Design methods to control violent pillar failures in room-and-pillar mines

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Synopsis

The sudden, violent collapse of large areas of room-and-pillar mines poses a special hazard for miners and mine operators. This type of failure, termed a 'cascading pillar failure' (CPF), occurs when one pillar in a mine layout fails, transferring its load to neighbouring pillars, which causes them to fail, and so forth. Recent examples of this kind of failure in coal, metal and non-metal mines in the U.S.A. are documented. Mining engineers can limit the danger presented by these failures through improved mine design practices.

Whether failure occurs in a slow, non-violent manner or in a rapid, violent manner is governed by the local mine stiffness stability criterion. This stability criterion is used as the basis for three design approaches to control cascading pillar failure in room-and-pillar mines—the containment approach, the prevention approach and the full extraction mining approach. These design approaches are illustrated with practical examples for coal mining at shallow depth.

Cascading pillar failure (CPF) in room-and-pillar mines can go by many other names, such as 'progressive pillar failure', 'massive pillar collapse', 'domino-type failure' or 'pillar run'. In this kind of failure when one pillar collapses the load that it carried transfers rapidly to its neighbours, causing them to fail, and so forth. This failure mechanism can lead to the rapid collapse of very large mine areas. In mild cases only a few tens of pillars might fail; in extreme cases, however, hundreds, even thousands, of pillars can fail.

CPF can have catastrophic effects on a mine, and sometimes these effects pose a greater risk to health and safety than the underlying ground-control problem. Usually, the CPF induces a devastating air blast as a consequence of the displacement of air from the collapse area. An air blast can disrupt the ventilation system totally by destroying ventilation stoppings, seals and fan housings. Flying debris can seriously injure or kill mining personnel. The CPF might also fracture a large volume of rock in the pillars and immediate roof and floor. In coal mines and certain other mines this can lead to the sudden release of large quantities of methane gas into the mine atmosphere; a methane explosion might result from the CPF.

CPF is at the far end of the spectrum of unstable pillar failure. At the other end are slow 'squeezes' that develop over days to weeks and, because of their slow progress, do not pose an immediate danger to mining personnel. There is ample warning time for men and machinery to get out of the way of the failure. In a CPF, however, the failure progresses so rapidly that men and equipment cannot be evacuated in time. Significant seismic energy is released as a consequence of the rapid failure and collapse.

CPF should not be confused, however, with coal-mine bumps and rockbursts. In some cases the damage can appear similar, but the underlying mechanics are completely different. As will be shown later, the mechanics of CPF depend on the applied vertical stress and the post-failure, i.e. strain-softening, behaviour of the pillars. In a CPF pillars shed their applied load rapidly and have very little residual strength after failure. The collapse itself may release significant seismic energy, but otherwise the mine is seismically quiet. After a CPF the openings in the affected mine workings have usually closed completely.

In contrast, coal-mine bumps and rockbursts occur in seismically active mines. Research has shown that coal-mine bumps and rockbursts are seismic events induced by mining that damage underground mine workings. Bumps and bursts are thus a subset of a much larger set of mining-induced seismic events.[1] Only some of these seismic events damage mine workings; fortunately, most do not. The mechanisms by which a mining-induced seismic event can lead to a damaging coal-mine bump or rockburst is still a significant research area.[2] After a bump or rockburst the affected mine workings may or may not be completely closed. For example, in the coal-mine bump described by Boler and co-workers[2] the mine workings remained open even though the pillars were destroyed during the bump event.

Because CPF differs from a coal-mine bump or rockburst, the design approaches to control their occurrence also differ. The design recommendations developed here apply to CPF and not to bump- or burst-prone mines.

Cascading pillar failure examples

Unfortunately, CPF has occurred in room-and-pillar coal, metal and non-metal 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 21 January, 1960.[3] Table 1 summarizes the mining dimensions of 13 examples of rapid pillar collapse in U.S. coal mines. All occurred during the 1980s and 1990s, and all happened suddenly or without significant warning. Most resulted in air blasts and damage to the ventilation system.

Table 2 gives the mining dimensions of six room-and-pillar metal and non-metal mines in the U.S.A. where failure occurred in all probability by the CPF mechanism. The collapse areas can be huge. Fortunately, some of these failures gave advance warning. At the lead–zinc mine slabbing from pillars and roof falls began four weeks prior to the main collapse.[3] At the copper mine considerable rock noise and smaller failures preceded the main collapse by five days.[5] At the copper–silver mine it is not known if nature provided a warning.[6] Evidently, the trona mine collapsed without warning.[7,8] Rock noise and other failure warnings preceded the silica mine collapse by three weeks.[9] The presence or absence of warnings at the salt mine is not known.[10] Most of these collapses induced a substantial air blast; damage to the ventilation systems was limited, however, to bent airdoors and a few downed stoppings, except at the trona mine, where extensive damage to the ventilation system resulted.

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Table 1 CPF examples in U.S. coal mines

Case	State	Depth, m	Pillar size, m	ARMPS safety factor	*W*/*H* ratio	Collapse area, m^2	Collapse size, m	Damage from air blast
A	WV	84	3 × 12	0.75	1.05	22 500	150 × 150	26 Stoppings, 1 injury
B1	WV	73	3 × 12	0.84	1.00	–	–	32 Stoppings, fan wall out
			3 × 18	0.96	1.00			
B2	WV	75	3 × 12	0.82	1.00	15 000	100 × 150	40 Stoppings
B3	WV	85	9 × 9	1.46	3.00	32 400	180 × 180	70 Stoppings
			6 × 12	1.30	2.00			
C1	WV	60	3 × 12	1.05	1.00	21 000	140 × 150	103 Stoppings
C2	WV	99	9 × 9	1.15	3.00	18 000	100 × 180	Minimal
D	WV	69	6 × 6	1.15	1.82	16 000	100 × 160	37 Stoppings
			9 × 9	1.42	2.73			
(N.I.)	WV	–	–	1.03	2.5	18 000	120 × 150	–
R	CO	120	4 × 24	0.57	1.71	27 000	180 × 150	Minor
E1	WV	91	3 × 12	0.79	1.42	69 600	240 × 290	Major
E2	WV	91	3 × 12	0.71	1.11	60 500	220 × 275	Major
F	OH	76	2 × 12	0.66	2.12	19 500	90 × 215	Minimal
G	UT	168	12 × 12	0.95	2.29	72 000	150 × 490	Major, 1 injury

Table 2 CPF examples in U.S. metal and non-metal mines

	State	Depth, m	Pillar size, m	*W*/*H* ratio	Extraction, %	Collapse area, m^2	Collapse size, m	Damage from air blast
Pb–Zn mine	IL	75	11 × 11	0.4	90	32 000	90 × 360	Minimal
Cu–Ag mine	MT	300	9 × 90	0.5	60–65	11 000	90 × 120	–
Cu mine	MI	600	7 × 7	2.0 – 0.9	68	540 000	600 × 900	Minor
Trona mine	WY	490	4 × 29	1.4	60–70	1 600 000	760 × 2100	Major
Silica mine	IL	18	9 to 15	1.0	56	6 800	75 × 90	–
Salt mine	NY	330	5.5 × 5.5	1.5	92	40 000	200 × 200	–

The mine dimensions summarized in Tables 1 and 2 can cover a wide range of mining practice. However, mines that have had a CPF have several important commonalties. *In general, the pillars themselves must be the weak link in the roof–pillar–floor system.* Extraction ratios are usually more than 60%. Where the safety factor of pillars involved in a failure can be estimated it has usually been close to 1. The width-to-height (*W*/*H*) ratio of panel pillars is always less than 3 for coal-mine failures, usually much less than 1 in the metal mines and may be less than 2 in the non-metal mine failures. Substantial barrier pillars with *W*/*H* ratios of more than 10 are usually absent from the part of the mine where the CPF occurs. For coal-mine failures the stability factor for the pillars is less than 1.5 according to the Mark–Bieniawski pillar strength formula in the Analysis of Retreat Mining Pillar Stability (ARMPS) method.[11] Further descriptions of the ARMPS method appear here under 'Practical design examples'. Typically, the roof rock is stiff and massive and can bridge wide spans without caving. Most importantly, though, for collapse events that caused significant damage the collapse area is at least 15 000 m^2, with a minimum dimension of at least 100 m.

Mechanics of cascading pillar failure

The simple explanation of CPF given above indicates that rapid load transfer away from failing pillars is an important part of the failure mechanism. The underlying mechanics of CPF are, however, more complex. The nature of the pillar failure process depends on the relative mechanical properties of the rock mass and the pillar. The most important structural characteristic is the post-failure stiffness and strength of the remnant pillars. Slender pillars with a low *W*/*H* ratio shed load rapidly when they fail. The transferred weight can overload adjacent pillars, and a rapid 'domino' failure of adjacent pillars can ensue. Pillars that are squatter, with a large *W*/*H* ratio, retain most of their load even after failure. Such pillars will squeeze slowly, rather than collapsing.

Laboratory data from the work of Das[12] illustrate this behaviour. As shown in Fig. 1, beyond a *W*/*H* ratio of about 8 the behaviour of the laboratory-scale specimens is nearly elastic–plastic, meaning that they shed little load after failure. Some data on the post-failure behaviour of full-scale coal pillars are also available. As shown in Fig. 1(*b*), beyond a *W*/*H* ratio of about 4 the post-failure modulus of full-scale coal pillars becomes positive and their behaviour is elastic–plastic. Again, such coal pillars do not shed their load rapidly when they fail.

On the basis of an analogy between a laboratory test specimen and a mine pillar Salamon[18] developed a criterion to predict whether the failure process occurs in a stable, non-violent manner or in an unstable, violent manner; Fig. 2 illustrates this well-known criterion.

Stable, non-violent pillar failure occurs when

$$|K_{\mathrm{LMS}}| > |K_{\mathrm{P}}| \qquad (1)$$

and unstable, violent pillar failure occurs when

$$|K_{\mathrm{LMS}}| < |K_{\mathrm{P}}| \qquad (2)$$

where K_{LMS} is local mine stiffness and K_{P} is post-failure stiffness at any point along the load–convergence curve for the pillar. As long as equation 1 is satisfied, CPF is unlikely to

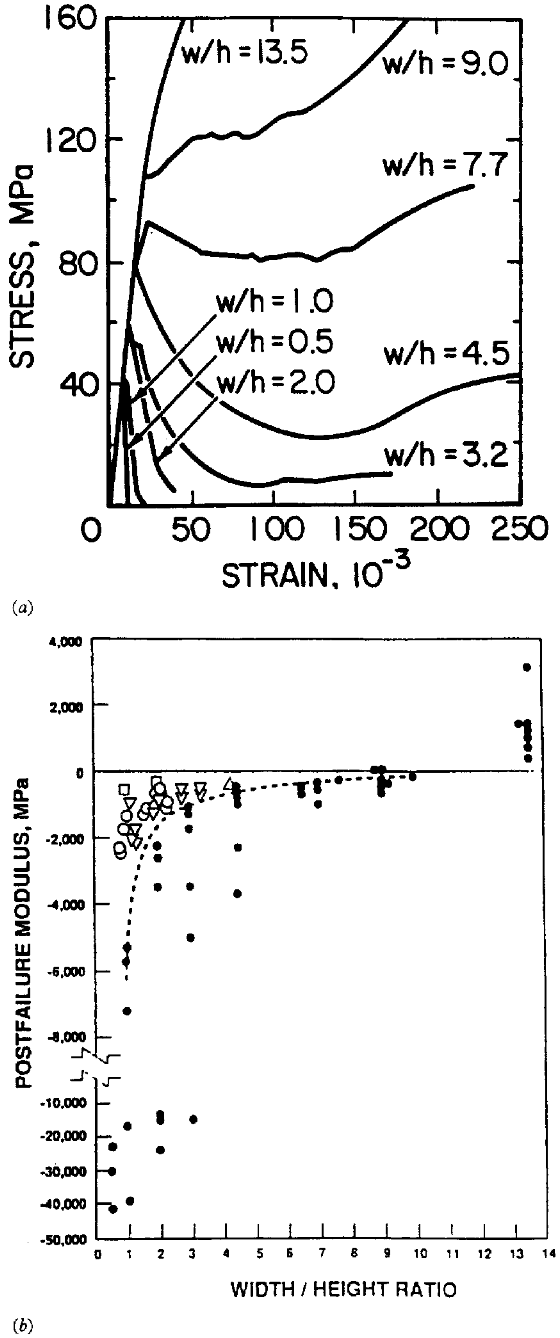

Fig. 1 (*a*) Complete stress–strain curves for Indian coal specimens, showing increasing residual strength and post-failure modulus with increasing *W/H* ratio;[12] (*b*) post-failure modulus of coal pillars, *in-situ* coal specimens and laboratory samples[13–17] (*filled circles*, Das;[12] *squares*, Bieniawski;[14] *blank circles*, Wagner;[15] *inverted triangles*, van Heerden;[16] *triangles*, Skelly and co-workers[17])

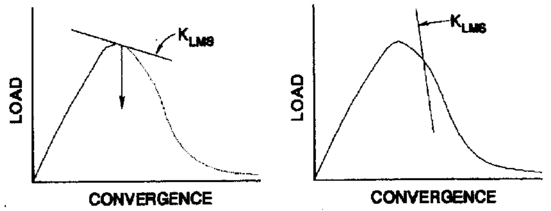

Fig. 2 Unstable, violent failure versus stable, non-violent failure: (a) local mine stiffness less than post-failure stiffness in 'soft' loading system; (*b*) local mine stiffness greater than post-failure stiffness in stiff' loading system

occur; however, if equation 2 is satisfied, CPF is possible.

K_{LMS} depends on the modulus of the immediate roof, floor and pillar materials and the layout of pillars, mine openings and barrier pillars. Numerical methods, such as the boundary-element method,[19] can be applied to calculate K_{LMS}. The post-failure stiffness, K_P, depends on the size and *W/H* ratio of the pillar. Some field measurements of the post-failure stiffness, K_P, exist for full-scale coal pillars, as shown in Fig. 1(*b*). Unfortunately, there is a paucity of similar data for full-scale pillars in room-and-pillar metal and non-metal mines.

As shown in Table 1, CPF in room-and-pillar coal mines occurs only when the *W/H* ratio of the affected pillars is less than about 3 or 4. Fig. 1 explains this observation. K_P becomes positive, i.e. the post-failure behaviour changes from strain-softening to elastic–plastic, at a *W/H* ratio of about 3 or 4. At that point CPF becomes a physical impossibility because the local mine stiffness stability criterion is necessarily always satisfied.

Similarly, for metal and non-metal mines Table 2 shows that CPF only occurs in room-and-pillar mines that have pillars of low *W/H* ratio (less than about 1 or 2). K_P must become positive beyond some critical *W/H* ratio. On the basis of the coal observations that transition may also occur at the *W/H* ratio range of 3–4.

Back-analysis or numerical simulations may provide the only route to estimate K_P for certain kinds of full-scale pillars. Zipf[19] followed this approach to calculate K_P and K_{LMS} and then evaluate the local mine stiffness stability criterion. The behaviour of the computer simulations changes depending on whether the model satisfies or violates this stability criterion. From a health and safety standpoint it is fortunate, however, that rock mechanics engineers have few examples of CPF from which to conduct back-analyses of the post-failure behaviour of full-scale mine pillars.

Design principles for control of cascading pillar failure

Most pillar design procedures merely consider the peak strength of the pillar, shown as *A* in Fig. 3. If the applied stress on the pillar reaches this level, its stability factor is 1. Similarly, if the applied stress on the pillar is half the peak strength, shown as *B* in Fig. 3, its stability factor is 2. There is a great economic incentive to design pillars with a low stability factor in that as the stability factor decreases the extraction ratio increases. Therefore, the most economic pillar designs in terms of resource recovery are necessarily very close to *A*, but still on the pre-failure side of the complete load–convergence curve for the pillar. Because of the inherent variability in pillar strength, however, it is important to consider what happens to a particular room-and-pillar mine plan if some of the pillars should exceed the peak strength at *A* and proceed into the post-failure side at *C*.

Engineers have known for some time about the post-failure behaviour of rocks and the implications of this behaviour for mine safety. However, it is another matter to translate that knowledge into efficient and economic mine designs for the extraction of bedded deposits by room-and-pillar or other mining techniques. Three different approaches to mine

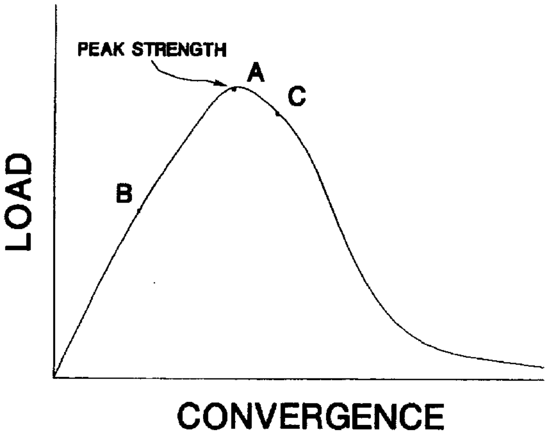

Fig. 3 Complete load–deformation curve for pillar. Peak strength at *A*. Left of *A* is pre-failure, right of *A* is post-failure

design are proposed to control CPF—containment of failure, prevention of failure and full-extraction mining.

Containment approach

The containment approach, shown in Fig. 4(*a*), limits the spread of a potential CPF with barrier pillars. It is used during retreat mining when the operator wants to reduce the likelihood and potential impact of a CPF. It is a non-caving room-and-pillar method in which low *W*/*H*-ratio panel pillars are surrounded by high *W*/*H*-ratio barrier pillars. The panel pillars violate the local mine stiffness stability criterion, as shown in Fig. 4(*b*), and can, therefore, fail violently. However, two factors will decrease the risk of a catastrophic CPF. First, the barrier pillars will tend to shield the panel pillars from full overburden stresses and thereby increase their safety factor and decrease their probability of failure. Second, if the panel pillars do begin to fail, the failure will not propagate beyond the barrier pillars. A conservative approach is to size the barrier pillars on the assumption that all the panel pillars within have failed. These barrier pillars must also have a large *W*/*H* ratio to eliminate any strain-softening behaviour.

If an engineer chooses to use panel pillars with a low *W*/*H* ratio that exhibit strain-softening behaviour and can violate the local mine stiffness stability criterion, it is imperative to limit the panel sizes and surround all panels with adequate barrier pillars. The load-transfer distance method presented by Abel[20] provides an approach for estimating the maximum panel width. Use of this method will help to ensure that panel pillars never experience the full tributary area stress. Even though the barrier pillars shield the panel pillars from the full tributary area stress, the small pillars should have the ability to withstand the full tributary area stress if possible.

To summarize, the main design characteristics of the containment approach are:

(1) Panel pillars have low *W*/*H* ratios (less than 4) and violate the local mine stiffness stability criterion. Their stability factor is at least 2 on advance and may be less than 1 on retreat.

(2) Barrier pillars have high strength and high *W*/*H* ratios (usually greater than 10). They must remain stable even if all panel pillars should fail.

(3) Panel sizes are limited by the minimum load-transfer distance to ensure that panel pillar stresses are less than full tributary area stresses.

(4) Panel sizes are also limited by the degree of damage due to an air blast that the mine layout can withstand should a CPF occur within the panel.

Prevention approach

The prevention approach, shown in Fig. 5(*a*), 'prevents' CPF from ever occurring by the use of panel pillars with proper mechanical characteristics. This approach is another non-caving room-and-pillar system, in which, however, high *W*/*H*-ratio panel pillars and optional barrier pillars are left. The approach should be used during advance mining when

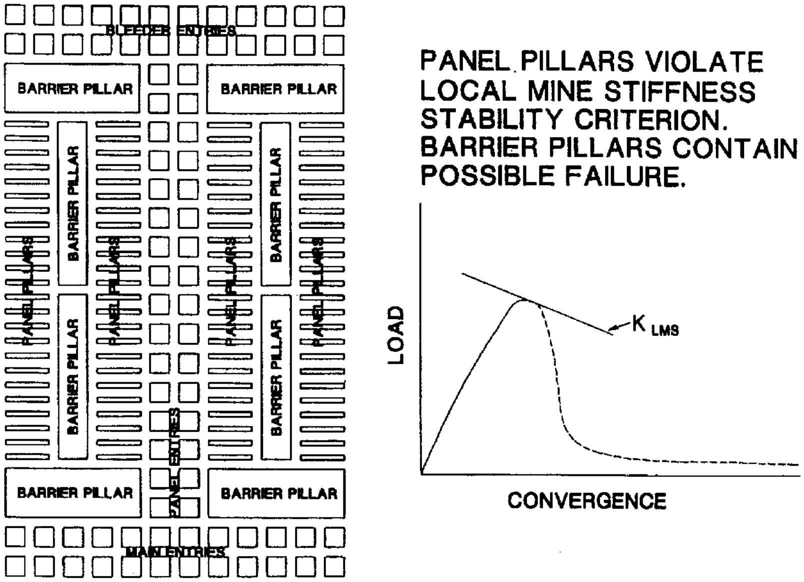

Fig. 4 Containment approach to room-and-pillar mine layout: (*a*) pillar failure is 'compartmentalized'; (*b*) stability condition is such that panel pillars with low *W*/*H* ratio violate local mine stiffness stability criterion; panel pillars can, therefore, fail violently, but adequate barrier pillars that restrict spread of unstable failure surround them. Extraction for layout as shown is 59%

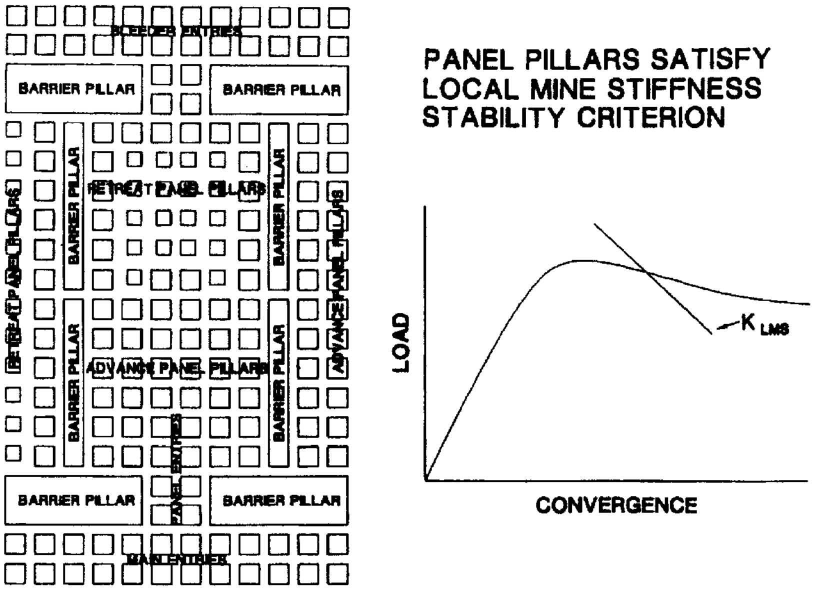

Fig. 5 Prevention approach: (*a*) unstable pillar failure is impossible because of either adequate stability factors (greater than 2) or high *W*/*H* ratios of panel pillars; (*b*) stability condition is such that high *W*/*H*-ratio panel pillars satisfy local mine stiffness stability criterion and CPF is physically impossible. Extraction for layout shown is 63%

the operator wants to ensure that CPF will not occur. There are two separate but related ways to prevent CPF. The first is to design pillars with an adequate stability factor (greater than 2) so that the risk of pillar failure is very small. The second is to design panel pillars that satisfy the local mine stiffness stability criterion, as shown in Fig. 5(*b*). Therefore, they cannot fail violently and CPF becomes a physical impossibility. The panel pillars will usually have high *W*/*H* ratios (greater than 4 for coal) and may have high stability factors as well (greater than 2). Strictly speaking, this approach does not need barrier pillars to ensure overall mine stability; however, their use is still advisable. Barrier pillars will always provide an additional margin of structural safety and may serve other purposes, such as ventilation control.

In the mine layout shown in Fig. 5(*a*) 12-m square pillars are developed on the advance with 6 m wide rooms. Instead of splitting the development pillar into two 3 m wide fenders with a *W*/*H* ratio of 1, two sides of that pillar are mined on

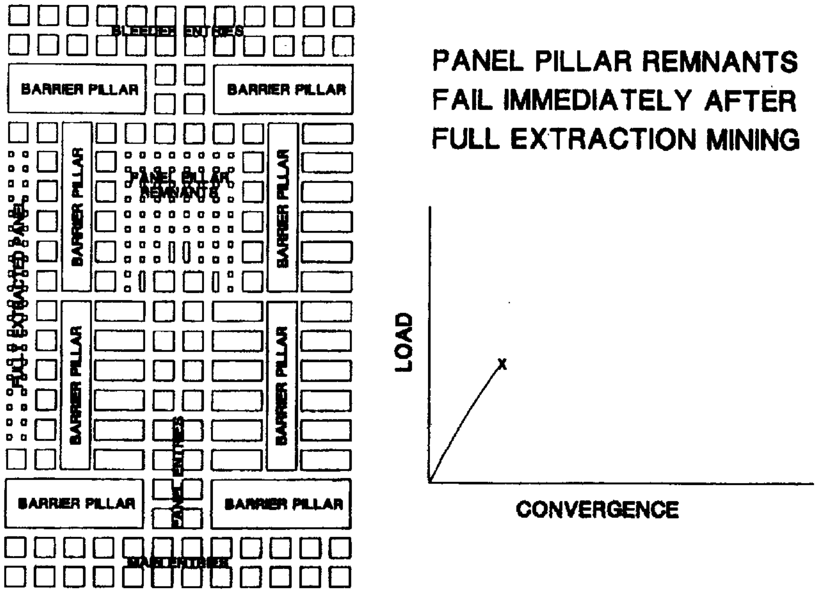

Fig. 6 Full extraction approach: (*a*) failure of pillar remnants along with overburden occurs immediately after pillar extraction; (*b*) retreat mining must ensure development of sufficiently weak remnant pillars. Extraction for layout shown is 67%

the retreat, leaving a 9-m square remnant with a *W/H* ratio of 3. With this approach the remnant pillars with a *W/H* ratio of 3 satisfy the local mine stiffness criterion and a violent failure (CPF) is a physical impossibility. Otherwise, the remnant pillars with a *W/H* ratio of 1 would violate the local mine stiffness stability criterion and a CPF and damaging air blast could result.

Extraction is about the same whether the development pillar is split into potentially unstable remnants or whether the prevention approach is applied and the pillar is shaved into an inherently stable remnant. The only potential drawback in this system from a ground-control perspective is room width. Mine layouts that use the prevention approach must usually have wider room spans during retreat mining. In this case the room width increases from 6 to 9 m during retreat. Therefore, this retreat-mining scheme is applicable only under a relatively competent roof and supplemental support, such as timber or mobile roof supports, may be required.

Full extraction approach

The full extraction approach, shown in Fig. 6(*a*), avoids the possibility of CPF altogether by ensuring total closure of the opening (and surface subsidence) on completion of retreat mining. This approach does not require barrier pillars for overall panel stability; they are, however, needed to isolate extraction areas and protect mains and bleeders. The main design characteristics of a full extraction approach are:

(1) Panel pillars on the advance must have adequate safety factors (greater than 2) and high *W/H* ratios (greater than 4). They should satisfy the local mine stiffness stability criterion.

(2) Panel pillars on the retreat must have safety factors much less than 1 to ensure their complete, controlled collapse soon after the retreat-mining phase, as indicated in Fig. 6(*b*).

Practical design examples for coal mining at shallow depth

The three design approaches outlined above lead to three practical options for maximizing extraction in coal-mine panels: partial pillar recovery on the retreat (a containment approach); small-centre mining on the advance (a prevention approach); and full pillar extraction on the retreat.

Full pillar extraction is relatively complex and has historically required special expertise to succeed. The development of remote-control continuous miners and mobile roof supports has made it economic for some mines to adopt this method.[21] Small-centre mining and pillar splitting, however, have important advantages of simplicity and predictability. A recent survey found that of 239 room-and-pillar mines with active gob areas, nearly half were practising partial recovery only.[22] Evidently, most employ small-centre mining exclusively.

Small-centre mining and pillar splitting both leave significant remnant pillars in the worked-out gob areas. For example, mining on 15-m centres with 6-m entries leaves about 35% of the coal in 9 m × 9 m pillars. Splitting pillars developed on 18 m × 18 m centres leaves about 22% of the coal. The remnant pillars can help support the roof over very large areas, and caving may not occur for some time.

The analyses presented here use the computer program ARMPS developed by the U.S. Bureau of Mines.[11] ARMPS calculates the stability factor based on estimates of the loads applied to, and the load-bearing capacities of, pillars during retreat-mining operations. Loads considered include development loads from the tributary area formula and abutment loads from gob areas in front and to the sides of the active mining zone. The strength of a pillar is determined with the Mark–Bieniawski formula for rectangular pillars given by

$$S_P = S_1\left(0.64 + 0.54\frac{W}{H} - 0.18\frac{W^2}{HL}\right) \qquad (3)$$

where S_1 is *in-situ* coal strength of 6.2 MPa, *W* is pillar width, *H* is pillar height and *L* is pillar length. A database of 130 case histories has been collected from room-and-pillar mines throughout the U.S.A. to verify ARMPS. With a stability factor of 1.5 only two of the 130 case histories experienced pillar failure. For a stability factor greater than 2.0 none of the cases showed failure.

Pillar splitting—a containment approach

Fenders left from pillar-splitting operations appear to be potential candidates for failure even at shallow depths. For example, 3 m × 12 m fenders in a 3-m seam have a stability factor of 2.0 at only 36 m of cover. If air blasts and massive collapses are not to result from partial pillaring, the size of the gob areas must be minimized. To separate the gob areas, rows of unsplit development pillars can be left as a barrier. This strategy is analogous to the way submarines are 'compartmentalized.' It is based on two assumptions: limiting the span above the mined-out area renders a bridging failure of the strong overburden less likely; and minimizing the size of the gob area would reduce the power of an air blast resulting from a collapse that did occur.

Table 1 shows that no major collapses have been documented where the gob area was smaller than 15 000 m^2. In the five cases where the gob area was between 15 000 and 19 000 m^2 about 60% of the incidents resulted in major damage. Also, none of the damaging incidents has occurred where the minimum dimension of the mined-out area was less than 100 m. On the basis of these data acceptable dimensions for a pillar-splitting operation might be a maximum area of 12 000 m^2 and a maximum width less than 90 m. For example: on the assumption of 18 m × 18 m centres and a nine-entry system, with four rows split, the mined-out area

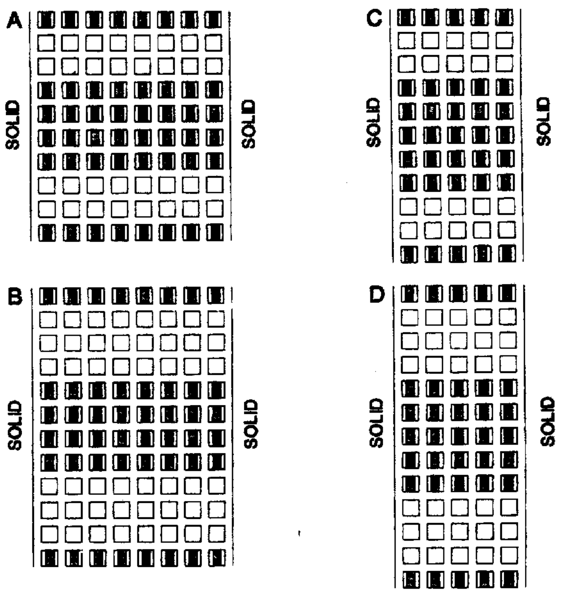

Fig. 7 Possible pillar-splitting plans for air-blast control using 6 m wide entries and 12 m wide pillars: (*a*) nine-entry system, two rows of unsplit pillars for barrier; (*b*) nine-entry system, three rows of unsplit pillars for barrier; (*c*) six-entry system, two rows of unsplit pillars for barrier; (*d*) six-entry system, three rows of unsplit pillars for barrier

would have a minimum dimension of 72 m and an area of about 11 000 m^2 (Fig. 7(*a*) and (*b*)). For the same pillar size in a six-entry system, with five rows split, the minimum dimension would be 90 m and the area would be about 10 000 m^2 (Fig. 7(*c*) and (*d*)).

The next question is how many unsplit rows should be left between these mined-out areas. The goal is to leave enough of a 'barrier' that the failure of one gob area does not spread to adjacent areas. ARMPS was used to evaluate the loading on unsplit pillars between two mined-out areas. The program was modified so that two 'front' gobs could be applied to the unsplit pillars. The analyses were run with abutment angles of 90°, which assumes that none of the load is carried by the gob, but is transferred instead to the barrier.

In the first set of analyses two rows of full-size pillars were used as the barrier. An ARMPS stability factor of 1.5 was assumed to prevent the collapse of one gob area from triggering the collapse of an adjacent area. With a stability factor of 1.5 only two of the 130 case histories with ARMPS showed pillar failure. Three rows of pillars were used in the second set of analyses, and the required stability factor was reduced to 1.0 because of the greater stiffness of the barrier. Pillars on 18 m × 18 m centres were used in all cases.

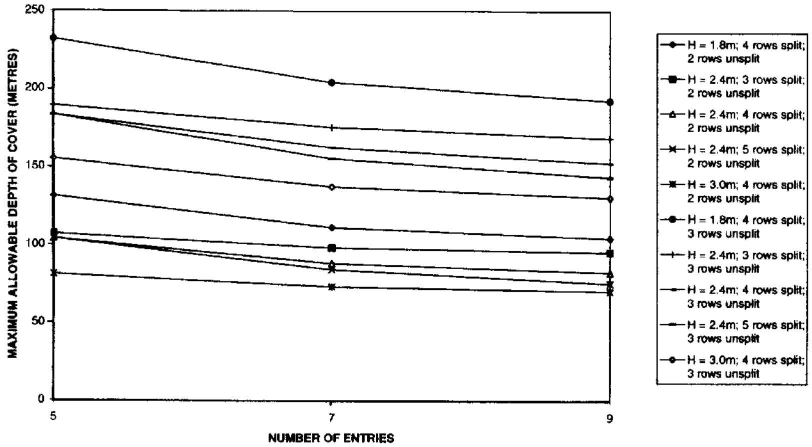

Fig. 8 Suggested maximum depth for two and three rows of unsplit pillars as barrier between gob areas with 5.5-m entries and 12.5 m × 12.5 m pillars

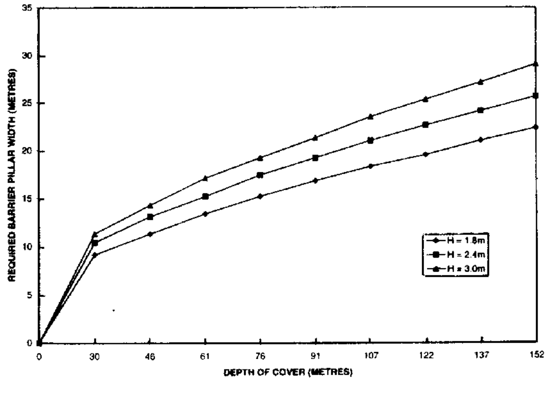

Fig. 9 Suggested solid coal barrier width between two areas where pillars have been split

Other parameters that were varied included the number of rows that were split (three, four and five), the entry width (5.5 and 6 m), the seam height (2, 2.5 and 3 m), and the number of entries in the section (five, seven and nine). The results are presented in the form of graphs (e.g. Fig. 8), showing the suggested maximum depth of cover for each combination of parameters. In general, for 5.5-m entries in a 2.5-m seam, it appears that two rows of unsplit pillars might be an adequate barrier at depths less than about 90 m, and three rows might be acceptable to about 170 m of cover.

Barriers must also be left between extracted panels. These can be unsplit development pillars or solid coal. If unsplit development pillars are used, the analysis in Fig. 8 should apply. For solid coal barriers Fig. 9 shows the suggested widths, under the same loading assumptions as before. For a 2.5-m seam a 17 m solid barrier seems appropriate at 75 m of cover, and 23 m might be needed at 120 m.

Small-centre mining—a prevention approach

Square pillars are generally used in small-centre mining. Table 1 indicates that three collapses have involved 9-m square pillars and one involved 12-m square pillars. Square pillars can be designed to be collapse-resistant in two ways. The first is to increase their *W*/*H* ratio. Since no collapses have been documented where the *W*/*H* ratio was greater than 3.0, a design *W*/*H* ratio of 4.0 is recommended to provide an adequate margin of safety.

Pillar collapses may also be avoided by maintaining a sufficiently large stability factor. A design ARMPS stability factor of 2.0 is suggested for long-term stability. For a stability factor greater than 2.0 none of the ARMPS case histories showed failure. A greater pillar stability factor can be achieved by increasing the pillar width, decreasing the extraction ratio, or both.

These two design criteria have been combined to develop guidelines for small-centre mining. Fig. 10 was developed on the assumption of square pillars with a stability factor of 2.0 or a *W*/*H* ratio of 4.0. When 6 m wide entries are used the minimum suggested pillar sizes are increased by about 6%. It should be noted that these design criteria are only for controlling massive pillar collapses. At greater depths pillar sizes may have to be increased beyond *W*/*H* = 4 to maintain an adequate stability factor. Should pillars of *W*/*H* = 4 become overloaded, however, a squeeze would be expected rather than a sudden collapse.

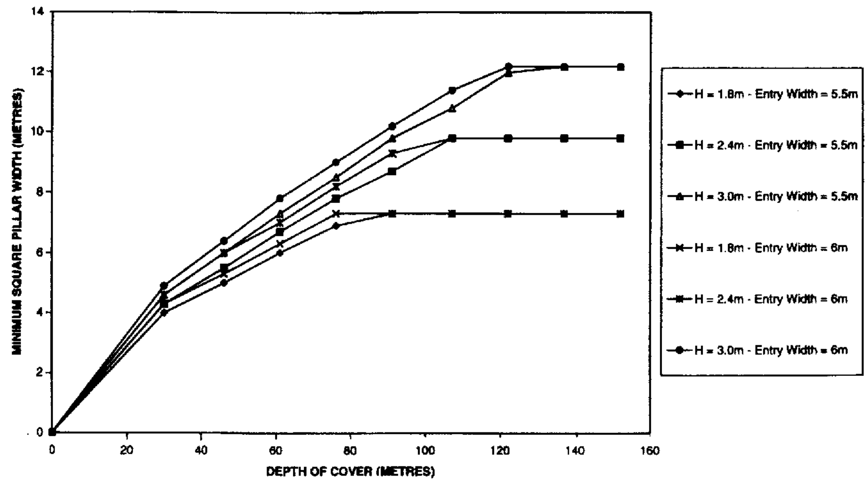

Fig. 10 Suggested minimum square pillar size for 5.5-m and 6-m entries

Discussion and conclusions

CPF is a potential problem faced at all room-and-pillar mines. It occurs when one pillar fails suddenly and thereby overstresses the neighbouring pillars causing them to fail, and so forth in very rapid succession. Very large mining areas can collapse via this mechanism within seconds and with little or no warning. The collapse itself can pose grave danger to nearby mining personnel. In addition, the collapse can induce a violent air blast that disrupts or destroys the ventilation system. Further grave danger to miners exists if the mine atmosphere becomes explosive or contaminated as a result of the CPF.

The study presented here has documented collapses in coal, metal and non-metal mines that have occurred within the past twenty years in the U.S.A. CPF, also known as 'massive pillar collapse', 'domino-type failure' or 'rapid progressive pillar collapse', is the likely mechanism behind these major mine failures. The mechanics of CPF are well understood. Strain-softening behaviour is the essential mechanical characteristic of pillars that fail rapidly via this mechanism. Pillars that exhibit strain-softening behaviour undergo a rapid decrease in load-bearing capacity on reaching their ultimate strength. The strain-softening behaviour of pillars is in part material-dependent; however, it also depends on pillar geometry. Pillars with a low *W/H* ratio tend to exhibit a greater degree of strain-softening behaviour than those with a higher *W/H* ratio, which typically show elastic–plastic or strain-hardening material behaviour.

The mechanics of a CPF differ significantly from those of coal-mine bumps and rockbursts. In a CPF pillars fail violently owing to the applied vertical load and the post-failure behaviour of the pillars. Research shows that coal-mine bumps and rockbursts result from nearby mining-induced seismic events that damage susceptible mine workings and structures. The mechanics of how a mining-induced seismic event damages a mine remains an important research topic. Thus, the design recommendations developed herein to control CPF do not apply to coal-mine bumps and rockbursts. For coal-mine bump control pillars less than about 10 m wide, i.e. yield pillars with *W/H* ratios less than about 3–4, generally do not fail explosively in a mining-induced seismic event. Pillars that are 15–25 m wide, i.e. abutment pillars with a *W/H* ratio ranging from 5 to 8, are most susceptible to explosive failure. Pillars greater than 30 m wide with a *W/H* ratio greater than 15 generally do not fail explosively.[23,24,25]

The local mine stiffness stability criterion developed by Salamon[18] provides a means to distinguish between mine layouts that fail in a stable, non-violent manner and those which fail in an unstable, violent manner via CPF. This stability criterion suggests three design approaches to minimize the risk of CPF—containment, prevention and full extraction. In an array of pillars that violate the stability criterion the containment approach applies. In this approach low *W/H*-ratio panel pillars that violate the stability criterion are surrounded by high-*W/H* barrier pillars that can shield the panel pillars from full tributary area stresses and 'contain' panel pillar failure should it initiate. However, if all panel pillars in an array satisfy the stability criterion or if their stability factor is very high (>2), the prevention approach applies. The panel pillars do not exhibit much strain-softening behaviour because their *W/H* ratio is sufficiently high (probably greater than 4). In the full extraction approach the stability issue becomes a moot point, because complete closure of the openings is assured soon after retreat mining is completed.

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