Assessment of stable and failed pillars in underground limestone mines

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Introduction

Underground limestone mines in the United States make use of the room-and-pillar method of mining to extract the relatively flat-lying limestone deposits in the Eastern and Midwestern regions of the United States. Limestone pillars are required to support the overburden and to provide a safe, stable working environment for mining personnel and equipment. Unstable pillars can result in rock falls from the pillar ribs and can lead to the collapse of the roof if one or more pillars should fail. Fall-of-ground injuries from the roof and pillar ribs accounted for about 15 percent of lost workdays in underground limestone mines from 1997 to 2006 (Mine Safety and Health Administration, 2007). Limestone pillars of various sizes and shapes are used to support the overburden rocks in U.S. limestone mines with varying degrees of success (Iannacchione, 1999; Esterhuizen et al., 2006).

This paper provides an assessment of the performance of these pillars as observed at 98 different locations in 34 mines in the Eastern and Midwestern regions of the United States. The results are presented in a stability chart that indicates the failed and stable pillars observed as well as the modes of observed instability. Data from one nonproducing mine in Ohio was added to the database, owing to its great depth of workings and reported stable pillar conditions (Bauer et al., 2005). Newly designed or current pillar layouts can be compared to the current experience by plotting them on the chart. An example is given in which a typical pillar layout is assessed using the chart data.

Abstract

Pillars in underground limestone mines are required to support the overburden and provide a safe, stable working environment for mining personnel and equipment. Pillar stability was assessed by the National Institute for Occupational Safety and Health in underground limestone mines in the Eastern and Midwestern United States. It was found that current mine layouts have been successful in providing support to the overburden, while a small number of isolated pillar failures were observed. The stable pillar layouts and failed pillars were plotted on a chart that demonstrates the relationship between pillar width-to-height ratio and pillar stress. The results show that pillar failures occurred at the lower range of width-to-height ratios and can occur at relatively low stress levels. Zones indicating the potential risk of pillar instability are shown on the chart, based on hazards associated with the onset of rib spalling, large angular discontinuities and unconfined pillars. The chart can assist limestone mine planners to evaluate potential instability in current or new pillar layouts that are similar to those included on the stability chart.

Observations of pillar stability

Pillars were assessed at underground limestone mines located in Illinois, Indiana, Iowa, Kentucky, Maryland, Missouri, Ohio, Pennsylvania, Tennessee and West Virginia. The pillar stability was evaluated at more than one location at each mine to capture the variety of geological and mining conditions. Two criteria were used to assess the success of the pillars. The first criterion is the requirement for regional stability, which is defined as the need for a pillar system to successfully support the overburden. If a pillar system fails in providing regional support, a wide area collapse is likely to occur with associated surface subsidence. The second criterion is the requirement for local pillar stability, defined as stable pillar ribs. Rib conditions were assessed by noting the presence of rib spalling, stress fractures or open cracks.

The presence of geological features such as joints, slips, faults and weak bedding planes was also recorded. Where unstable conditions or failed pillars were observed, the likely factors contributing to pillar instability were noted. In addition, pillar and room dimensions were measured and information on the depth of cover, extent of floor benching and other mining parameters collected. Mine maps were obtained so that the pillar loads could be calculated using the tributary area method or numerical models.

Rock samples were collected to determine the uniaxial compressive strength (UCS) of the rocks. The UCS results were grouped into three categories based on the average strength obtained at the individual mine sites and are shown in Table 1. It can be seen that there is a considerable variation in the strength of the limestone being mined. This variation in strength was accounted for in the assessment of pillar stability. Table 2 summarizes the dimensions and cover depth of the pillar layouts that were investigated.

The results of the survey showed that all the mine sites visited were successful in terms of the criterion for regional stability. No case of wide area collapse or signs of large areas of overloaded pillars were observed. However, a number of isolated failed pillars in otherwise stable layouts were observed. These isolated failed pillars are

FIGURE 1

Remaining stump of a collapsed pillar in an abandoned area. Thin weak beds in the pillar and moist conditions are thought to have contributed to the failure. The width-to-height ratio was 0.82, and the average pillar stress was about 11 percent of the UCS.

FIGURE 2

Pillar that has an original width-to-height ratio of 1.7 failed by progressive spalling. Thin weak beds are thought to have contributed to the failure. The average pillar stress was about 11 percent of the UCS prior to failure.

likely to be the lowest strength members of the pillars in a layout, and do not represent the average strength of the pillars. It was further observed that most of the failed pillars had been stable on initial mining but became unstable when the height was increased by floor benching.

The key parameters describing the unstable pillars are summarized in Table 3, and examples of the failed pillars are shown in Figs. 1 through 4. It can be seen that stress related rib slabbing and spalling is a feature in three of the four failed pillars shown. In addition, the weakening effects of angular discontinuities or thin weak bands within the pillars are clearly demonstrated.

The criterion for local stability was assessed by considering all cases where rib spalling or slabbing was observed. Figure 5 shows an example of rib spalling at approximately 900 ft of cover. It was found that rib spalling can initiate when the average pillar stress exceeds about 11 percent to 12 percent of the UCS. In some cases, it becomes necessary to install rib support, such as screen and bolts, to secure the rib walls. However, not all of the pillars that exceeded the 11 percent to 12 percent stress ratio showed signs of rib spalling. Therefore, 11 percent to 12 percent stress level should be interpreted as the lower limit for the onset of rib spalling. An assessment of the results further showed that instability caused by jointing or geological structures was not directly related to the pillar stress but was simply a function of the presence or absence of unfavorable geology.

Development of pillar stability chart

All data collected on pillar performance were collated in a spreadsheet, and a pillar stability chart was developed in which the pillar stress, normalized by the UCS, was plotted against the width-to-height ratio of the pillars, as shown in Fig. 6. The pillar dimensions used in this chart are the minimum pillar width and maximum pillar height. This means that the smaller width of a rectangular pillar and the maximum height of partially benched pillars were used in creating the chart. Where possible, dimensions are based on actual underground measurements. However, in the case of the failed pillars, it was not always possible to measure the original pillar dimensions and these were obtained from mine maps showing the original dimensions. The chart shows both stable pillar layouts and the individual failed pillars. The diameter of each stable layout data point is related to the number of pillars in the layout, and varies from tens of pillars to more than 1,000 pillars in some of the cases. The failed pillar data points, on the other hand, each represent only a single pillar.

A number of lines have been added to the chart to highlight potential failure mechanisms, while the background shading indicates the relative risk of pillar instability. Each of these lines and shaded zones are discussed below:

- Limit of experience: A curve that bounds the case histories was drawn to indicate the limit of current limestone pillar experience. It can be seen that the lower bound width-to-height ratio is about 0.25 at a low stress-to-strength ratio. The upper limit of stress is about 25 percent of the UCS. This curve simply bounds the current experience and does not represent a pillar strength equation.
- Unconfined pillar core: Studies of stress distributions within pillars (Lunder and Pakalnis, 1997; Esterhuizen, 2006) show that when the width-to-height ratio decreases below a value of about 0.8, the core of the pillar becomes unconfined. Because much of the strength of a pillar is derived from the confined core, the lack of confinement can result in reduced pillar strength. Notably, about 75 percent of the observed failed pillars had width-to-height ratios of less than 0.8. A review of failed pillar data in hard rock mines (Lunder and Pakalnis, 1997; Martin and Maybee, 2000; Esterhuizen, 2006) showed that pillar strength is highly variable at these low width-to-height ratios. Factors that can contribute to the variable strength include the sensitivity of slender pillars to the presence of unfavorable geological structures and the phenomenon of rock

FIGURE 3

Partially benched pillar failing under elevated stresses at the edge of bench mining. Typical hourglass formation indicating overloaded pillar. Width-to-height ratio was 0.44 based on full benching height and average pillar stress was about 12 percent of the UCS.

FIGURE 4

Partially benched pillar that failed along two angular discontinuities. Width-to-height ratio is 0.58 based on full benching height and average pillar stress is about 4 percent of the UCS.

splitting parallel to the applied load in low confinement (Diederichs, 2002). Splitting and slabbing of limestone was observed at stress levels that are only less than 12 percent of the UCS of the rock (Iannacchione, 1999), which indicates that pillar strength might be significantly reduced in the absence of confinement.

- The onset of spalling: As discussed earlier, spalling and slabbing of pillar ribs was observed to start when the average pillar stress was around 11 percent to 12 percent of the UCS. Spalling represents an additional rock-fall hazard that must be addressed when mining. Limited spalling can typically be addressed by repeated scaling of pillar ribs. In cases of severe spalling or slabbing of a pillar ribs, it has been necessary to support the ribs with screen and rock bolts where long-term access is required.
- Angular discontinuity hazard: Angular discontinuities that are exposed on both sides of a pillar can cause a significant reduction in the strength of a pillar. Figure 7 shows a pillar that was severely compromised by an angular discontinuity. It was necessary to install long rock bolts right through the pillar to prevent it from failing. During the survey of pillar conditions, large angular discontinuities were observed in several mines, but did not appear to be widespread within the limestone formations currently being mined. When the width-to-height ratio of a pillar is less than 1.5, a discontinuity with a dip of 30° can be exposed on both sides of the pillar. When designing pillars in this zone, the potential for encountering unfavorable angular discontinuities should be considered.

Table 1

Uniaxial compressive strength of limestone rocks collected at mine sites.

Group	Average, psi	Range, psi	Samples tested	Representative limestone formations
Lower strength	12,800	6,400-20,800	50	Burlington, Salem, Galena-Plattesville
Medium strength	19,600	11,900-30,000	100	Camp Nelson, Monteagle, Plattin, Vanport, Upper Newman, Chickamauga
High strength	31,800	22,000-43,700	32	Loyalhanna, Tyrone

The shaded zones in Fig. 6 indicate the relative risk of instability based on a qualitative assessment of the likelihood and consequences of pillar instability. Darker shading indicates a relatively higher risk. The following four risk zones are indicated:

- Very low risk: No failed pillars or stress related rib instability was found in this zone. Pillar layouts that plot within this zone can, therefore, be expected to have a very low risk of failure.
- Low risk: A few isolated cases of pillar instability were observed within this zone. Pillars should be designed with due consideration of the potential for rib spalling and pillar weakening by large discontinuities.
- Moderate risk: Two moderate-risk zones are indicated. Pillars that plot near the upper part of the experience curve are subject to increasing stress and there is limited experience with pillar performance at those stress magnitudes. Slender pillars with width-to-height ratios of less than 0.8 are vulnerable to the effects of large angular discontinuities and the lack of confinement.

FIGURE 5

Example of rib slabbing when the average pillar stress exceeds about 11 percent of the UCS.

Several failed pillars were observed within this zone.

- High risk: Pillars within the high-risk zone are potentially exposed to a combination of increasing stresses, rib spalling, large discontinuity hazards and the lack of confinement. In addition, pillars that fall outside the limit of current experience are considered to represent an elevated risk. Several of the single failed pillars fall within the high-risk zone.

It can be seen that many of the stable pillar layouts shown in the chart fall within one or more of the shaded zones. These zones do not imply that the pillar layouts are necessarily unstable, but rather indicate the types of stability hazards that might be encountered and that would need to be accounted for in the design and during the course of mining.

Table 2

Summary of mining dimensions and cover depth of mines included in study.

Dimension	Average	Minimum	Maximum
Pillar width (ft)	43.0	15.0	70.5
Pillar height (ft)	36.5	15.8	124.6
Width-to-height ratio	1.41	0.29	3.52
Cover depth (ft)	385	75	2,200

Example of applying the stability chart to assess a pillar layout

Consider a new limestone mine in the Midwestern United States that will use 40-ft-wide square pillars on 80-ft centers with 40-ft wide headings and crosscuts. The pillar height on development will be 28 ft. Benching of an additional 28 ft of floor stone is planned, which will result in an ultimate pillar height of 56 ft. The initial width-to-height ratio will, therefore, be 1.43, reducing to 0.71 after floor benching. The UCS of the rock is 140 MPa (20,000 psi). If the maximum depth of cover is 300 ft, the average pillar stress in square pillars can be estimated using the tributary area method

$$\sigma_p = 1.1h\frac{(w+b)^2}{w^2} \tag{1}$$

where

σ_p is the average pillar stress in pounds per square inch,

h is the depth of cover,

w is the pillar width and

b is the room width in feet.

The average pillar stress for the example is calculated to be 9.10 MPa (1,320 psi), which is 6.6 percent of the

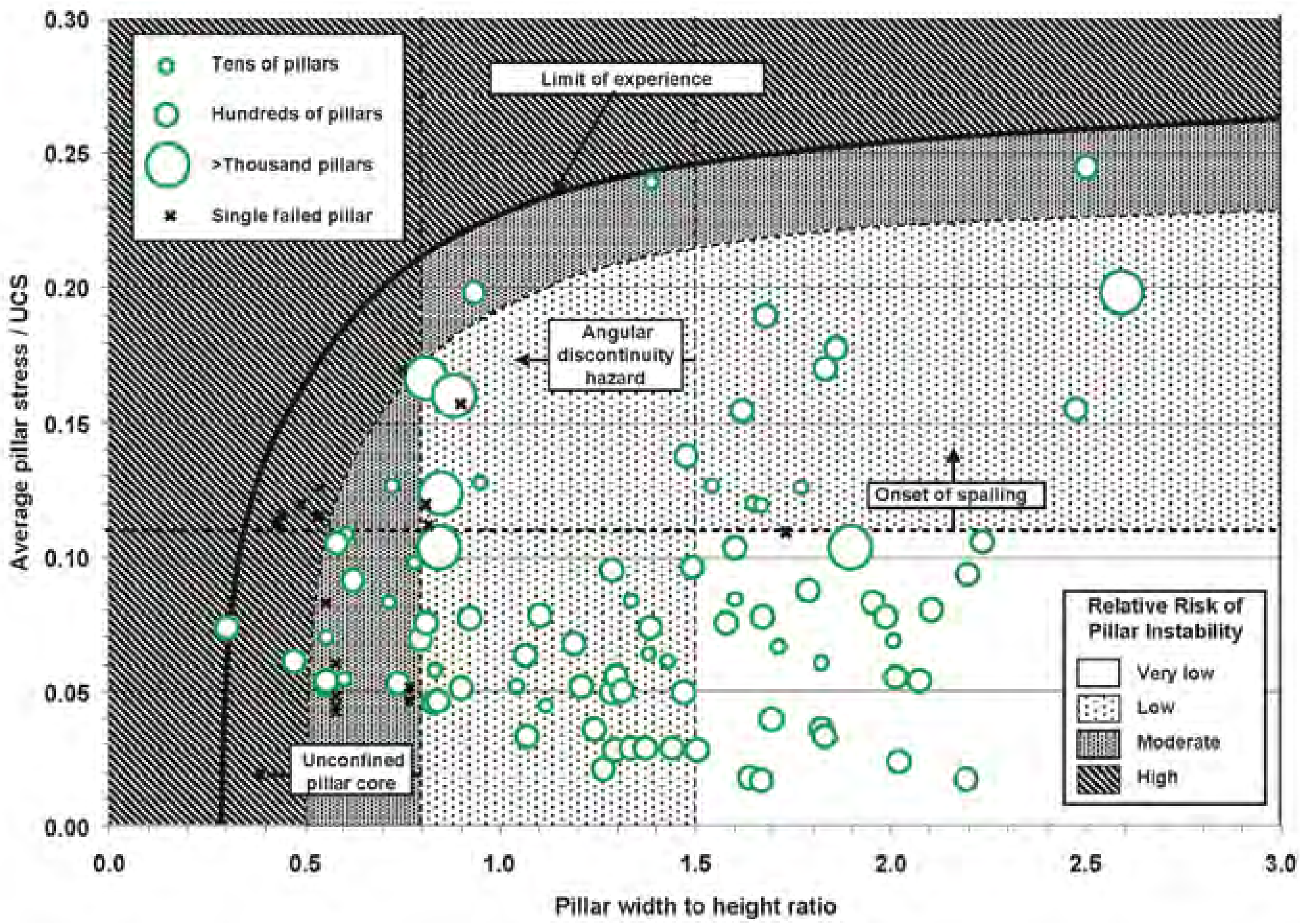
Table 3

Summary of observed failed pillars.

Case	Pillar width, ft	Pillar height, ft	Width-to-height, ratio	Average pillar stress, psi	Rock strength, psi	Factors contributing to pillar failure
1	35	60	0.58	1,305	31,175	Partially benched pillar, contains angular discontinuities
2	35	60	0.58	1,363	31,175	Partially benched pillar, contains angular discontinuities
3	35	60	0.58	1,494	31,175	Partially benched pillar, contains angular discontinuities
4	50	90	0.56	1,827	22,185	Pillar fully benched to 90-ft height reduced width-to-height ratio
5	35	60	0.58	1,856	31,175	Benched pillar, contains angular discontinuities
6	40	90	0.44	2,494	21,750	Partly benched pillar
7	28	52	0.54	2,494	21,750	Large steep dipping discontinuity and elevated stress ahead of benching
8	40	90	0.44	2,509	21,750	Partly benched pillar
9	26	32	0.81	2,755	23,200	Thin weak beds in limestone, pillar undersized causing elevated stress
10	42	24	1.73	2,525	23,200	Thin weak beds in pillar causing progressive spalling
11	41	50	0.82	2,583	23,200	Thin weak beds in pillar and moist conditions, pillar collapsed
12	20	40	0.49	2,755	23,200	Benched pillar is undersized causing elevated stresses
13	22	40	0.54	2,900	23,200	Benched pillar is undersized causing elevated stresses
14	12	28	0.43	3,495	31,175	Undersized pillar
15	27	30	0.90	3,625	23,200	Thin weak beds in pillar caused progressive slabbing
16	18	24	0.75	3,915	23,200	Undersized pillar subject to elevated stress
17	40	52	0.77	1,220	23,900	Partially benched pillar, contains angular discontinuities
18	40	52	0.77	1,100	23,900	Partially benched pillar, contains angular discontinuities

FIGURE 6

Limestone pillar stability chart showing stable pillar layouts and single failed pillars. Potential failure mechanisms and relative risk of pillar instability are indicated.



UCS. This point plots within the "Low Risk" zone in Fig. 6. The pillars should be free of stress related rib spalling during initial mining but unfavorable angular discontinuities can compromise their strength. A geotechnical investigation might be warranted to confirm or refute the presence of such structures. The chart further shows that after bench mining to a height of 56 ft, the pillars will plot within the "Moderate Risk" zone because the pillar cores will become unconfined in addition to being vulnerable to large angular discontinuities. It might be prudent to reduce the bench height to 20 ft for example, which will increase the benched pillar width-to-height ratio to 0.83. This will reduce the potential for instability of the benched pillars.

Conclusions

The assessment of pillar conditions in U.S. limestone mines has shown that:

- pillars in current mining operations have been successful in providing support to the overburden and preventing wide area pillar collapse and associated surface subsidence;
- pillar rib instability in the form of spalling or stress related slabbing appears to initiate when the average pillar stress exceeds about 11 percent of the uniaxial compressive strength of the rock; and
- a small number of isolated failed pillars were observed in otherwise stable layouts.

Factors contributing to the isolated pillar failures included unfavorably oriented geological structures and elevated stress levels in undersized pillars. Stress related pillar failures were associated with progressive slabbing and spalling of pillar ribs. Unfavorable geology, such as angular discontinuities in the pillars and thin weak beds in the limestone formation, contributed to failure in some cases. Notably, about 75 percent of the observed failed pillars have width-to-height ratios of less than 0.8.

A pillar stability chart developed from the data shows that a limiting curve can be drawn that encloses the observed cases. The limiting curve does not represent a pillar strength equation, but simply bounds the current pillar experience. The potential failure mechanisms and relative risk of pillar instability have been indicated on the chart, based on observations and analysis of pillar performance. The chart and the indicated stability zones can assist mine designers in anticipating stability issues in their pillar layouts and implementing appropriate risk mitigation measures.

As a cautionary note, the stability chart is based on observations of limestone mine pillars in the Midwestern and Eastern United States and should not be used to assess pillar stability in cases outside of this geographic area. In addition, the validity of the chart is limited to pillar cases that have similar dimensions, rock strength and depth of cover as those used to develop the chart.

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FIGURE 7

Example of a pillar that is bisected by a large angular discontinuity.