TOWARD PILLAR DESIGN TO PREVENT COLLAPSE OF ROOM-AND-PILLAR MINES

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ABSTRACT

In some instances, extensive room-and-pillar workings can collapse with little warning and pose a serious risk to underground miners. Traditional strength-based pillar design methods applicable to coal or hard-rock mines use a factor of safety defined as pillar strength divided by pillar stress. Factor of stability, defined as local mine stiffness divided by post-failure pillar stiffness, may offer a way to design room-and-pillar mines and eliminate collapses. Three alternative design approaches to decreasing the risk of large-scale catastrophic collapses are described: the containment approach, the prevention approach, and the full-extraction approach. Until good data on the post-failure behavior of pillars become available, the containment and full-extraction options are the safest. The limitations in our ability to evaluate both the stability of old workings and the long-term performance of room-and-pillar mines are described.

INTRODUCTION

Room-and-pillar mining accounts for a significant portion of the total mineral production in the United States As shown in table 1, well in excess of $6 billion worth of mineral commodities are produced each year by this method. A substantial portion ($3.55 billion) of coal production still comes from room-and-pillar mining. Metallic minerals valued at about $1 billion, plus nonmetallic minerals valued well in excess of $1 billion, are also produced via room-and-pillar mining. A significant ($600 million) and growing portion of stone and aggregate production uses room-and-pillar mining. In addition, many other mineral commodities not noted in this table (talc, iron, copper) are or have been produced in the United States using the room-and-pillar technique.

The objective of this paper is to show mine layouts for selected coal, metal, and nonmetal mines that have experienced large-scale, catastrophic pillar collapse. Basic pillar mechanics are reviewed along with the important factors that govern stability. Finally, alternative design approaches are discussed that decrease the risk of catastrophic collapse. Research issues related to collapse of room-and-pillar mines are summarized.

If the strength of a pillar in a room-and-pillar mine is exceeded, it will fail, and the load that it carried will be transferred to neighboring pillars. The additional load on these pillars may lead to *their* failure. This mechanism of pillar failure, load transfer, and continuing pillar failure can lead to the rapid collapse of very large areas of a mine. In some cases, only a few tens of pillars might fail; however, in extreme cases, hundreds, even thousands, of pillars can fail. This kind of failure has many names—progressive pillar failure, massive pillar collapse, domino-type failure, or pillar run. Swanson and Boler (1995) coined the term “cascading pillar failure,” or CPF, to describe these rapid pillar collapses. A recent review by Zipf (in press) provides some documentation on 21 instances of large-scale pillar collapses in room-and-pillar mines, mainly in the United States

CPF can have catastrophic effects on a mine, and sometimes these effects pose a greater health and safety risk than the underlying ground control problem. Usually, the CPF induces a devastating airblast caused by displacement of air during the collapse. An airblast can totally disrupt the ventilation system at a mine by destroying ventilation stoppings, seals, and fan housings. Flying debris can seriously injure or kill mining personnel. CPF might also fracture large volumes of rock in the pillars and the immediate roof and floor, leading to the sudden release of large quantities of methane into the mine atmosphere and possibly a methane explosion.

Table 1 – Value and production by room-and-pillar mining in the United States

Commodity	Total U.S. production, tons	Room-and-pillar mining: Percentage	Room-and-pillar mining: Tonnage	Room-and-pillar mining: Value, million U.S. dollars	Typical extraction, %
Coal[1]	1,014,000,000	20	202,000,000	$3,550	60
Lead[2]	493,000	90	444,000	$432	75
Zinc[2]	722,000	60	433,000	$491	75
Soda ash[2]	10,100,000	80	8,000,000	$664	65
Potash[2]	1,300,000	100	1,300,000		50
Salt[2]	40,800,000	60	32,000,000		50
Gypsum[2]	19,000,000	50	9,000,000	$66	75
Stone and aggregate[3]	1,200,000,000	10	120,000,000	$600	75

[1] National Mining Association, Coal Data, 1999. [2] U.S. Geological Survey, National Mineral Surveys, 1998. [3] National Stone Association, The Aggregate Handbook, 1996.

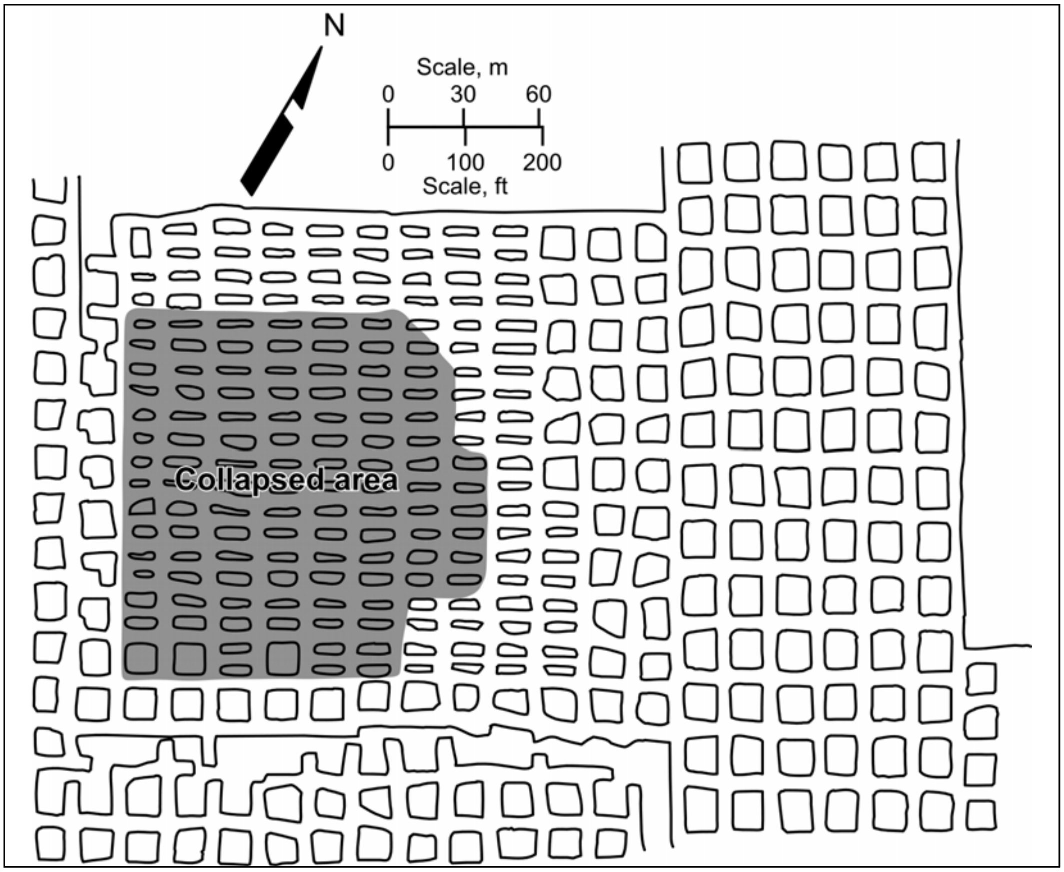

Figure 1.—Mine layout for coal mine collapse 1 (Chase et al. 1994)

Many case histories exist of CPF in coal mines. The most infamous example is the Coalbrooke Colliery in South Africa where 437 miners perished when 2 km^2 of the mine collapsed within a few minutes on January 21, 1960 (Bryan et al., 1964). During the 1990's, U.S. coal mines had at least eight of these failures (Zipf, in press). Recent reports from India (Sheorey et al., 1995) and Australia (Galvin, 1992) indicate that catastrophic pillar collapses and the associated airblasts have caused problems there as well.

Chase et al. (1994) documented a massive pillar collapse. Figure 1 shows the mine layout and collapse area. Seam thickness was about 3 m. Using 6-m-wide rooms, a system of 12-m^2 pillars with a width-height ratio of 4 was developed on advance. On retreat, these pillars were split down the middle with a 6-m-wide room to leave two 3-m-wide fenders having a width-height ratio of 1. The mine had split about nine rows of pillars with this method when a CPF occurred, causing seven rows of fenders to fail. The airblast destroyed 26 stoppings and caused one injury. The extraction ratio in the failed area was about 78%.

A recent Mine Safety and Health Administration (MSHA) report (Richmond, 1998) describes another massive ground failure in a panel in the process of being secondarily mined by pillar splitting. Figure 2 shows the mine layout and collapse area. Seam thickness was about 2 m. The collapse area measured approximately 180 by 460 m and occurred in a panel adjacent to a set of mains. Pillars in the mains were 12 by 18 m, and panel pillars were 9 by 18 m. The panel pillars were mined with a 6-m-wide split, leaving 6- by 9-m stumps having a width-height ratio of about 3. An array of approximately 9 pillars by 14 pillars collapsed. The airblast destroyed 23 stoppings plus the weakest wall of the fan house. Fortunately, there were no injuries. The extraction ratio in the failed area was about 70%.

Catastrophic pillar failures have also happened in many metal mines. At least four examples have occurred in the United States since 1972 (Zipf, in press). Dismuke et al. (1994) describe a large pillar collapse in a major section of a room-and-pillar base metal mine. Figure 3 shows the collapse area. The failure began in four centrally located pillars and spread rapidly to include almost 100 pillars. Pillar width was 8.5 m, and room width was 9.7 m. Pillar height was about 12 m for a width-height ratio of 0.70. The extraction ratio was about 78%. Damage caused by the airblast from the collapse was minor, and no one was injured.

The largest and most devastating examples of CPF have occurred in nonmetal mines. During the 1990's, U.S. nonmetal mines had at least five such failures (Zipf, in

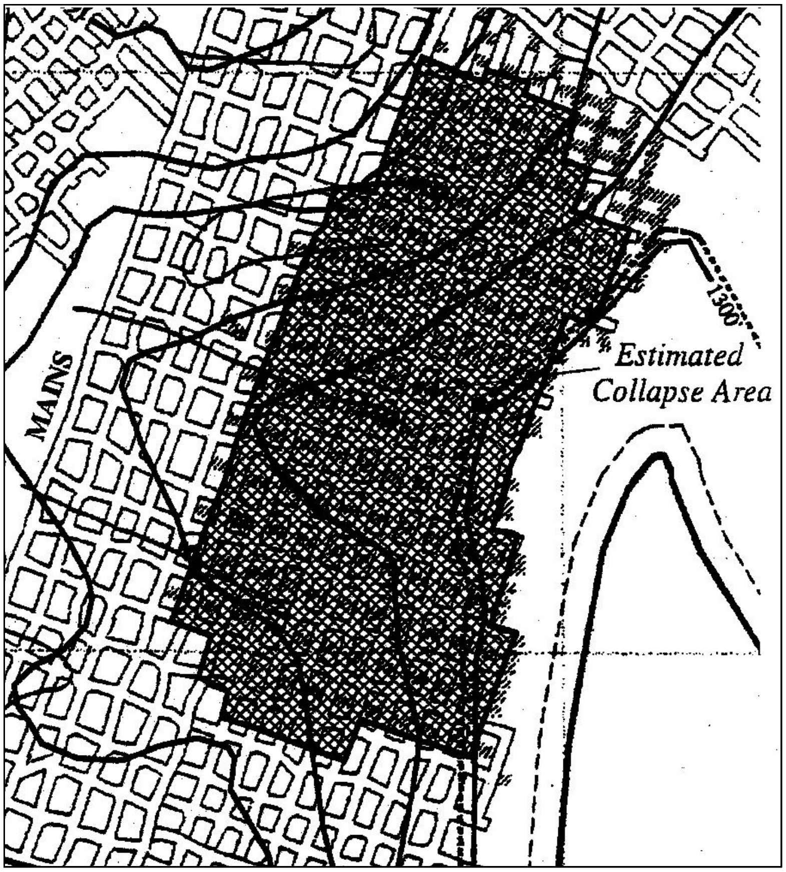

Figure 2.—Mine layout

for coal mine collapse 2 (Richmond 1998)

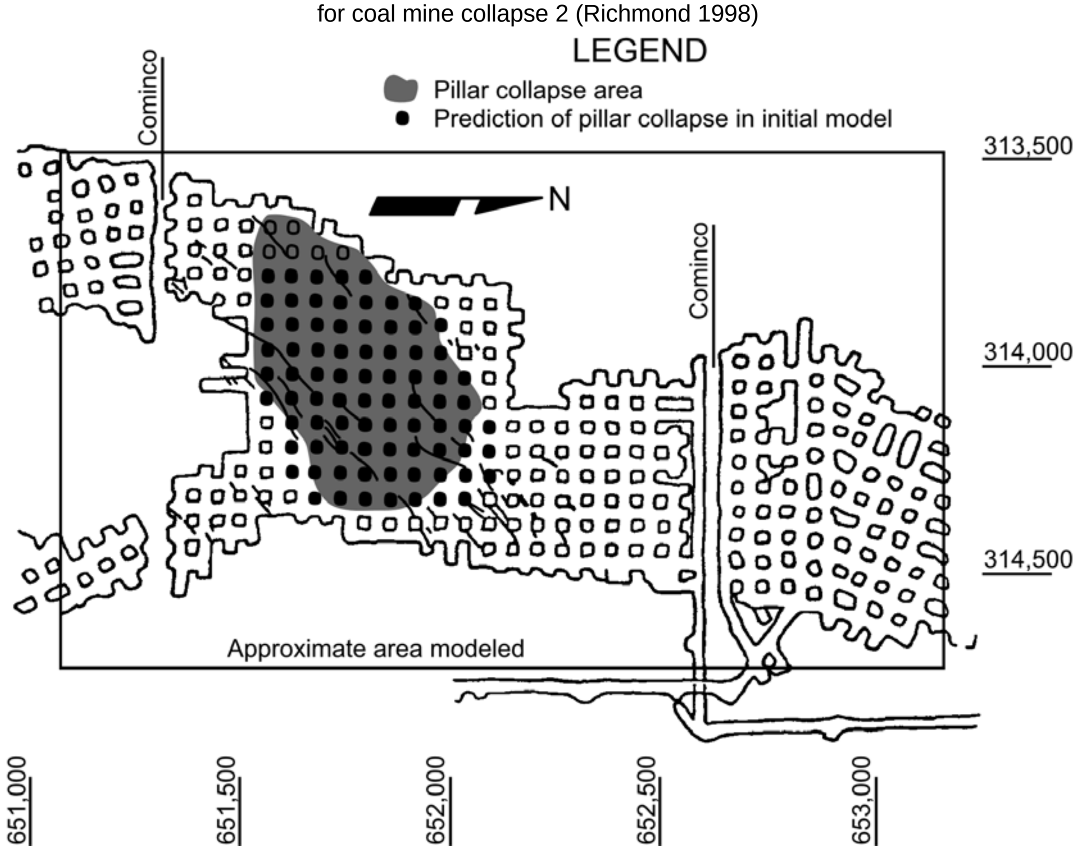

Figure 3.—Mine layout for metal mine collapse (Dismuke et al. 1994)

press). Swanson and Boler (1995) and Zipf and Swanson (1999) describe the mine geometry and aftermath of a collapse in a major evaporite mine. Figure 4 shows the layout for this mine. The bed mined had a thickness of about 2.85 m. During advance mining, a system of 12-m-wide chain pillars using 4.3-m-wide rooms was developed off a set of mains. At the same time, the rooms were mined down one side, leaving long, narrow, 3.8-m-wide panel pillars having a width-height ratio of 1.33. A small pillar about 7.6 m wide with a width-height ratio of about 2.66 was left between panels. On retreat, additional rooms were mined on the other side of the chain pillars. The mine achieved an overall extraction of about 60%; extraction within a panel was a little more than 70%.

Mines experiencing a cascading pillar failure generally exhibit the following characteristics.

(1) Extraction ratios are usually more than 60%. A high extraction ratio will put pillar stress close to peak strength and provide ample expansion room for the failed pillar material.

(2) Width-height ratios of pillars are always less than 3 for coal mine failures, usually much less than 1 in metal-mine failures, and less than about 2 for nonmetal mine failures. A low width-height ratio ensures that the failed pillar material can easily expand into the surrounding openings and that the failed pillar will have little residual load-bearing capacity.

(3) The number of pillars across the panel width is always at least five and usually more than 10, which typically ensures that pillars have reached their full tributary area load. Minimum panel widths for CPF are at least 80 m.

(4) Substantial barrier pillars with width-height ratios more than 10 are absent from the mine layout.

(5) Although CPF seems more prevalent in shallow mines less than 100 m deep, this may be only a reflection of the prevalence of shallow room-and-pillar coal mines.

TRADITIONAL STRENGTH-BASED PILLAR DESIGN METHODS

Traditional strength-based pillar design first requires an estimate of pillar stress and then an estimate of pillar strength. The factor of safety for the pillar is then evaluated as pillar strength divided by pillar stress. An acceptable safety factor depends on the tolerable risk of failure. A safety factor of 2 is typical for pillars in main development headings or panels during advance mining. Safety factors of 1.1 to 1.3 are typical for panel pillars after retreat mining. Safety factors much less than 1 are possible within panels where pillar failure is the intent.

Estimating pillar stress first requires an estimate of in situ vertical stress as $\sigma_V = \gamma z$, where γ is the unit weight of rock and z is depth to the mining horizon.

The tributary area method (Farmer, 1992) then provides a first-order estimate of average pillar stress. The tributary area approach makes many simplifying assumptions: the mined area must be extensive, all pillars should have the same dimensions, and pillars at the edge of a panel should have the same stresses as those in the middle.

The method ignores the deformation properties of the surrounding rock mass relative to pillar rock along with any rock failure, such as pillar yielding and associated stress re-distribution. In actuality, pillars at the center of a panel have higher stress levels than pillars at the edge of a panel. Quasi-three-dimensional, boundary-element programs such as Examine[TAB] (2000), MULSIM/NL (Zipf, 1992a, 1992b) and LAMODEL (Heasley, 1997, 1998) can provide reasonable estimates of pillar stresses across a panel or within an individual pillar.

Over the past several decades, a large amount of rock mechanics literature has addressed pillar strength in both coal and metal/nonmetal mines (Obert and Duvall, 1967; Hoek and Brown, 1980; Bieniawski, 1992; Mark and Iannacchione, 1992; Brady and Brown, 1993; Mark, 1999). Much of this work is empirical and has addressed two issues—the size effect whereby rock strength decreases as specimen size increases and the shape effect whereby rock strength increases as the width-height ratio increases.

Classic empirical pillar strength formulas usually follow one of two general forms.

$$\sigma_P = \sigma_{S'}\left(a + b\frac{W}{H}\right)$$

or

$$\sigma_P = K\frac{W^{\alpha}}{H^{\beta}}$$

Pillar strength formulas by Obert and Duvall (1967) and Bieniawski (1968) follow the first form, whereas formulas by Salamon and Munro (1967) and Holland (1964) follow the second. In these forms, size effect is accounted for directly via the unit pillar strength $\sigma_{S'}$ or the rock constant K. $\sigma_{S'}$ is the strength of a cubical pillar (width-height = 1) at or above the critical size, and K is a constant characteristic of the pillar rock. For most U.S. coal, Mark (1999) recom-mends 6.2 MPa for $\sigma_{S'}$. In the Bieniawski formula, the constants a and b are 0.64 and 0.36, respectively.

Traditional strength-based pillar design methods can determine panel pillar size directly. Operational considera-

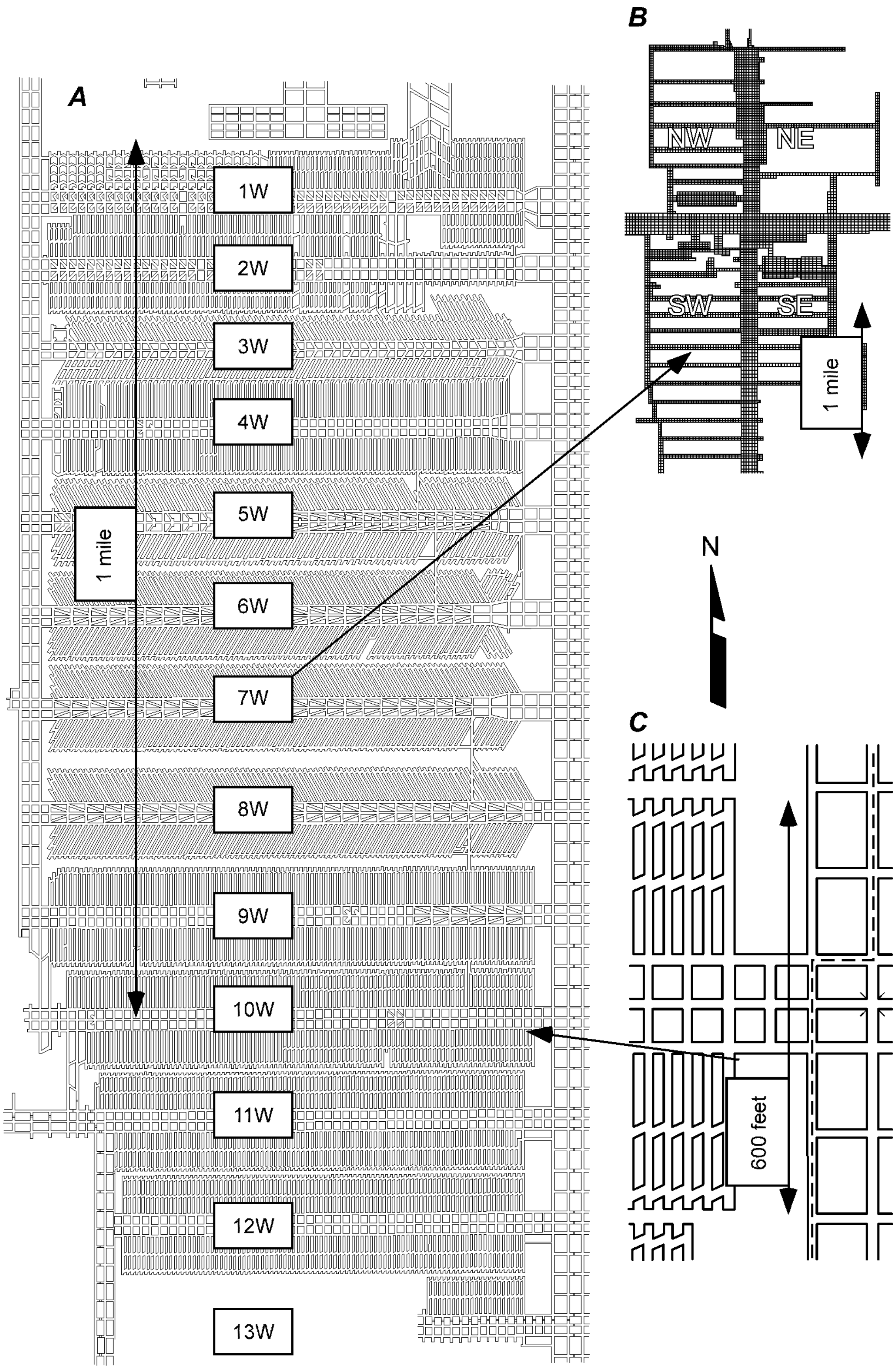

Figure 4.—Mine layout for evaporate mine collapse (MSHA 1996). *A,* Overall layout for part of mine; *B,* layout of southwest panels; *C,* details of typical panel

tions such as equipment and productivity requirements frequently set the panel width, and usually it is set large. Barrier pillar width will then depend on panel width. Based on strength considerations alone, a narrow panel will require a narrow barrier pillar and a wide panel will require a wide barrier pillar. Rock mechanics factors such as the strength and deformability of the rock mass do not into enter panel width determination with the traditional strength-based design methods. Other rock mechanics considerations are needed to determine maximum panel width rationally along with panel pillar and barrier pillar sizes.

STABILITY-CRITERION-BASED PILLAR DESIGN METHODS

Understanding CPF requires more than just understanding pillar strength and applied pillar stress of the traditional strength-based pillar design method using factor of safety. The underlying mechanics of CPF are more complex. The nature of the pillar failure process depends on the relative magnitude of certain mechanical properties of the rock mass and the pillar.

A rock specimen loaded in a laboratory test frame is analogous to a mine pillar loaded by the surrounding rock mass. Based on this analogy, Salamon (1970) developed a stability criterion that determines whether the failure process occurs in a stable, nonviolent or in an unstable, violent manner. Figure 5 illustrates the criterion. Stable, nonviolent failure occurs when

$$\left|K_{LMS}\right| > \left|K_P\right|$$

and unstable, violent failure occurs when

$$\left|K_{LMS}\right| < \left|K_P\right|$$

where $\left|K_{LMS}\right|$ is local mine stiffness and $\left|K_P\right|$ is post-failure stiffness at any point along the load-convergence curve of the pillar.

In the traditional strength-based pillar design method, pillars are sized using a factor of safety, which is defined as pillar strength divided by pillar stress. Stability-criterion-based pillar design methods also consider a factor of stability, which is defined as the local mine stiffness (K_{LMS}) divided by post-failure pillar stiffness (K_P). Considering the factor of stability leads to three different approaches to controlling large collapses in room-and-pillar mines: containment, prevention, and full extraction.

Containment

In the containment approach, shown in Figure 6, an array of panel pillars that violate the local mine stiffness stability criterion and can therefore fail in an unstable, violent manner if their strength criterion is exceeded are surrounded or "contained" by barrier pillars. The panel pillars have a factor of safety greater than 1, but the factor of stability is less than 1. The primary function of barrier pillars is to limit potential failure to just one panel. Barrier pillars have a high width-to-height ratio, typically greater than about 10, and contain panel pillars with a low width-to-height ratio, typically in the 0.5 to 2 range. It is a noncaving room-and-pillar method in that panel pillars are not meant to fail during retreat mining. Applying the containment approach does not explicitly require evaluation of the factor of stability, hence calculation of local mine stiffness, and good data on the post-failure stiffness of pillars are not required.

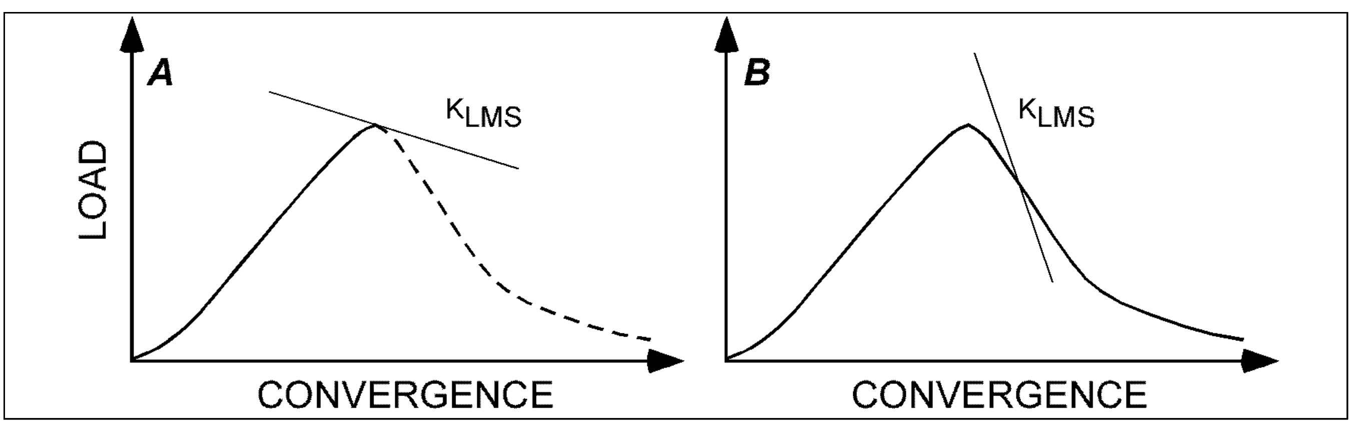

Figure 5.—Unstable violent failure versus stable nonviolent failure. *A*, Unstable failure in a soft loading system. Loading machine stiffness is less than post-failure stiffness. *B*, Stable failure in a stiff loading system. Loading machine stiffness is greater than post-failure stiffness. (Swanson and Boler, 1995)

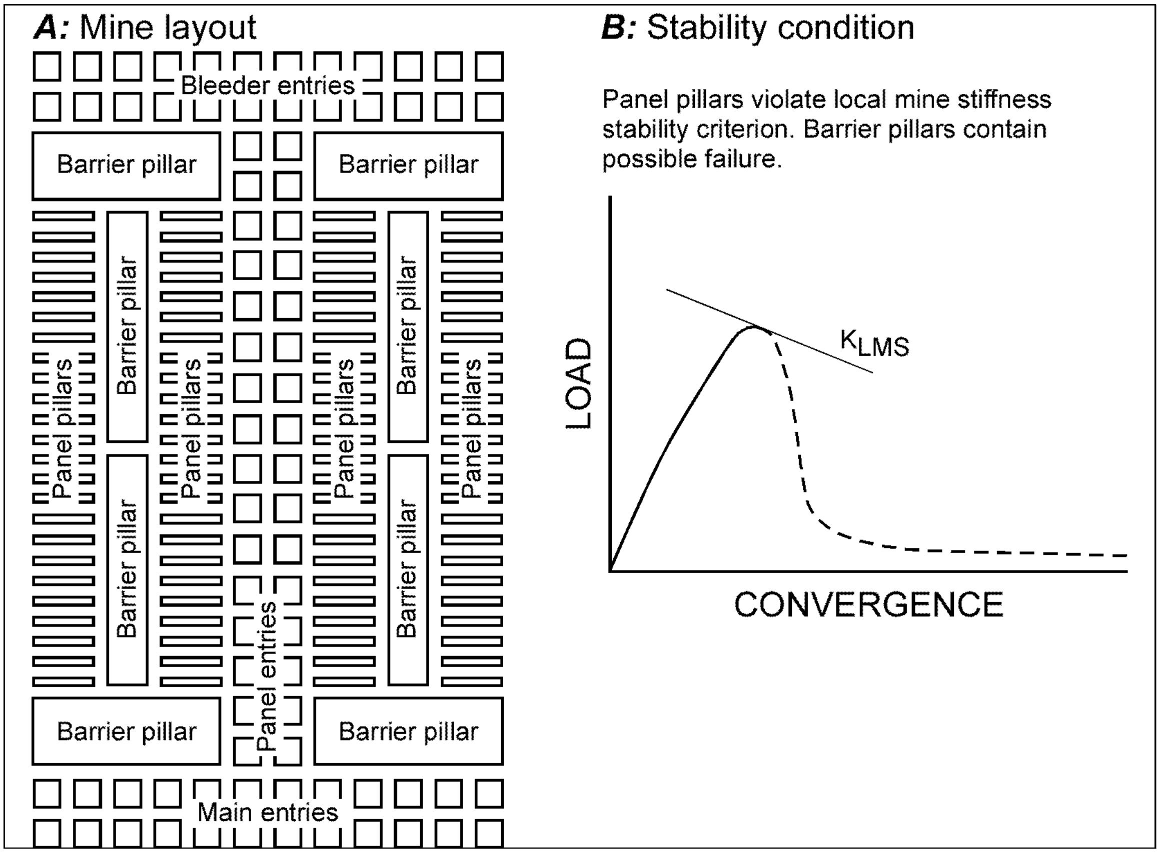

Figure 6.—Containment approach to room-and-pillar layout. *A,* Mine layout. Pillar failure is compartmentalized. *B,* Stability condition is such that pillars with low width-height ratios violate the local mine stiffness stability criterion, and a panel can fail violently. Adequate barrier pillars that restrict the spread of unstable failure surround them. Extraction for layout shown is 59%.

Prevention

In contrast to the containment approach, the prevention approach shown in Figure 7 "prevents" CPF from ever occurring by using panel pillars that satisfy both the local mine stiffness stability criterion and a strength criterion. The factor of safety and the factor of stability for the panel pillars are both greater than 1. Therefore, panel pillars cannot fail violently, and CPF is a physical impossibility. Strictly speaking, this approach may not need barrier pillars to ensure overall stability against CPF; however, their use is still advisable. To satisfy the local mine stiffness stability criterion, the panel pillars will usually have high width-height ratios (greater than about 3 or 4) and high strength safety factors as well (greater than 2). Another approach to increase local mine stiffness and satisfy the stability criterion is to limit panel width with properly spaced and sized barrier pillars. Applying the prevention approach requires evalua-tion of the factor of stability, calculation of local mine stiffness, and good data on the post-failure stiffness of pillars.

Full-Extraction Mining

The full-extraction approach shown in Figure 8 avoids the possibility of CPF altogether by ensuring total closure of the opening and full surface subsidence on completion of retreat mining. This approach does not require barrier pillars for overall panel stability; however, they are needed to isolate extraction areas and protect mains and bleeders. The factor of safety for the panel pillar remnants is much less than 1 to force them to fail immediately after retreat mining.

CONCLUSIONS AND RECOMMENDATIONS

CPF is a potential problem faced by all room-and-pillar mining operations. CPF occurs when one pillar fails suddenly, which then overstresses the neighboring pillars, causing them to fail in very rapid succession. Within seconds, very large mining areas can collapse while giving little or no warning. The collapse itself poses danger to miners. In addition, the collapse can induce a violent airblast that disrupts or destroys the ventilation system. Additional hazards to miners exist if the mine atmosphere becomes explosive as a result of a collapse. At least 17

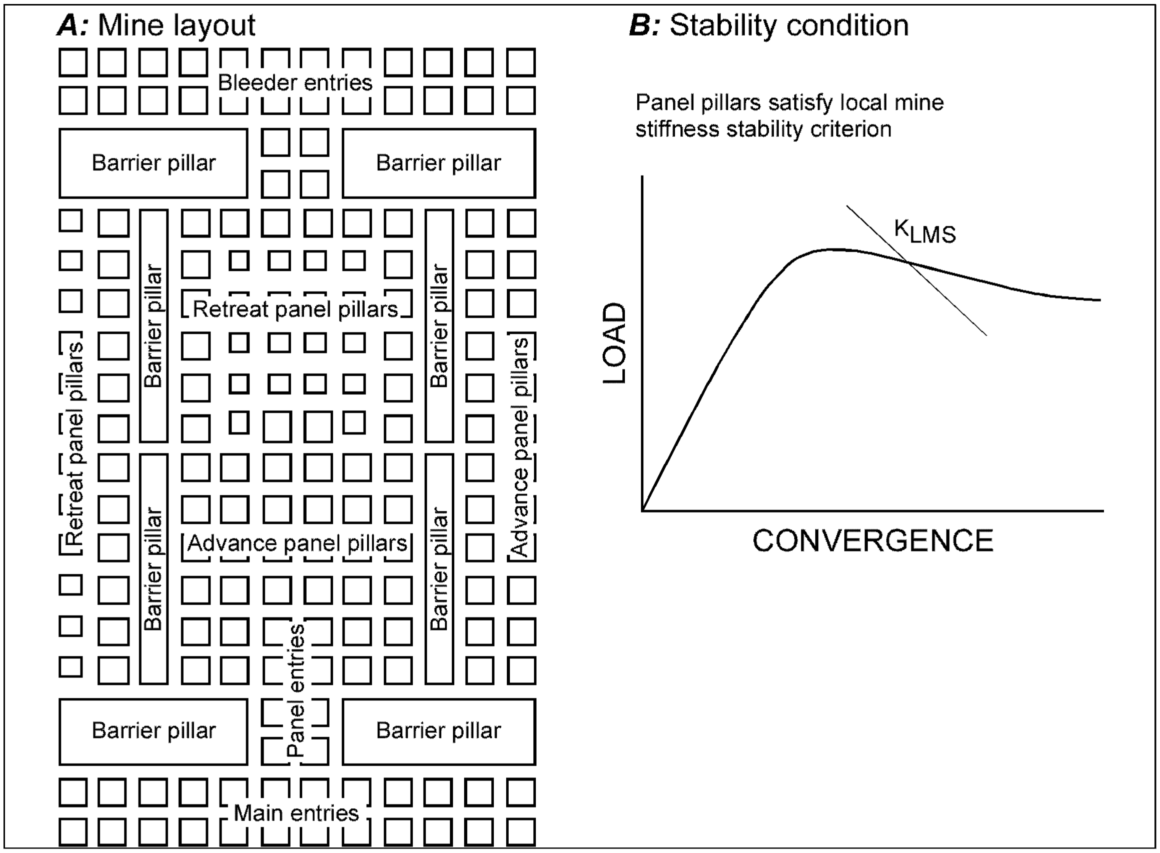

Figure 7.—Prevention approach. *A,* Mine layout. Unstable pillar failure is impossible because panel pillars with higher width-height ratios or a combination of panel and barrier pillars satisfy the local mine stiffness stability criterion. *B,* CPF is physically impossible. Extraction for layout shown is 63%.

collapses have occurred in the past 20 years in U.S. room-and-pillar mines (Zipf, in press).

Traditional strength-based design methods using a factor of safety are not sufficient to eliminate the possibility of CPF in room-and-pillar mines, and the number of documented collapses in the United States alone provides mute testimony to that statement. Pillar arrays with large average strength safety factors can fail in a CPF if just a few pillars in the array begin to fail. Pillars with large strength-based safety factors (for example 1.5) still have a finite probability of failure, and if the number of pillars in an array is large, failure somewhere in the array can become a near certainty, so that failure could in turn initiate CPF. Advanced rock mechanics considerations using the local mine stiffness stability criterion and a factor of stability are needed to design room-and-pillar mines that control CPF.

The mechanics of CPF are well understood. Strain-softening behavior is the essential mechanical characteristic of pillars that fail rapidly via this mechanism. Pillars that exhibit strain-softening behavior can undergo a rapid decrease in load-bearing capacity upon reaching their ultimate strength. The strain-softening behavior of pillars depends on both inherent material properties and geometry. Pillars with a low width-height ratio exhibit a greater degree of strain-softening behavior than pillars with a higher width-height ratio and typically elastic-plastic or strain-hardening material behaviors.

While the principles behind CPF are fairly well understood, there are significant gaps in our ability to evaluate the stability of existing room-and-pillar mines and assess the performance of alternative mine layouts. The limitations stem from a lack of

(1) Field data on the complete stress-strain behavior of full-scale mine pillars,

(2) Material property data under dynamic loading conditions, and

(3) Simple assessment techniques to delineate and monitor how stresses are transferred among panel pillars, barrier pillars, and solid abutments.

Such rock mechanics knowledge is critical for utilizing the design approaches suggested. Large mine collapses can pose enormous safety hazards to miners and room-and-pillar mining operations. Of the three alternative design approaches described to decrease the risk of large-scale catastrophic collapses, containment and full extraction

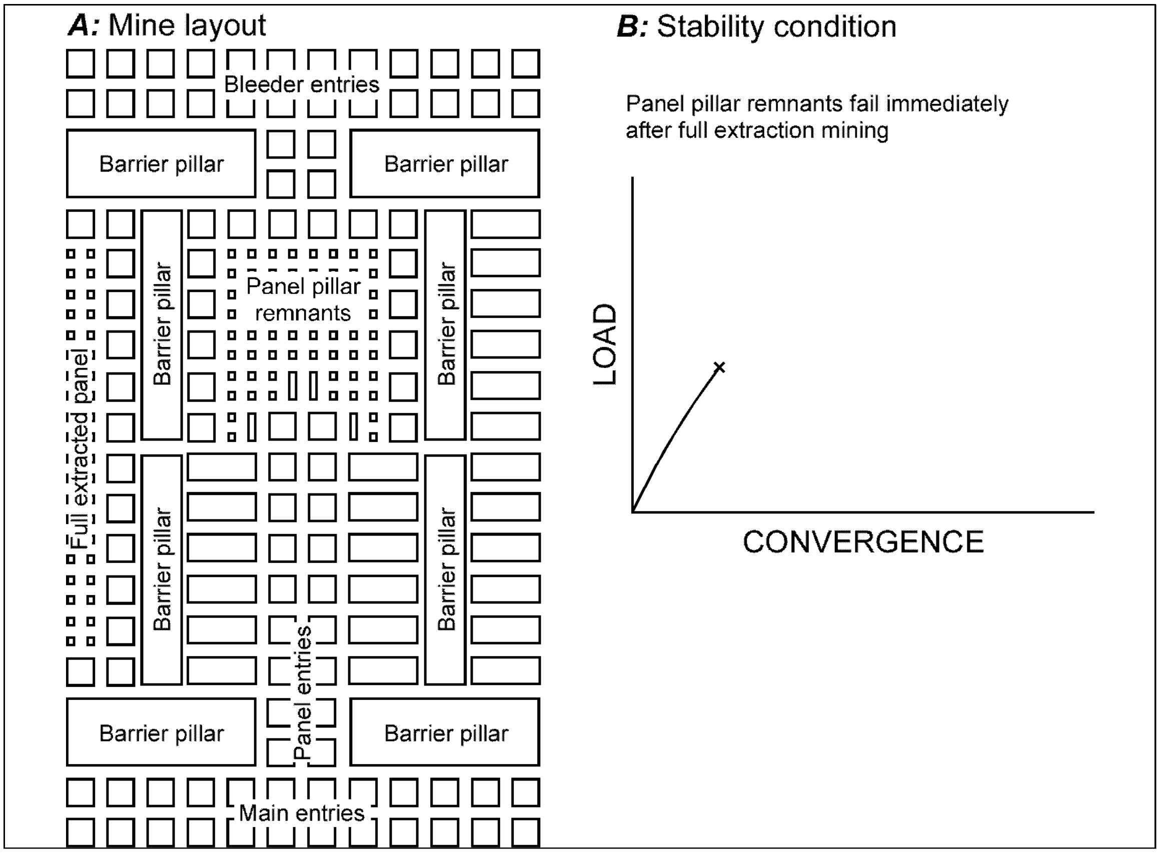

Figure 8.—Full extraction approach. *A*, Mine layout. Failure of pillar remnants along with overburden occurs immediately after pillar extraction. *B*, Stability condition. Retreat mining must ensure development of sufficiently weak remnant pillars. Extraction for layout shown is 67%.

options are the safest approaches to apply until good data on the post-failure behavior of pillars become available. Then, the prevention approach based on an evaluation of the factor of stability with the local mine stiffness stability criterion may enable safe room-and-pillar mining with higher extraction.

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