Roof and rib hazard assessment for underground stone mines

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Abstract

From 1991 through 1995, 44 miners out of a total work force of less than 2,000 were fatally injured in the stone industry. Of these, 12 occurred at underground mining operations with nine deaths resulting from roof or rib falls. A safer environment can be achieved by evaluating the nature of the hazardous ground and by developing more efficient and effective ground-control strategies. Roof and rib conditions were observed and assessed in 33 underground stone mines in Illinois, Indiana, Kentucky, Maryland, Missouri, Pennsylvania and West Virginia (Fig. 1). Hazard assessment indicated that the ground failures that occurred under moderate to substantial overburden, i.e., >30 m (100 ft), were caused by stress concentrations and geologic structures. Ground failures near the surface are caused by solution (water) processes. Selection of the mining horizon and mine-layout decisions tremendously influence ground stability.

Hazard assessment techniques

Of the 33 mines visited, 32 used the room-and-pillar method. This method is most efficient and safest when the mining results in a smooth, competent roof (back) and the ribs (walls) are free of loose rocks. Finding a mining horizon that has both a stable roof beam and a stable roof line and determining an optimal mine layout are critical tasks in developing a safe and productive mine. Room widths, heights and lengths and pillar orientations and shapes should be predetermined to minimize roof and rib hazards. During development of a new mine, detailed consideration should be given to the mine portals and main access drifts, as these openings must remain stable for the life of the underground mine.

Finding a stable roof beam. Perhaps the first critical roof-safety consideration is to find a stable roof beam. The ideal roof beam is massive, strong, persistent and weather resistant. Local stratigraphy (the layers of stratified rock) dramatically affect ground stability, especially when certain lithologic thickness, bedding lamination and cross-bedding features are present. In general, a thick competent bed of rock (preferably limestone) within the immediate roof horizon results in a stable roof beam. This is because limestone is generally stronger and more massive than shale or siltstone (which is soft and bedded). Stiffer rocks sag (deflect) less than softer rocks, and thicker roof beams sag less than thinner beams. Therefore, the immediate roof should consist of a limestone beam of sufficient strength and character so as to minimize roof sag.

In general, the less a roof beam sags, the less chance for beam failure. A meter (3 ft) or more of competent (having few joints) limestone was observed to form a stable beam in 10-m-(35-ft-) wide rooms in many underground mines. As more joints intercept the roof beam or the associated room is widened, the chance for instabilities increase. Therefore, changes in roof beam characteristics should always be considered as new faces are advanced.

Massive limestone is very strong, often having compressive strengths of 207 MPa (30,000 psi) and tensile strengths of 14 MPa (2,000 psi). Unfortunately, like any other rock, limestone contains discontinuities (vertical joints or fractures and horizontal bedding planes) that can affect roof-beam strength. These discontinuities (breaks) in the rock control the strength of the rock mass. Therefore, hazard assessment is based mainly on recognizing the characteristics and structure of the local roof geology.

Rock characteristics that should be measured or observed are: the orientation, the dip and scale (spacing) of the horizontal bedding planes (smooth surfaces), and the high-angle vertical joints (breaks). When drilling exploration holes, a geologist should be employed to log and examine the core from the mining horizon, identifying the character of both the intact rock and the observed fractures or breaks. When a highwall exposure of the mining horizon is present, measurement and observation should be made of the bedding and joint characteristics within the highwall. If the face is weathered, a new "clean" exposure should be developed if possible. Presplitting a small cut of highwall can minimize blast damage and maximize the percentage of observable "in-place" breaks. It is also important to examine the rock debris left on benches after blasting. Often, competent horizons will produce large boulders. Note the location and character of rock fragments from different strata. Most surface quarries have boulders placed along road sides to act as beams or barriers. Find out where these boulders came from.

As a mine develops away from the highwall or outcrop, underground exposures must be analyzed to determine stable beam characteristics. These exposures are found in existing roof falls, shafts or declines (ramps). In addition, observation holes should be drilled into the roof at regular intervals. A great deal of information can be gained from these observation holes. Drill-hole penetration rates and drill cuttings can often be used to identify the roof-beam rock type and thickness. Any breaks or separations and relative indications of material hardness should be noted and recorded for future comparisons as development proceeds.

Weather, humidity, temperature and groundwater can all have a detrimental effect on the strength of roof and rib rocks. In general, rocks that are resistant to these forces are highly desirable. Shales and clays are generally very susceptible to weather influences, especially if they possess swelling characteristics. Limestones and sandstone generally weather slowly. However, the occurrence of certain minerals, bands of shale or clay, internal structures, etc., can provide gaps or openings by which weathering forces attack and eventually weaken even limestone.

Several practical and simple techniques exist for determining the weathering characteristics of rocks. If rocks are clays or shales, specimens placed in a glass of water overnight can deteriorate into fine particles, indicating that they react unfavorably to moisture. For limestone, an equally simple technique exists. Rocks from different potential roof beams can be marked, photographed and located outside the underground mine. Routine temperature and moisture fluctuations attack the full-scale specimen, allowing for the direct observation of the weathering characteristics (Winick, 1996).

FIGURE 1

Locations of underground stone mines evaluated in this study.

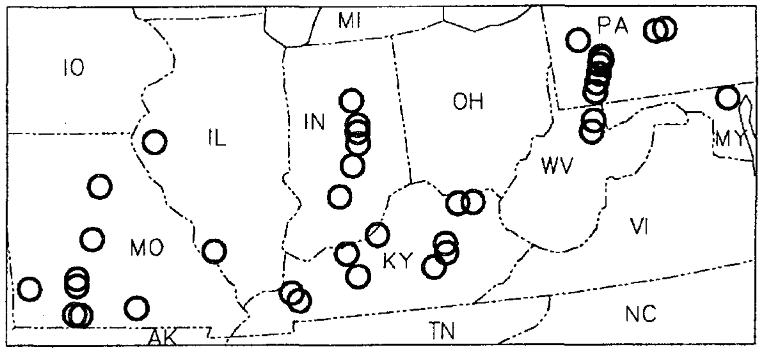


FIGURE 2

A smooth roof line produced by a persistent bedding-plane lamination within the limestone roof beam.

Finding a stable roof line. Another important assessment factor is to evaluate potential stable roof lines. If several stable roof beams exist, the one that produces a persistent, smooth roof profile most often should be selected. If the stable roof line does not occur then a smooth roof profile should be produced using drilling (altered drilling densities near the roof and rib line) and blasting (pre- and post-splitting) techniques.

A persistent, smooth roof line is generally formed by bedding-plane laminations and rock-layer interfaces (Fig. 2). A technical definition of bedding-plane laminations can be found in Krumbein and Sloss (1963). They refer to a bed (beam) as a rock unit composed of several strata or laminae. The laminations contained within each layer are characterized by their ease of breaking along bedding planes. Interfaces between beds of different limestone types or even different rock types (shale, clay, etc.) often separate with the same ease of breaking as the bedding planes. Both bedding planes and interfaces can have thin layers of clay which greatly facilitate the separation process.

The advantage of bedding-plane laminations and rock interfaces is that properly drilled blastholes can result in a clean break along such a horizon. However, if too many bedding plane laminations or rock-layer interfaces exist, the roof can separate with time into many thin layers that are inherently unstable.

Blasting also has a tremendous influence on roof and rib stability. Overbreak can damage the roof rock, while bootlegs (poor rock breakage at the end of a blasthole due to inadequate explosive burn) can leave broken rock along rib and face surfaces. If a natural smooth roof plane does not exist, blasting procedures such as presplitting can be used to produce a smooth roof plane. Presplitting requires additional drill holes along the roof and rib line, often drilled at close spacing

FIGURE 3

Width-to-height ratios of pillars used in development and benching sections.

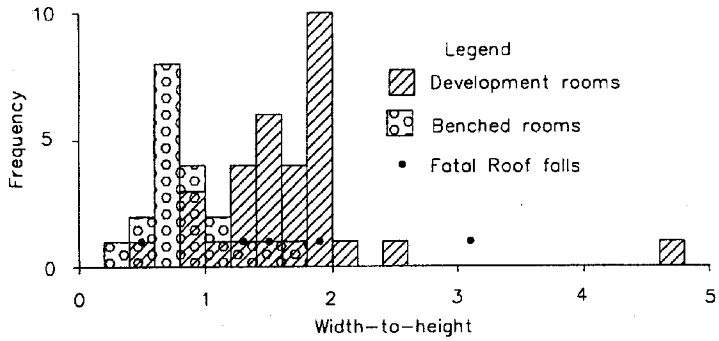


FIGURE 4

Buckling failure in a limestone roof beam caused by high horizontal stresses. Note the low-angle shear associated with the failure.

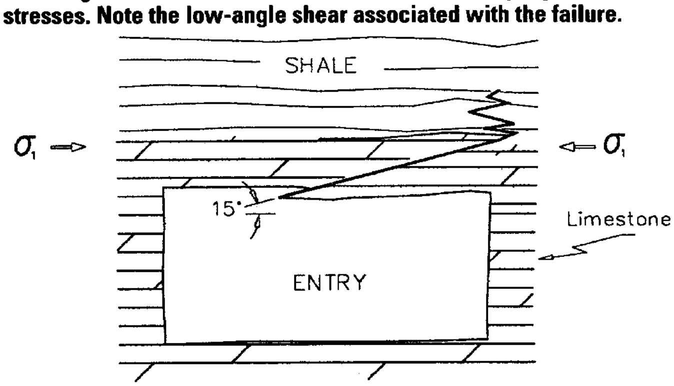
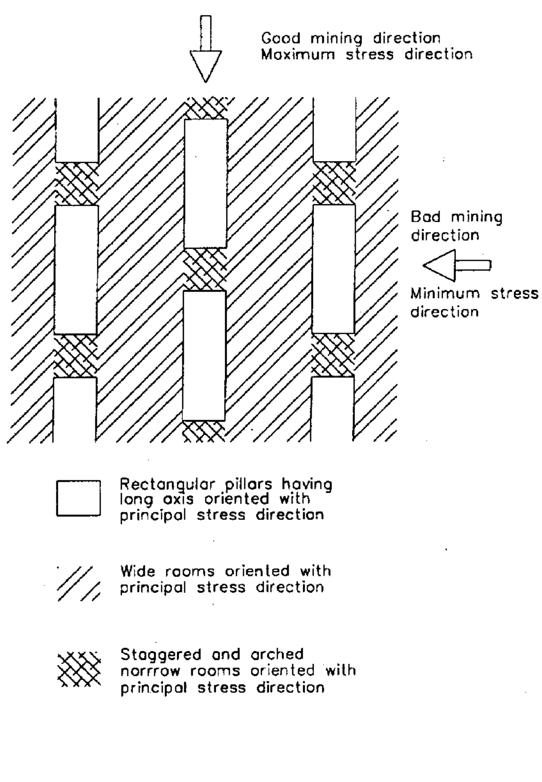


FIGURE 5

Optimum mine layout for controlling strata in high horizontal-stress conditions.



and charged with special low-strength explosives. As the face is blasted, the perimeter holes are shot prior to the rest of the drill holes to initiate a breakage plane. Post-splitting or trimblasting is another technique used to produce smooth, undamaged rock around the surface of the face. The drill holes around the perimeter of the face are blasted last and are loaded with either a higher or lower strength explosive. These techniques act to evenly break the final rock pulled along a perimeter plane.

Safe mine layouts

After determining the optimal mining horizon, safe mine layouts need to be evaluated. Typically, mine layouts are controlled by haulage, ventilation, crushing and storage requirements. Observations indicate that more consideration should be given to designing the shapes, sizes and orientations of mine structures that minimize stress and geologic related hazards.

Vertical stress. In general, dangerous levels of vertical stress were only observed in very deep, benching or multiple-level mining operations where pillar sizing and pillar positioning produced high stress concentrations. Overburdens ranged from <10 to 360 m (<30 to 1,200 ft), but most were between 30 and 100 m (100 and 300 ft). Vertical stress is a function of the overburden. Because most underground stone mines are relatively near to the surface, high vertical-stress conditions are uncommon.

Pillar design is generally perceived as a less critical design issue in underground stone mines, because of the low vertical-stress conditions and the inherent high strength of limestone. Therefore, the pillar width-to-height ratio for development rooms are relatively low, averaging 1.72 with a standard deviation of 0.66 from a sample of 33 mines (Fig. 3). Pillar design becomes a much more significant issue when second mining or benching is practiced. Twenty of the 33 mines extracted benches ranging from 3 to 24 m (10 to 80 ft) and averaging 8.6 m (28 ft) in one to as many as three lifts. The width-to-height ratios of pillars in bench rooms were significantly lower, averaging 0.84 with a standard deviation of 0.31 (Fig. 3). These pillars are slender and are more susceptible to buckling failure or to failure along large geologic structures such as faults or slips angled through the entire pillar.

Multiple-level mining was observed at four mines. Three of the mines did not practice superposition of the pillars (i.e., superimposing developing pillars directly over or under existing pillars using similar sizes and shapes). Superpositioning helps to funnel vertical loads through a continuous column of rock and has been highly successful in mitigating stress-related rock failures in other mining situations (metal, nonmetal and coal multilevel mines). It is also beneficial for long-term stability to leave a substantial interburden between mining levels. The median for the four mines was 12 m (40 ft), which appeared adequate considering the geology and mine layout.

Horizontal stress. Perhaps one of the most unrecognized factors affecting mine layouts is high horizontal stress. When limestone roof contains extensive horizontal bedding or is laminated in nature, the roof beam can be thought of as a plate loaded along its slender axis. As in any structure, high axial loads can cause the beam to bend and finally buckle (Fig. 4). The shear planes developed in response to this buckling occur at low angle to the mine roof and are oriented perpendicular to direction of loading.

High levels of horizontal stress, ranging from 14 to 70 MPa (2,000 to 10,000 psi) in the first 5 m (16 ft) above the mine roof, were measured at stone mines in Pennsylvania (Iannacchione et al., 1996) and in Kentucky (Parker, 1996). The horizontal-stress field is biaxial with one direction usually greater than its orthogonal horizontal-stress component. The greater stress magnitude is called the major principal horizontal stress, and the lesser stress magnitude is called the minor principal horizontal stress. The directionality of the horizontal-stress field is considered to be largely the result of tectonic forces due to movements of the earth's plates. Many of the underground stone operations in the United States lie within the large midplate stress province that is compressional in nature and usually exhibits a ENE or EW principal horizontal-stress direction.

The direction and magnitude of the horizontal-stress field and its application at shallow limestone mining depths (where the vertical stress is generally very small) has resulted in the development of novel control measures. For instance, openings driven parallel, or nearly so, to the major principal-stress direction at affected mines will usually have more stable conditions. Conversely, those driven perpendicular to the major stress direction (in the minor principal stress direction) will have the poorest ground conditions (Fig. 5). Therefore, control techniques such as orienting openings in the favorable direction(s), maximizing mine layout in the good direc-

FIGURE 6

A histogram of major joint orientations in the Loyalhanna formation near the Lake Lynn Laboratory, showing the relationship between orientation and structural folding of stone bearing strata.

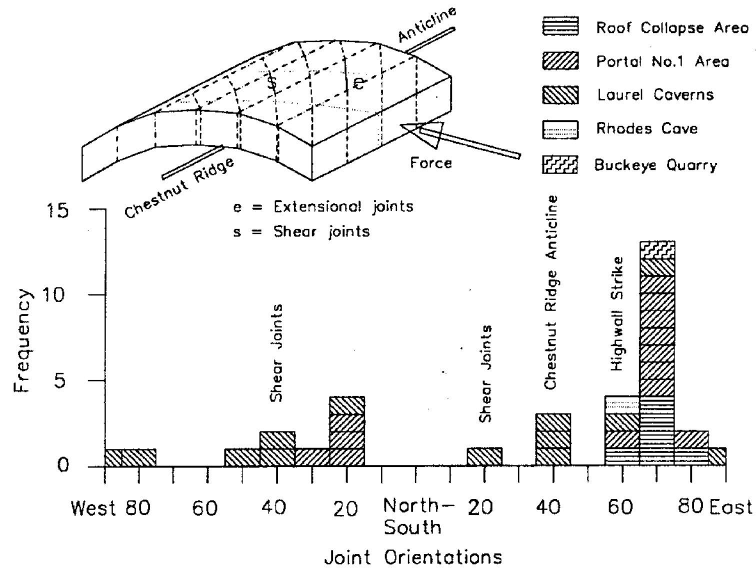
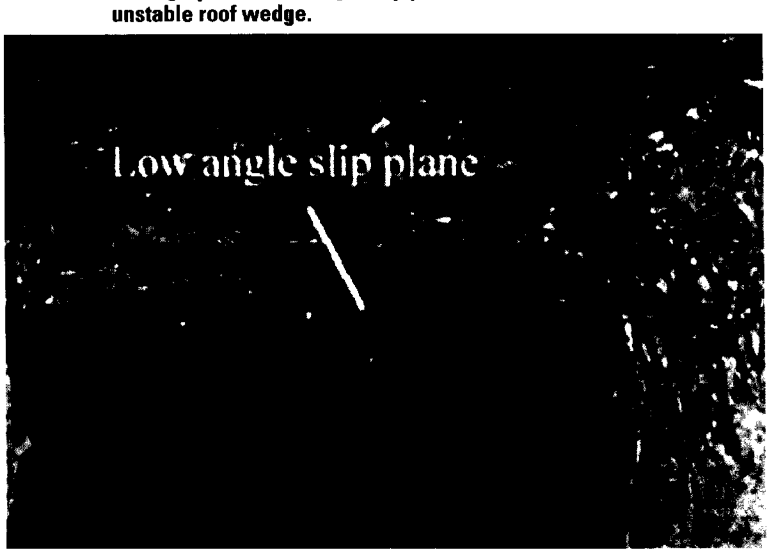


FIGURE 7

Photograph of a low-angle slip plane that created an unstable roof wedge.



tion, and mining smaller width rooms, possibly with arched openings in the bad direction, are methods that can help control horizontal-stress damage.

Geologic discontinuities. Joints are naturally occurring cracks or fissures present in all rock that are created by geologic processes or in place stress conditions. While it often seems as if there is no consistency associated with joint location, orientation and dip, a closer examination often reveals preferential characteristics. Knowing what these preferential characteristics are allows for planning that can reduce long-term roof and rib instability problems.

There are many techniques available to measure joint orientation, dip and spacing, but, for the miner, one instrument has provided reliable information with minimal cost and implementation. That instrument is the pocket or Brunton compass with the following essential features: a magnetic needle, a graduated surface, a "bull's-eye" level, a level tube and a line-of-sight viewing capability.

The display of joint orientation and dip data using simplified graphical solutions is the preferred means of evaluating large amounts of measurement data. The stereographic and histogram projection techniques are recommended for graphical display. Because most of the field applications in stone mining involve vertical joints with dips approaching 90°, a simple histogram plot provides an excellent means of evaluating preferential joint trends. A histogram uses rectangular bars to represent frequency, where the width of each rectangle represents a band of orientations (usually in bands of 5° to 10°), and the height of each rectangular bar represents the frequency of joints within that band (Fig. 6).

Rock joints pose special problems when they are closely spaced, <0.5 m (1.6 ft), and their orientations match those of the maximum unsupported spans found within mine entries. Joints also play a very important role in initiating rib instability, especially when benching operations lower the width-to-height ratio of supporting pillars. Once the orientation and dip of the joints have been determined, the spacing of the major joint trends should be determined. Spacing is a major concern in determining the size of the mine room along with the determination of roof-bolt patterns and the need for additional support like screening.

Cross-bedding features (low-angle, relatively short natural breaks in the strata) were found to be particularly important in scaling operations and rib control. In general, when cross bedding is present, these strata breaks are from 0.3 to 2 m (1 to 6 ft) apart and are capable of producing dangerous loose wedges of roof rock (Fig. 7). Scaling procedures must concentrate on removing as many of these wedges as soon as possible.

Solution related failures such as weathered joints and sink holes occasionally occur in limestone mines near the formation outcrop, under <30 m (100 ft) of overburden (Iannacchione et al., 1995). Solution failures are caused by water dissolving limestone along joint surfaces that sometimes develop into silt filled cavities or voids (sink holes). In general, vertical weathered joints isolate large unsupported blocks in the roof beam. Optimization of mine layouts can minimize unsupported spans. These optimization techniques consist of altering room widths, staggering crosscuts, and changing entry orientations to minimize the occurrence of unsupported roof beams. In new mine developments, joint patterns and locations should be known and considered so that portals are not later subjected to unstable conditions brought on by weather changes.

Conclusions

Roof and rib hazards represent a significant safety concern for underground stone mines. These hazards can be reduced by proper assessment and utilizing techniques that minimize strata instabilities. These assessment techniques consist of finding a stable roof beam, selecting a stable roof line and designing a safe mine layout specific to local stress, geologic and mining conditions. A stable roof beam should be massive, strong, persistent, weather resistant and as thick as required. If several stable roof beams exist, the one that provides a persistent, smooth roof profile should be selected. If the stable roof line does not exist, a smooth roof profile should then be developed using drilling and blasting techniques. After determining the optimal mining horizon, safe mine layouts need to be evaluated. The shape, size and orientation of mine structures should be designed to minimize stress and geologic related hazards. These roof and rib hazard assessment techniques can be used to develop stable mine structures and minimize roof, rib and face falls. ■

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