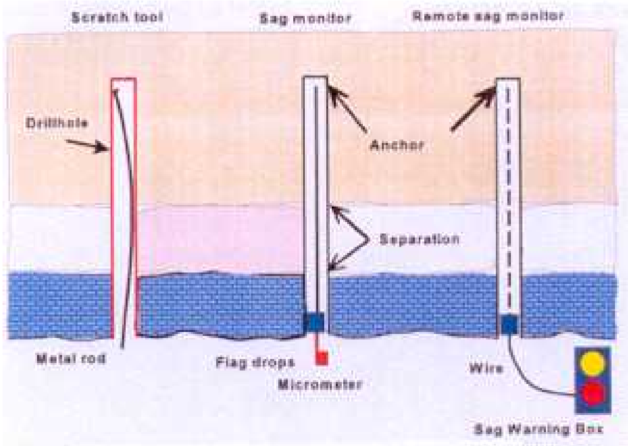


FIG. 10

Typical cycles experienced by failing stone roof beams. Note the periods of decelerating, quiet and accelerating deflection rate.

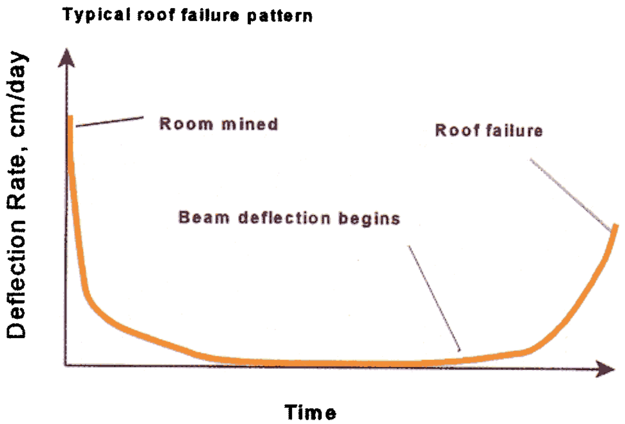
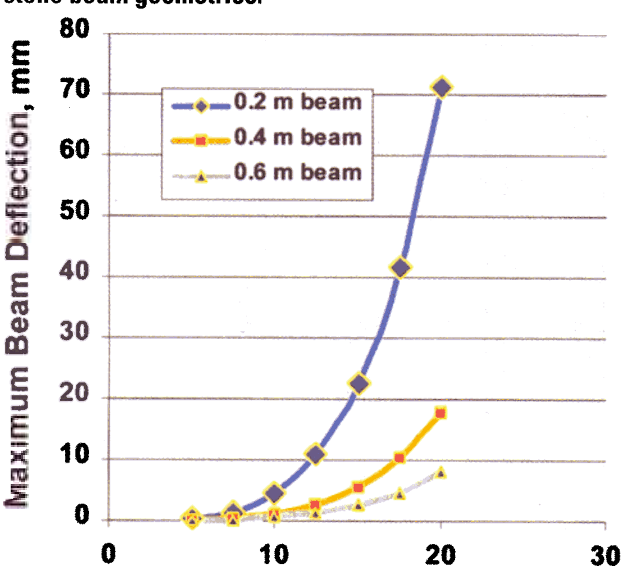


FIG. 11

Maximum deflection from gravity loading for various limestone beam geometries.



beams or plates. Figure 11 shows the effect varying beam lengths and thickness have on the maximum deflection of a 23.5 kN/m^3 (150 lb/cu ft), 41.4 GPa (6 million psi) fully intact beam of limestone. This deflection is small and can take place quickly after an opening is excavated. Or it can take place much later as weathering processes aid in forming new, thinner beams.

Tectonic processes can produce additional roof-beam deflection by axially loading roof beams. Two-dimensional models have demonstrated how different levels of horizontal stresses may cause up to several centimeters of deflection before failure of roof beams (Iannacchione et al., 1998).

Vertical loading of roof beams from overlying or adjacent mining can load roof beams that, in turn, can accelerate deflection. In all of these examples, roof beam deflection is viewed as a precursor of failure and, if recognized early, could result in pro-active control solutions.

Site-specific example of a proactive ground-control plan

A site-specific field test was performed to illustrate how information from roof monitors can help make safety decisions about the stability of mine roofs. In 1996, the immediate roof at an operating stone mine began to fail about 90 m (300 ft) from the end of a previous directionally controlled roof fall.

This original failure took on the appearance of a series of low-angled shear planes cutting or ripping the rock. The orientation of these planes was perpendicular to the orientation of the local horizontal-stress field. Seven deflection monitors were placed along the projected failure trend. Two of the seven monitors used the 20-anchor point sonic probe. The other five were three-anchor point prototypes of the RMSS.

Data collected from three of these monitors are shown in Fig. 12. Monitor No. 7 collected deflection measurements for almost 70 days before total roof collapse. During this time, the roof deflected in three distinct phases. The first phase was marked by a slow but steady deflection in the lower roof beam. At about 40 days, there was a sudden increase in the deflection of the beam. The third phase indicated that the beam deflection rate lessened but ended in total roof failure. About 50 mm (2 in.) of roof deflection occurred before roof collapse.

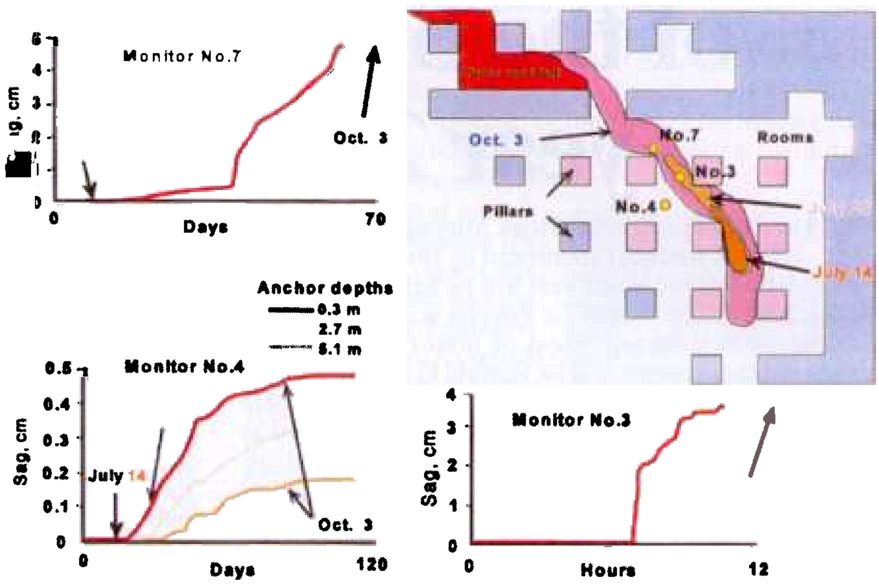
Data from monitor No. 3 showed a much different trend. Unlike monitor No. 7, this instrument was placed close to an existing failure. Therefore, significant beam deflection could have already occurred. The area began to cut, or rip, on July 26, rapidly extending the zone of failed roof. The roof associated with monitor No. 3 went from stable to unstable in five hours.

Monitor No. 4 was purposely placed slightly away from the main failure trend. The magnitude of deflection measured from this instrument was one-tenth of that from the instruments within the failure trend. However, these measurements did show that beam bending and associated shearing extended significant lateral distances on the order of 6 m (20 ft) from the fall's edge and 12 m (40 ft) from the center of the fall. This monitor also showed that, while deflection was initiated in the lowest beam, beam separations quickly moved much higher in the roof.

This information proved valuable to the mine. Several proactive ground-control strategies were implemented as a result of supplemental roof monitoring. Unstable roof areas were identified and personnel were restricted from entering. A new roof-support plan was initiated. It prevented the progressive failure of the various roof beams. Roof monitoring was initiated in other areas of questionable stability.

FIG. 12

Roof behavior associated with a large roof fall caused by high horizontal stresses. Monitor No. 7 was a three-anchor point prototype of the RMSS and Monitor No. 4 was a 20-anchor point sonic probe.



Critical issues and the need for cooperation

RMSS technology has the potential to provide information that could be used to solve associated rock mechanics issues, such as:

What are critical deflection rates?

What geologic factors influence deflection magnitudes prior to a roof fall.

At what locations in the roof does the failure initiate?

The answers to these questions can provide the basis for recommendations and guidelines. And they can be used effectively and efficiently to improve the safety conditions for underground stone miners.

While much has been learned, more knowledge will be needed to help know when monitoring techniques should be used. Because performance results depend heavily on site-specific conditions related to geologic, stress and mining conditions, all monitoring data must be calibrated for site-specific conditions. The solution to this problem requires research efforts founded on a common goal and good communication. The best way to achieve this is to have industry, labor and government working together to gain the required data and knowledge.

Conclusions

This research is intended to serve as a catalyst to develop better engineering tools and strategies that will improve safety by better understanding roof behavior. An understanding of the complex behavior associated with roof instabilities is expected to provide a method for developing the safest decisions in concert with existing mining practices. Developing a proactive roof control plan allows for a quick and timely response. And it ensures that every response is the one that is most appropriate in relation to existing conditions. Here are some of the important characteristics associated with a proactive roof control strategy:

Visual and hands-on roof condition information is the basis of any roof control strategy.

Supplemental observational and monitoring techniques provide additional useful information.

Regularly recorded and charted information from basic and supplemental monitoring, placed on mine maps and shared with miners, fosters the development of a proactive roof-control plan.

There are many useful monitoring techniques available to underground stone mines. However, many of them have operational problems and often lack adequate information to apply them at local mine sites.

To help address these problems and to provide a better means of collecting and sharing roof deflection data, NIOSH has developed the RMSS. The RMSS has several advantages. It is inexpensive and can be fabricated locally. It can be placed in boreholes protected from blast damage. It can be read remotely. And it is compatible with many kinds of data acquisition systems.

A first step has been made here through the presentation of the RMSS. But improvements are possible and indeed likely. For example, both the single- and multiple-point RMSS can be incorporated into a minewide monitoring system. It is hoped that improvements can be made to fabrication procedures/components and the development of computer software to assist in managing the large streams of data associated with minewide monitoring scenarios.

Hazardous roof-beam deflection depends on site-specific geologic, stress and mining characteristics. So any roof-monitoring technique must be calibrated for local conditions. This can occur only if industry, mine workers and government work together to gain the required data and knowledge.

The use of the RMSS and other observational and monitoring techniques by the underground stone mines is expected to enhance miners' understanding of roof behavior and provide a tool for proactive intervention when hazardous ground conditions exist.

Knowledge gained through shared experiences will aid in developing innovative engineering techniques that will mitigate falls of ground and reduce the potential for injuries to mine workers. (References are available from the authors.) ■