Roof Span Design for Underground Stone Mines

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ABSTRACT

Underground stone mines in the United States use the room-and-pillar method of mining. The stability of the roof between pillars determines the mining dimensions and size of equipment that can be used. The findings of a survey of roof span stability issues and design practices are presented, and the observed factors contributing to roof instability are discussed. Identified stability issues are evaluated, such as maximum roof span, horizontal stress, and roof beam stability. The results of field observations, roof monitoring, and numerical analyses are used in the evaluation. The importance of the first roof beam thickness and its impact on roof stability and support requirements is presented. An evaluation of the current experience with stone mine roof spans relative to international experience is presented. A step-by-step design procedure is suggested which emphasizes the need to collect adequate geotechnical data, understand the immediate roof stability, select a mining direction, and meet support requirements.

INTRODUCTION

In room-and-pillar mines, the roof between the pillars is required to remain stable during mining operations for haulage as well as access to the working areas. Roof and rib falls account for about 15% of all reportable injuries in underground stone mines (Mine Safety and Health Administration, 2009). Therefore, the stability of the roof is an important safety consideration. The size of the rooms in underground stone mines is largely dictated by the size of the mining equipment. Large mining equipment is used, requiring openings that are on average 13.5 m (44 ft) wide by approximately 7.5 m (25 ft) high to operate effectively (Esterhuizen et al., 2007). The dimensions of the roof spans are largely predetermined by the equipment requirements, and design is focused on optimizing stability under the prevailing rock conditions. If the rock mass conditions are such that the desired stable spans cannot be achieved cost effectively, it is unlikely that underground mining will proceed. In addition, large roof falls can extend across the full width of a room and may extend more than 5 m (16 ft) above the roof line. These large falls are a safety hazard and can have a significant impact on mine access and production. The National Institute for Occupational Safety and Health (NIOSH) research into stone mine roof stability has focused on identifying both the causes of roof instability and techniques to optimize stability through design.

OBSERVED ROOF STABILITY ISSUES IN STONE MINES

Observations were carried out at 34 operating stone mines to identify the factors that contribute to roof instability. Data were collected on rock strength, jointing and other geological structures, room and pillar dimensions, roof stability, and pillar performance (Esterhuizen et al., 2007). Two to 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 x 100 m (300 x 300 ft). The range of roof spans observed is shown in Figure 1, which shows that the 92% of the mine openings are more than 10 m (33 ft) wide. Of the mines visited, 41% were installing support in a regular pattern, while the remaining 59% did not install any roof support, or only rarely installed spot bolting if required.

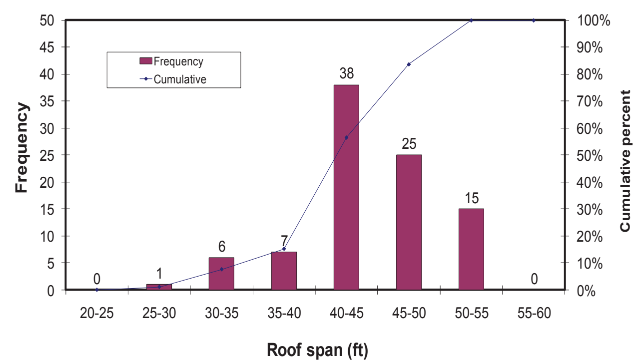

Figure 1. Distribution of roof span dimensions measured at 34 different underground stone mines.

Thirty of the 34 mines visited had experienced small-scale or larger roof falls. The smaller-scale falls were typically less than 1 m (3 ft) in length and were categorized as follows:

- Thin slabs/slivers of rock that spall from the roof
- Joint bounded blocks that are released from the roof

- Bedding defined slabs that fail by separating along bedding planes

Figure 2 shows an example of a 13-m (43-ft) wide, naturally stable excavation with excellent roof conditions. Most of the smaller scale instabilities are addressed by scaling, rockbolting, or screen installation as part of the normal support and rehabilitation activities.

Figure 2. Naturally stable 44-ft (13-m) wide roof span in a stone mine.

Large falls, which typically extend over the full width of the opening, were observed at 19 of the 30 mines that experienced roof instability. Large falls were categorized by identifying the most significant factor contributing to each fall. A summary of these factors and the relative frequency of occurrence of each are presented below:

- Stress: High horizontal stress was assessed to be the main contributing factor in 36% of all large 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 (160 ft) in one case. The characteristics of stress-related roof falls are described in Iannacchione et al. (2003) and Esterhuizen et al. (2007). Figure 3 shows a typical ellipsoidal stress-related fall, and Figure 4 shows an example of how such a fall progressed through the mine workings in a direction perpendicular to the major horizontal stress.
- Weak bedding planes: The beam of limestone between the roof line and some overlying weak band or parting plane failed in 28% of all observed large roof falls.
- Discontinuities: Large discontinuities extending across the full width of a room contributed to 21% of the large roof falls.
- Weak roof rocks: The remaining 15% of the roof falls was attributed to the collapse of weak shale inadvertently exposed in the roof or progressive failure of weak roof rocks.

Figure 3. Example of a large elliptical-shaped roof fall that was related to high horizontal stress in the roof.

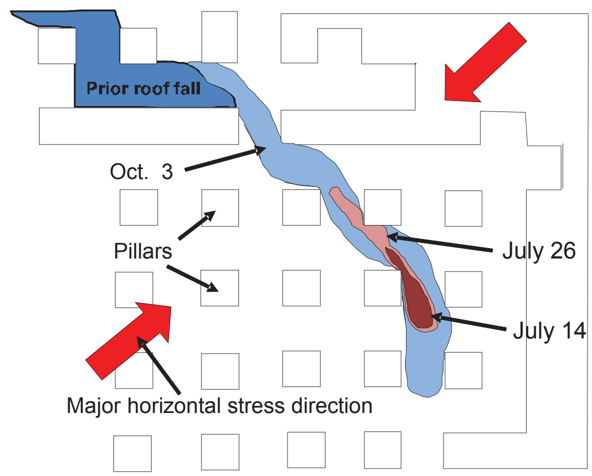

Figure 4. Plan view showing the development of a stress-related roof fall in the direction perpendicular to the direction of the major horizontal stress, after Iannacchione et al. (2003).

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.

MAXIMUM STABLE ROOF SPAN

The majority of roof spans in operating mines fall within a narrow range of 10 m to 17 m (35 ft to 55 ft) and are related to the space needed to effectively operate large loaders and haul trucks. A small number of mines used roof spans wider than 15 m (50 ft), so it is not clear whether the stability limit is approached at 17 m (55 ft) or whether it simply satisfies the practical requirements for equipment operation. Given that a large proportion of the mines are able to mine without installed support, it seems to indicate that wider spans can be achieved if additional supports are used.

One way of assessing the potential maximum span is to compare the stone mine data to experience in other mine openings around the world. The Stability Chart, originally developed by Matthews et al. (1980) and then modified by Potvin (1988), Nickson (1992), and Hutchinson and Diederichs (1996), was used as a basis for comparison. The Stability Chart plots a modified Stability Number *N´,* which represents the rock mass quality normalized by a stress factor, an orientation factor, and a gravity adjustment. Stability zones have been indicated on the chart based on 176 case histories from hard rock mines around the world. The following stability zones are indicated:

- Stable – Support generally not required.
- Stable with support – Support required for stability, the support type is cable bolting.
- Transition – Stability not guaranteed, even with cable bolt support.
- Unsupportable – Caving occurs, cannot be supported with cable bolts.

The stability number for each stone mine case history was calculated using the procedure described by Hutchinson and Diederichs (1996) and was based on the rock classification data collected at each site. Figure 5 shows the Stability Chart with the stone mine case histories and stability categories. In this chart, the actual heading width is shown instead of the "hydraulic radius" which is customarily used. The hydraulic radius, in this context, is the ratio of the area to the circumference of the roof of the excavation. For a parallel-sided excavation, the hydraulic radius is 50% of the excavation width. It was assumed that the headings in stone mines are parallel-sided excavations. The chart also indicates the average Stability Number of the stone mine case histories as a horizontal dashed line.

It can be seen that the majority of stone mine case histories plot in the region of "stable" to "stable with support," and only one is located in the transition zone. This agrees reasonably well with the observed stability and support usage in stone mines, although stone mines have been able to achieve stability with light support compared to cable bolting used in the hard rock mine case histories. Based on the average Stability Number for stone mines, it would appear that stable, supported excavations can reliably be achieved with spans of up to about 20 m (65 ft) using cable bolt supports. Cable bolt lengths in the hard rock mines are typically greater than half the excavation span, which would imply 10-m (33-ft) long or longer cable bolts to achieve stability in a 20-m (65-ft) wide stone mine entry. Unsupportable and caving conditions are indicated when the span increases to about 27 m (90 ft). These results are in line with current experience. It appears that stone mines are working near the span limit that can reliably be achieved using rock bolts as the support system. Increasing the spans beyond the 15–17 m (50–55 ft) range is likely to incur considerable cost and productivity implications as cable bolting would become necessary.

STABILITY OF THE IMMEDIATE ROOF BEAM

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. In some cases, the upper surface of the beam was a pronounced parting plane while in others it was a change in lithology, typically when the limestone beam is overlain by weaker rocks. 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.

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 did so to alleviate the effects of high 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. There was no correlation between roof beam thickness and excavation span.

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 high horizontal stress can contribute to roof instability resulting in the need for rock bolt support. However, experience seems to indicate that a roof beam thickness of less than about 1.2 m (4 ft) is highly likely to be unstable and a regular pattern of rock bolt supports will be required to maintain the roof stability.

HORIZONTAL STRESS CONSIDERATIONS

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 (Dolinar, 2003; Iannacchione et al., 2003). Observations show that the tectonic stresses in limestone formations that outcrop may have been released over geologic time by relaxation towards the outcrop (Iannacchione and Coyle 2002). Consequently, outcropping mines can have highly variable horizontal stress magnitudes that depend on the amount of relaxation that occurred over geologic time and the distance from the outcrop.

A review of horizontal stress measurements in limestone and dolomite formations in the eastern and midwestern U.S. and eastern Canada (Dolinar, 2003; Iannacchione et al., 2002) has shown that the maximum horizontal stress can be expected to 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 (2009). The minimum horizontal stress is approximately equal to the overburden stress.

An analysis of the impact of horizontal stress on beams of rock that may exist in the roof of stone mine workings showed that horizontal stress can be expected to cause buckling of thinly bedded roof strata (Iannacchione et al., 1998). Further analyses using numerical models showed that brittle spalling (Kaiser et al.,

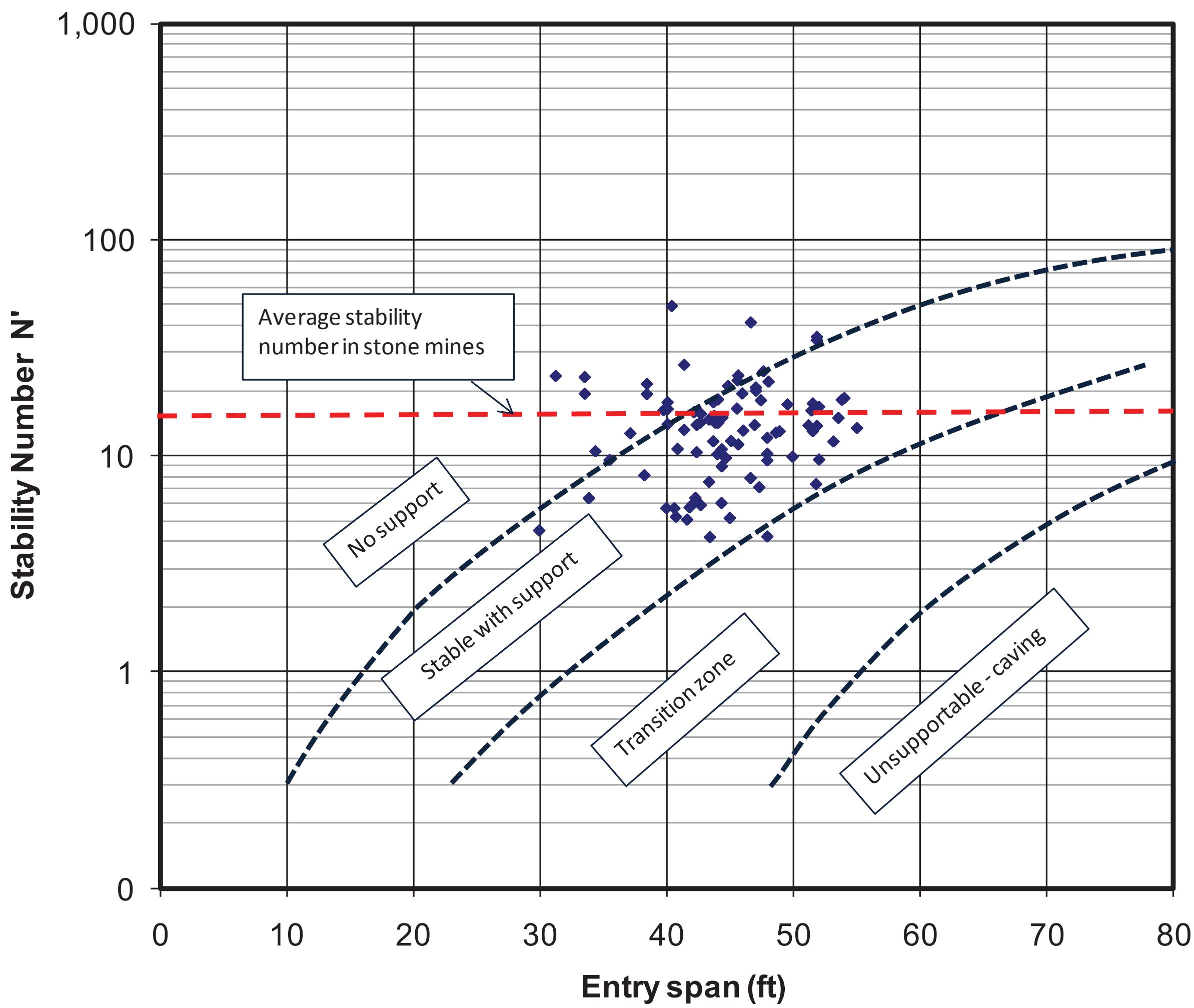

Figure 5. Stability chart showing stone mine case histories and stability zones, modified after Matthews et al. (1980), Potvin (1988), Nickson (1992), and Hutchinson and Diederichs (1996).

2000) of the roof rocks under near-uniaxial loading conditions can explain roof failure at the stress levels encountered in stone mines (Esterhuizen et al., 2008).

Once a stress-induced roof fall has occurred, it can be costly and difficult to arrest the extension of the fall into adjacent areas. Avoidance of these falls through layout modifications has proved to be very successful in several operating mines (Iannacchione et al., 2003). It is first necessary to establish the direction of the major horizontal stress, which can be determined by various stress measurement techniques or can be inferred from stress-related roof failures (Mark and Mucho, 1994). The layout is then modified so that the main development direction is parallel to the maximum horizontal stress and the amount of unfavorably oriented cross-cut development is minimized (Parker, 1973). A further modification that has proved to be successful is offsetting the cross-cuts and increasing the length of the pillars, so that a continuous path does not exist along which a roof fall can progress across the layout. Modifying a layout in this manner will not necessarily eradicate all stress-related problems, but it has been shown to considerably reduce these problems (Kuhnhein and Ramer, 2004).

Figure 6 shows a mine layout that has been optimized for high horizontal stress. The main heading direction is parallel to the maximum horizontal stress; pillars are elongated so that unfavorably oriented cross-cuts are minimized; the cross-cuts are narrower than the headings; and the cross-cuts are off-set so that potential stress related roof falls will abut against solid pillar ribs, rather than snake through the layout.

ROOF REINFORCEMENT

The survey of roof support practices showed that grouted rock bolts are the most widely used form of support. Bolt lengths are typically between 1.8 m (6 ft) and 2.4 m (8 ft), and where the bolts are installed in a regular pattern, the most commonly used bolt spacings are either 1.5 m (5 ft) or 1.8 m (6 ft). As with most other roof bolting designs in strong rocks and high strength, and stiff bolts are more likely to provide the desired rock reinforcement than low strength and low stiffness systems (Iannacchione et al., 1998).

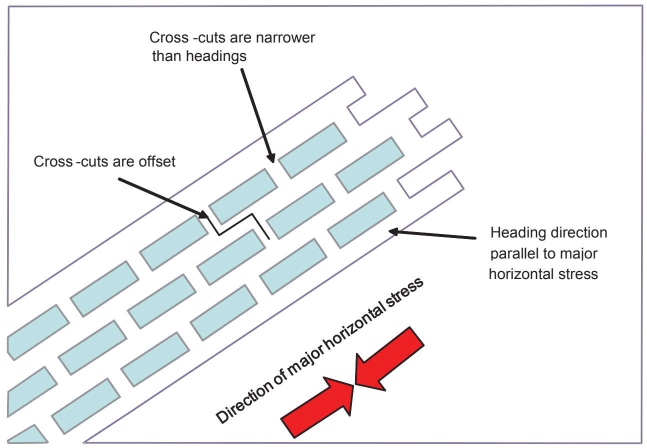

Figure 6. Diagram showing room and pillar layout modified to minimize the potential impact of horizontal stress related damage.

Roof screen or other supplemental supports such as cable bolts are rarely used.

Roof reinforcement in the relatively strong-bedded rock encountered in stone mine can have one or more objectives. Depending on the geological conditions, the support system can be expected to do the following:

- Provide suspension support for a potentially unstable roof beam
- Provide local support to potentially unstable blocks in the roof
- Combine thinly laminated roof into a thicker, stronger unit
- Provide surface control when progressive spalling and small roof falls occur

The above support functions can usually be achieved by the 1.8-m (6-ft) and 2.4-m (8-ft) bolts used in the stone mines. When poor ground is encountered locally or when horizontal-stress-related roof failures occur, intense bolting, steel straps, and cable bolts have been used with mixed success to halt the lateral extension of these large roof falls.

From a design point of view, a stone mine is unlikely to be economically feasible if heavy support such as cable bolts and screen would be required on a daily basis. Such rock conditions would probably require reduced excavation spans; otherwise, the support costs would be prohibitive. Therefore, the first objective in designing an underground stone mine should be to confirm that the rock mass quality is adequate for creating the typical 10 to 17 m (35 to 55 ft) roof spans without resorting to elaborate support systems.

ROOF SPAN DESIGN GUIDELINES

Designing stable roof spans for underground stone mines should be conducted using basic engineering principles. Good geotechnical information, combined with a pragmatic assessment of the likely modes of instability, along with providing the required support is likely to produce a stable initial design. Once an initial design has been developed, performance monitoring can be carried out to optimize the design.

Useful information can be obtained from neighboring mines that are operating under similar conditions. A particularly useful piece of information would be to identify whether horizontal-stress-related roof problems exist and if so, the orientation of the stress-related damage. This information can go a long way in selecting the orientation of the main headings in the proposed mine. The following steps should be followed to carry out a mine layout and roof span design:

1. Geotechnical characterization: Designing stable roof spans for stone mines can be successfully carried out if adequate geotechnical investigations are conducted ahead of the design. Such investigations are best conducted by experienced ground control specialists and are likely to include rock strength testing, core logging, bedding layering assessment, joint orientation assessment, and rock mass classification. If horizontal-stress-related issues are expected, stress measurements can assist in providing an indication of the orientation and magnitude of the maximum horizontal stress.
2. Confirm rock mass quality: Using the results of a rock mass classification or direct inspection of workings, confirm that the rock strength and rock mass quality is similar to that found in eastern and midwestern stone mines. The RMR should exceed a value of 60.0 and the rock strength should exceed 45 MPa (6,400 psi).
3. Selection of mining direction: The direction of the headings in the production areas should be favorably oriented to potentially high horizontal stress and the prevalent jointing. As with any underground excavation layout, it is preferable to intersect the main joint strike direction by more than 45° to limit the size of potential blocks formed in the roof and ribs of the excavation. Since room-and-pillar mines have two orthogonal directions of mining, the heading direction should be favored over the cross-cut direction when selecting the orientation of the layout. If the orientation of the maximum horizontal field stress is known, and stress related problems are anticipated, the heading direction should be oriented parallel to the direction of major horizontal stress, with due consideration of joint orientations and cross-cut stability. Often it will be a compromise to select the final heading orientation. Other modifications to the pillar layout should be considered, as discussed below.
4. Modification of pillar layout: A simple square pillar layout with headings and cross-cuts of equal width is sufficient in most cases. However, if horizontal-stress-related instability is expected, the pillar layout can be modified to improve the likelihood of success. Possible layout modifications were shown in Figure 6.
5. Selection of mining horizon: The location of the roof-line relative to pronounced bedding planes or lithology changes should be identified next. Experience has shown that if the immediate roof beam is less than 1.2 m (4 ft) thick, it is very likely to be unstable. Thicker roof beams may be required if excessive horizontal stresses are encountered. Persistent parting planes can be selected to form the roof-line if they are present at a convenient location in the formation being mined. Using a pre-existing parting plane as the roof line helps to act as a marker and usually provides a clean breaking surface for blasting operations. Many of the mines that do not use roof supports have a natural parting as the roof line.
6. Selection of roof span: Past experience has shown that stable roof spans in the range of 10 m to 15 m (35 ft to 50 ft) have

been regularly achieved in underground stone mines. NIOSH studies have shown little correlation between mining roof spans and rock quality, mainly because there is such a small range of rock qualities in operating mines. For an initial design, it might be prudent to design for no more than 12-m (40-ft) spans. The spans can be increased incrementally, if warranted by monitoring of actual roof performance. There is little experience with spans that are greater than 15 m (50 ft).

7. Support considerations: Depending on the characteristics of the immediate roof, basic support in the form of patterned rockbolts may be required. The importance of the thickness of the first beam in the roof, the orientation of excavations relative to the maximum horizontal stress, and the characteristics of rock joints will determine whether and how much support is required. Mines that do not use bolting are located in formations with a favorable combination of geological conditions, and they conduct blasting practices that maintain an unbroken roof horizon.
8. Monitoring and confirmation: Once a roof design has been finalized and mining is underway, monitoring should be implemented to verify the stability of the roof. Monitoring results can be used to identify potential stability problems before they occur and may indicate that a change in the design is required. Monitoring technologies that are available include borehole-video logging (Ellenberger, 2009), roof deflection monitoring (Marshall et al., 2000), roof stability mapping using the Roof Fall Risk Index (RFRI), (Iannacchione et al., 2006), and microseismic monitoring of rock fracture (Iannacchione et al., 2004; Ellenberger and Bajpayee, 2007).

DISCUSSION AND CONCLUSIONS

A study of pillar and roof span performance in stone mines that are located in the eastern and midwestern United States showed that various stability issues can be addressed by appropriate design. A roof span design procedure is proposed that systematically addresses each of the main stability issues. The procedure focuses on selecting an appropriate mining horizon and mining direction. The importance of the thickness of the first bed in the roof and the likelihood for added rock bolting is described. Layout modifications are described that can be made to reduce the incidence of horizontal-stress-related instability.

Roof span design requires a good understanding of the geotechnical characteristics of the formation being mined. The essential data are the uniaxial compressive strength of the rock, characteristics of the discontinuities in the immediate roof, and the rock mass classification. Knowledge of the magnitude and orientation of the stress field can assist in orienting the layout appropriately.

The design procedure is based on observation of the actual performance of pillars and roof spans in stone mines within the eastern and midwestern United States. The guidelines should only be used for design under similar geotechnical conditions.

DISCLAIMER

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

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