The Massive Collapse of Coal Pillars - Case Histories from the United States

Frank E. Chase, *Geologist*

U.S. Bureau of Mines
Pittsburgh Research Center
Pittsburgh, PA

R. Karl Zipf, Jr., *Structural Engineer*

U.S. Bureau of Mines
Denver Research Center
Denver, CO

Christopher Mark, *Mining Engineer*

U.S. Bureau of Mines
Pittsburgh Research Center
Pittsburgh, PA

ABSTRACT

A massive pillar collapse occurs when undersized pillars fail and rapidly shed their load to adjacent pillars which in turn fail. This chain reaction-like failure may involve hundreds, even thousands, of pillars and the consequences have been catastrophic. One effect of a massive pillar collapse can be a powerful, destructive, and a potentially hazardous airblast. On eleven recent occasions, massive pillar collapses have occurred in six southern West Virginia coal mines. Two other instances of massive pillar collapses in U.S. mines have been documented in the literature.

Research was conducted at four mines where massive pillar collapses occurred. Geotechnical evaluations of roof rock, coalbed, and floor conditions were made. Evidence indicates that in each case a massive and competent roof rock unit was able to bridge a relatively wide span, creating a pressure arch. Eventually, the pressure arch apparently broke down, and the structural characteristics of the pillar system were such that sudden, massive pillar failures occurred. Data collected at the failure sites also indicates that all the massive collapses occurred where the pillars width-to-height ratio was 3.0 or less. Numerical modeling, performed with a modified version of the MULSIM/NL computer program, supports the conclusions that the extent of the mined-out area, the bridging capability of the main roof, and the width-to-height ratio of the pillars are probably all significant factors in the occurrence of massive pillar failures.

INTRODUCTION

Although somewhat rare, massive pillar collapses can be cataclysmic in nature. The most infamous collapse occurred in 1960, at Coalbrook North colliery which was located in South Africa. As indicated by Bryan et al., (1966), thousands of 12 x 12 m (40 x 40 ft) pillars collapsed over a 750 acre area in five minutes, killing 437 miners. Between 1990 and 1993, The Joint Coal Board (University of New South Wales, 1993) reported three massive pillar collapses in Australia. In 1992, The U.S. Bureau of Mines (USBM) was asked to investigate a massive pillar collapse and resultant destructive air blast which occurred in Mingo County, WV. To determine how widespread a problem massive pillar collapses are in the United States, numerous State and Federal Roof Control Specialists were contacted across the country. Five additional mine sites were identified. Complete documentation of the massive pillar collapses which occurred at two of the operations was unavailable. One mine was located in Kanawha Co., WV, and damage was limited to blown out stoppings. Two other occurrences of pillar collapses were recorded at another mine located in Webster Co., WV, in 1993. In the first collapse, the fan and 18 stoppings were blown out. The resultant air blast expelled debris outby the drift opening and broke out windows in 3 pickup trucks and the endloader. In the second collapse several stoppings were blown out and the fan was damaged. Both mines have since been sealed. In addition, a literature search yielded two additional U.S. cases (Khair and Peng, 1985; Abel, 1988).

Geotechnical evaluations of massive pillar collapses were conducted at four southern West Virginia mines. The competency of the immediate roof was determined using the USBM's Coal Mine Roof Rating (CMRR) system (Molinda and Mark, 1994). Also, the main roof's competence and susceptibility to cave were examined. The Bureau's Analysis of Retreat Mining Pillar Stability (ARMPS) program (Chase and Mark, 1993) was used to determine stability factors (SF). ARMPS is a computer program which estimates development and abutment loading pressures generated by retreat mining operations. Development loading is estimated using the tributary area formula. Pillar strength is determined using the Bieniawski formula (Bieniawski, 1987) with an assumed in situ coal strength value of 6.2 MPa (900 psi). Abutment loads are estimated using the same formulations employed in the ALPS program for longwall mining (Mark, 1990). To date, back analysis of more than 90 pillar design case histories indicates that ARMPS can be helpful tool in aiding in the design of retreat mining sections.

CASE HISTORIES

Mine A is located in Mingo County, WV, and is extracting the 2.9 m (9.5 ft) thick Coalburg coalbed. A 25 m (82 ft) thick massive sandstone unit with a compressive strength of 83 MPa (12,000 psi) forms the roof in the affected areas to be discussed. The CMRR was calculated to be 74. Below the non-cleated coalbed is 10.4 m (34 ft) of competent sandy shale and sandstone units. All roadways were 6 m (20 ft) wide.

In 1991, the panel shown in figure 1 was developed. All roadways were driven on 18 m (60 ft) centers and were under 84 m (275 ft) of cover. After the panel was completed, partial pillar recovery was begun. A 6 m (20 ft) wide split was mined through the middle of each pillar, and two 3 x 12 m (10 x 40 ft) fenders with an ARMPS SF=0.75 remained. Because of the competency of the roof and the support provided by the regular spaced uniform fenders, no caving occurred while the panel was being retreat mined. Three weeks after the panel had been abandoned, an area approximately 138 x 154 m (450 x 500 ft) containing 107 fenders collapsed (figure 1). Miners on a nearby section were knocked to the floor by the resultant airblast. One miner sustained a head injury. Fortunately, no miners were near the collapse. However, had the failure occurred 15 minutes later, two miners would have been rock dusting ribs immediately outby the area which collapsed. The airblast destroyed 26 cinder block stoppings (figure 2) and the fan house weak wall, closing the mine for days. As was the case in some of the other collapses to be discussed, not all the under sized fenders in the panel failed. Two possible explanations are put forth to explain this behavior. First, the collapse might terminate as soon as the competent roof units are again able to bridge a given span. Or, the collapse may terminate where the under sized fenders are still of sufficient size and strength to support the now cantilevering immediate roof. For example, it is conceivable that the sufficiently

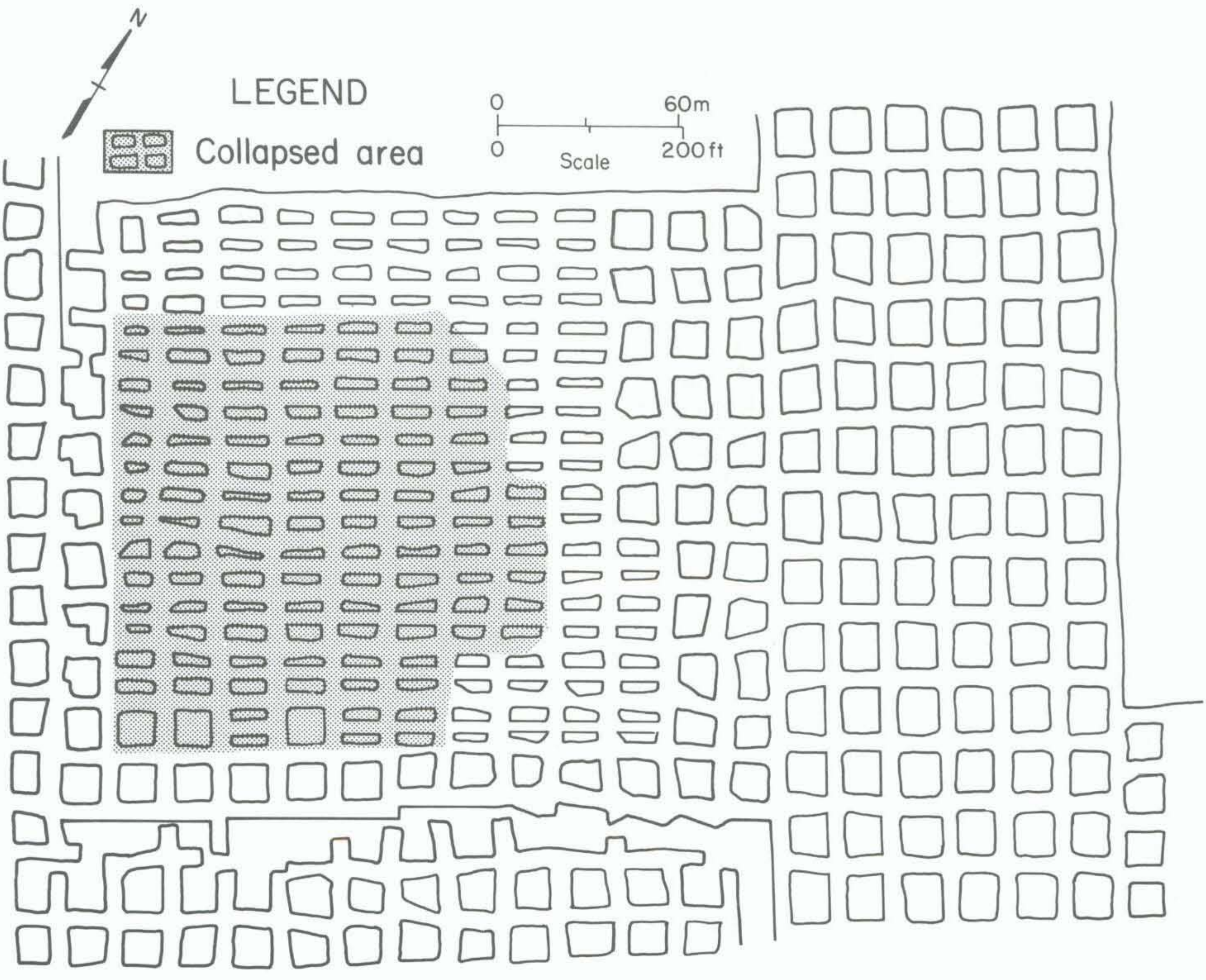

Figure 1. Failed fender workings in Mine A.

Figure 2. Concrete cinder block stopping damaged by airblast.

sized 12 x 12 m (40 x 40 ft) pillars with a SF=2.23 provided a hinge line from which the immediate roof cantilevered helping to terminate the collapse.

Mine A also experienced a prior massive collapse of fenders in partially pillared workings under very similar conditions mentioned above. Damage was limited to blown out stoppings and no one was injured. Complete documentation of this case was unavailable.

After the accident, the practice of pillar splitting was reexamined at the mine. Full pillar extraction would induce the roof to cave in a regular fashion, but would require extensive timbering in the 2.9 m (9.5 ft) thick seam. Company officials determined that an additional 43 posts (commonly referred to as being trees) would be required to fully extract each 12 x 12 m (40 x 40 ft) pillar. This is no small chore considering each post weighs approximately 80 kg (175 lbs), and requires 3 miners to set it. Production of 3,500 tonnes (3,200 tons) per shift was achieved during pillar splitting in Mine A. Production time lost setting additional posts and sometimes waiting for the roof to break during full pillar recovery justified the abandonment of the coal contained in the fenders. Scenarios similar to that indicated in Mine A have prompted other operators to go to full pillar extraction with the aid of mobile roof supports (figure 3). These units have repeatedly proven themselves to be a viable cost effective solution to setting turn posts in high coal conditions.

Mine B is operating in the 3 m (10 ft) thick Stockton coalbed in southern WV. The roof is primarily composed of massive sandy shale and shale units and has a CMRR=77. An extremely competent 2.3 m (7.5 ft) thick flint unit is situated 9 m (30 ft) above the coalbed. Within the coalbed, no butt cleat was observed and the face cleat was only semi-developed. The immediate floor was a slickensided shale 1.2 m (4 ft) thick. Below this shale was a 4.6 m (15 ft) thick sandy shale unit. All roadways and pillar splits in the mine were 6 m (20 ft) wide. Three separate severe airblasts resulting from pillar collapses have occurred in Mine B. In 1988, an area in which pillar splitting had been conducted failed. The area contained 128 fenders measuring 3 x 12 m (10 x 40 ft) with a SF=0.84 and 114 fenders measuring 3 x 18 m (10 x 60 ft) with a SF=0.96. The fan house weak wall

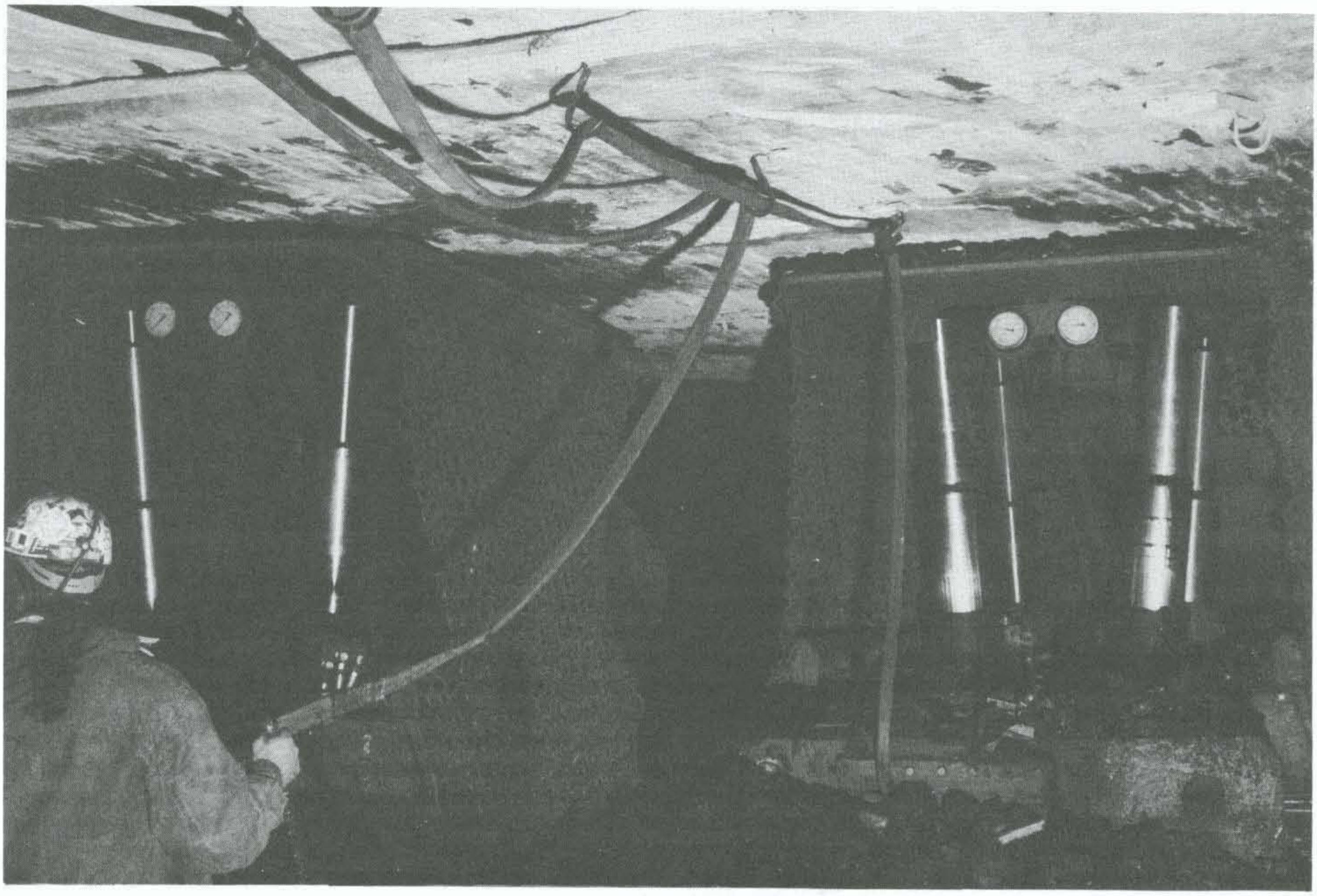

Figure 3. Full pillar extraction using mobile roof supports.

and 32 stoppings were blown out. Pillars measuring 12 x 18 m (40 x 60 ft) with a SF=3.33 helped terminate the collapse. There was 73 m (240 ft) of overburden in the area.

The second collapse occurred later that same year. Eighty six 3 x 12 m (10 x 40 ft) fenders with a SF=0.82 failed (figure 4). The airblast blew out 40 stoppings. Pillars measuring 12 x 12 m (40 x 40 ft) with a SF=2.45 assisted in halting the collapse. There was 75 m (245 ft) of cover over the workings.

The third airblast happened in 1992. The collapse most probably began where pillar splitting had taken place. Seventy two 6 x 12 m (20 x 40 ft) fenders with a SF=1.46 and fifty 9 x 9 m (30 x 30 ft) development pillars with a SF=1.36 failed. Seventy stoppings were blown out. The overburden over the area was 85 m (280 ft).

The partial pillar recovery plan at Mine B was changed after the third airblast. Pillar measuring 20 x 20 m (65 x 65 ft) were extracted using the "Virginia 3 cut method" as shown in figure 5. In the collapsed areas where 12 x 12 m (40 x 40 ft) pillars were split, the extraction percentage was 78% as opposed to 74% using the 3 cut method. However, the 3 cut method leaves non-uniformly spaced stumps that have an irregular geometry in the gob. According to the mine operator, these stumps routinely yielded and crushed out. Since the 3 cut method has been used in Mine B, no airblasts have been recorded.

Mine C is located in Logan County, WV, and is extracting the 3 m (10 ft) thick Dorothy coalbed. The immediate and main roof throughout the mine is comprised of a fine grained semi-laminated sandstone with a CMRR=64, and the floor was composed of an extremely firm sandstone. Coalbed cleating was non-existent. All roadways in the mine were 6 m (20 ft) wide and were driven on 18 m (60 ft) centers in the concerned area.

In 1992, the operator was splitting pillars in the panel shown in figure 6. After the 6 m (20 ft) wide split, two 3 x 12 m (10 x 40 ft) fenders with a SF=0.94 to 1.15 remained. When the operator began to mine the pillar row outby the last row shown split, a massive collapse of the fenders in the gobbed out area initiated. The roof bolter operator on the section indicated that he and his coworkers were knocked to the floor by the resulting airblast and 103 stoppings were destroyed. Because the area was inaccessible, it could not be determined if the unsplit pillars located approximately at mid-panel (figure 6) had failed. The pillars where the collapse terminated had a SF=2.05. Overburden in the collapsed area ranged from 53-66 m (175-215 ft).

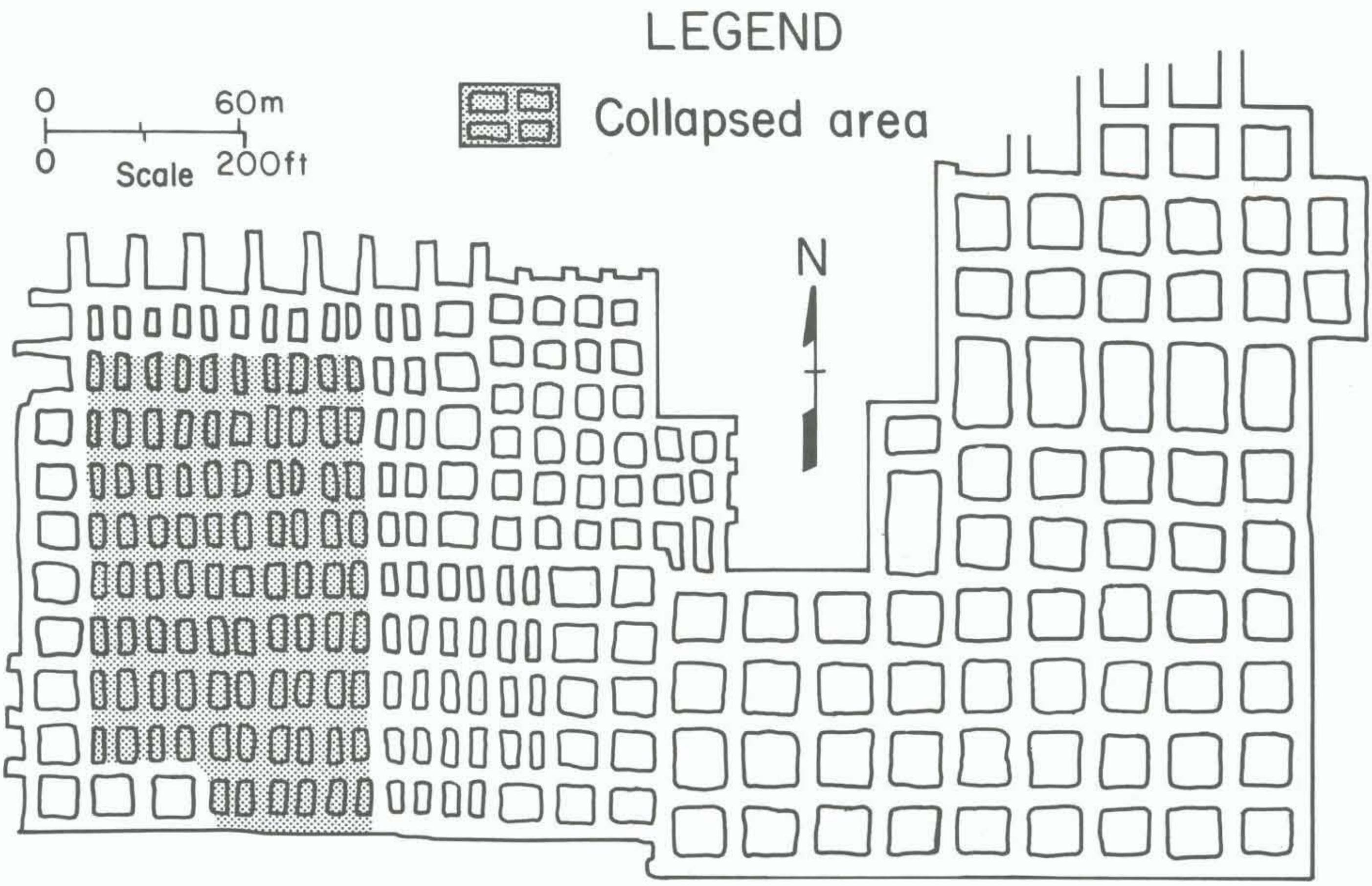

Figure 4. Location of the second pillar collapse at Mine B.

Mine C later experienced another pillar collapse, apparently triggered by time deterioration and the abutment pressures generated by full extraction. Roadways in the collapsed area were driven on 15 m (50 ft) centers and ninety-one pillars with a SF=1.15 failed. Pillars with a SF= 1.76 helped terminate the collapse. These roadways were driven on 18 m (60 ft) centers. No stoppings were damaged, and the overburden in the area was 99 m (325 ft).

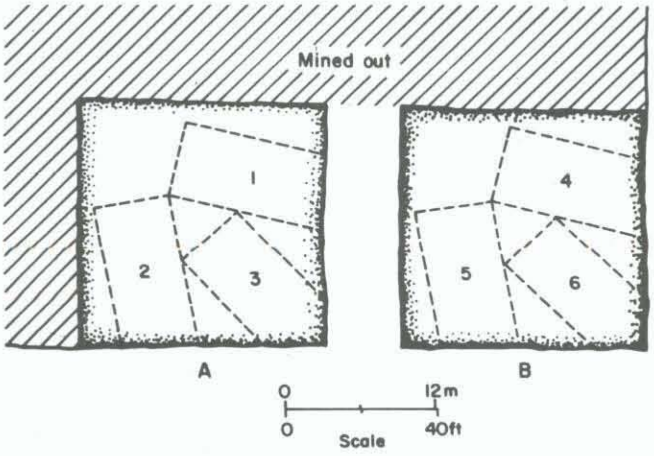

Figure 5. Virginia 3 Cut pillar extraction method.

Mine C was visited in February 1994, to observe diagonal pillar splitting which is not a very common practice. Roadways were driven on 15 m (50 ft) centers and the pillar splits were 5 m (16 ft) wide. The extraction percentage was 86%. The triangular shaped remnant stumps were observed to routinely crush out after finishing the pillar row, and the roof caved immediately inby the breakers. The breakers and wedges showed no weight. Where the first pillar collapse occurred in Mine C using the traditional 6 m (20 ft) wide split through a 12 x 12 m (40x40 ft) pillar, 78 pct of the coal was extracted. This 8 pct increase in resource recovery, coupled with a less stable triangular shaped stump with a smaller perimeter, may explain why the roof caves more readily than it does with traditional pillar splitting.

Mine D is located in Mingo County, WV, and is extracting the 3.4 m (11 ft) thick Dorothy coalbed. The roof consisted of 76 cm (2.5 ft) of laminated fossiliferous shale, 7 cm (3 in) of rider coal, and 24 m (80 ft) of cross-bedded sandstone was observed in the highwall. The roof had a CMRR=81. Below the non-cleated coalbed was 1.5 m (5 ft) of sandy shale and 28 m (91 ft) of sandstone. All roadways in the mine were 6 m (20 ft) wide.

In 1992, ninety four 6 x 6 m (20 x 20 ft) pillars with a SF=1.15 and thirty two 9 x 9 m (30 x 30 ft) pillars with a

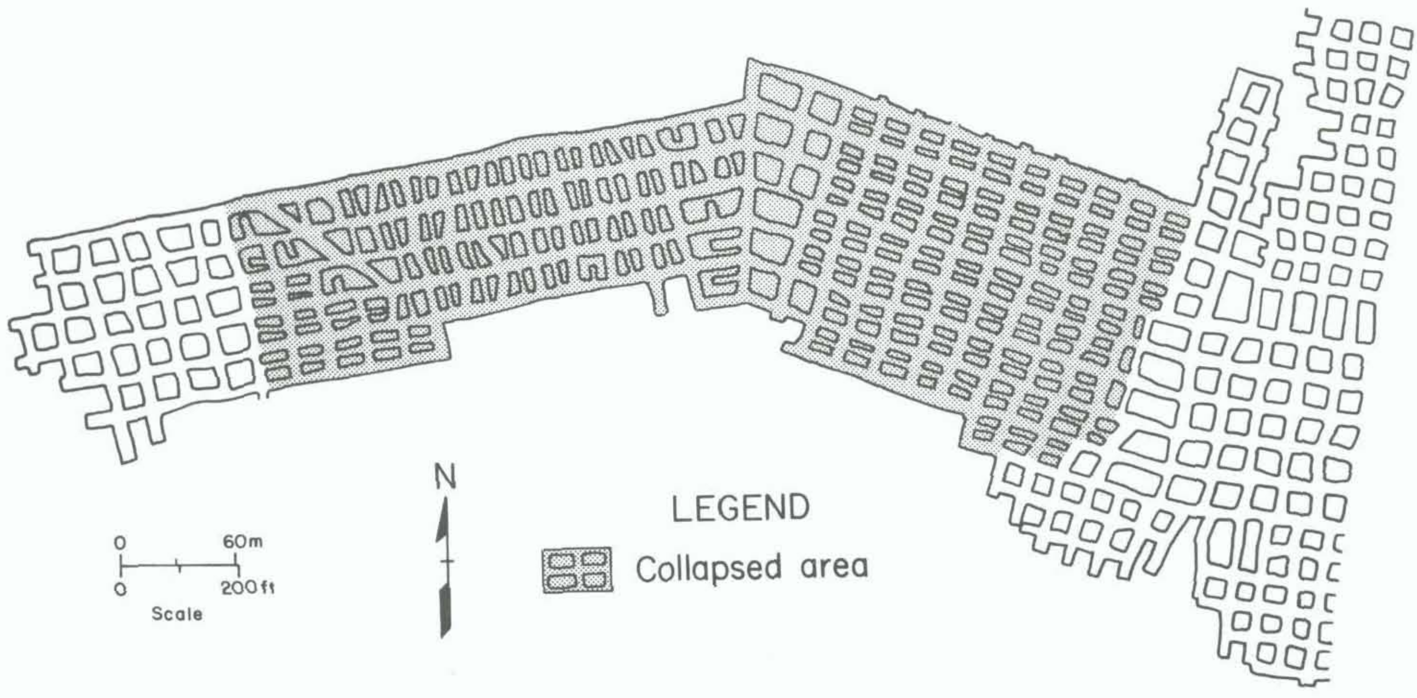

Figure 6. Location of the first pillar collapse at Mine C.

SF=1.45 failed. As shown in figure 7, the occurrence happened in a panel driven off the mains. The resultant airblast blew out 37 stoppings. The only other stopping in the mine had a hole in it. Some of these stoppings were as far away as 244 m (800 ft) from the perimeter of the collapse. In one stopping, it was determined that some of its 14 kg (30 lb) cinder blocks had been hurled 152 m (500 ft). Fortunately, the occurrence happened on a idle shift and no one was in the mine. The collapse was halted by pillars in the main entries which were 12 x 12 m (40 x 40 ft) and had a SF=3.38. Cover over the collapsed area was 69 m (225 ft).

DISCUSSION

Table 1 summarizes the pertinent information obtained from the field and the literature. In each case, the pillars had a SF of less than the recommended 1.50 (Bieniawski, 1987; Chase and Mark, 1993). Also, the pillars width to height ratio was 3.00 or less. Geotechnical evaluations of the roof at the four mines visited indicate that the roof was very competent (CMRR>64). Based on roof rock conditions cited in the literature, and discussions with the two concerned U.S. coal operators, the roof in the last three mines listed in Table 1 was also competent.

Evidence indicates that massive and competent roof rock units are able to bridge relatively wide spans, particularly when these units are aided by the support provided by the regularly spaced undersized pillars. When the extraction area is still small, the remnant pillars are not subjected to the full overburden load due to the stiffness of the roof. A pressure arch is created, with most of the weight being carried by barriers surrounding the extraction area. Eventually, the bridging capability of the main roof can be exceeded, either by over-extending the extraction area or by the weakening of the roof and/or remnant pillars over time. Once the pressure arch breaks down, the structural characteristics of the system are such that sudden, massive pillar failures can occur. The most important of these characteristics are the postfailure strength and stiffness of the coal pillars themselves.

Figure 8 presents complete stress-strain curves for laboratory tests on coal specimens with different width-to-height (w/h) ratios. These curves show the peak strength of the coal specimens and their postfailure modulus. Peak strength is the maximum applied stress on a specimen prior to the initiation of specimen failure. Postfailure modulus is the slope of the downward-curving portion of the complete stress-strain curve after peak strength. Figure 8 shows that peak strength increases as the w/h ratio increases. Furthermore, specimens with a w/h ratio less than three have almost no residual strength, which means that their load-bearing capacity decreases to almost zero after they fail. In addition, specimens with low w/h ratio have a lower (more negative) value for the postfailure modulus. As suggested in figure 8, the postfailure modulus increases and becomes positive beyond a certain w/h ratio.

The importance of the postfailure modulus of coal specimens and coal pillars is explained by theories of mine stability developed by Salamon (1970) and discussed by Zipf (1992). Salamon's stability theory explained the mechanics behind gradual, stable pillar failures and sudden, violent pillar collapses. The theory states that if the stiffness of the mine roof (the local mine stiffness) is less than the pillar's postfailure stiffness, the failure will be stable and gradual. Otherwise, if local mine stiffness exceeds postfailure stiffness,

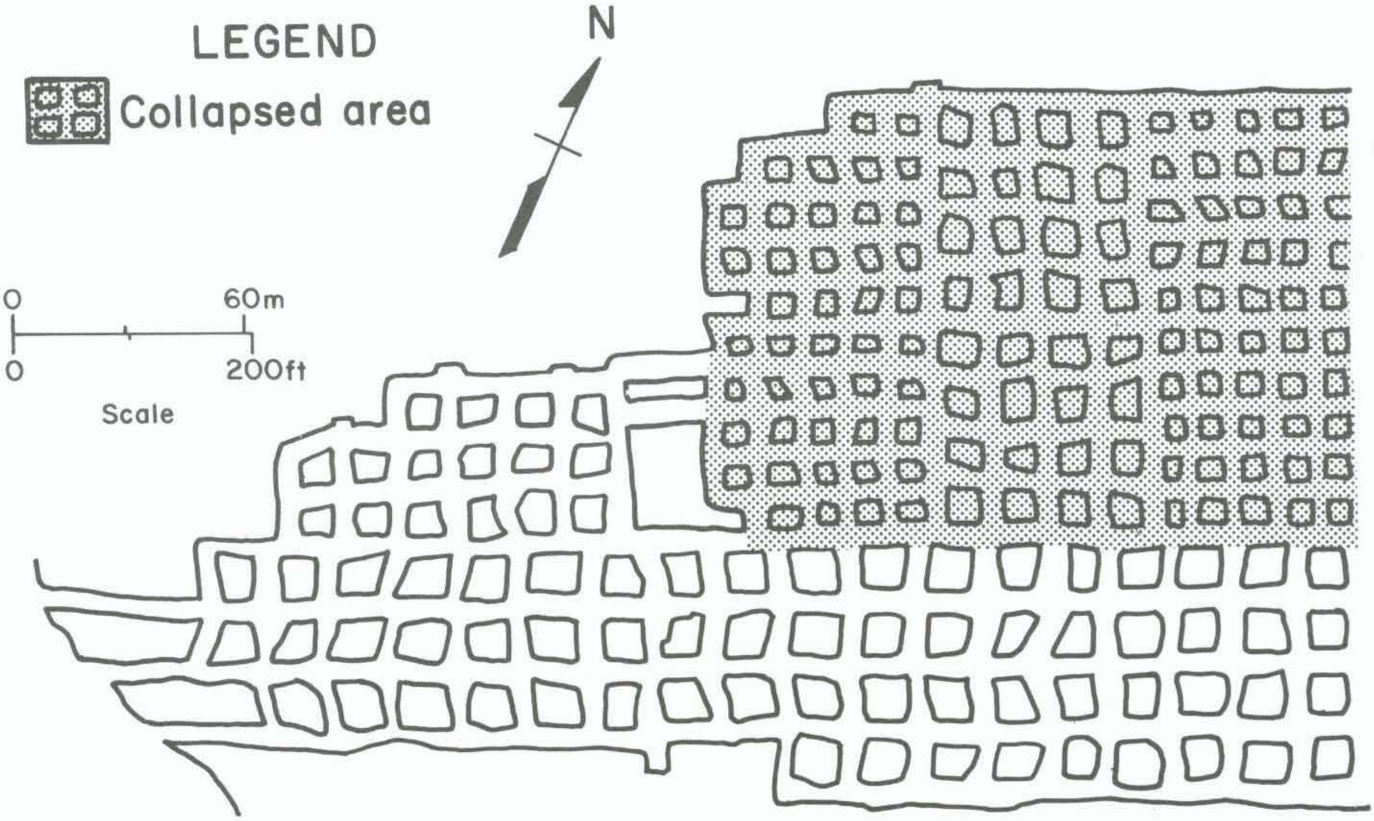

Figure 7. Failed development pillars in Mine D.

Table 1. Coal pillar and roof rock parameters for case histories

Mine	ARMPS SF	CMRR	w/h Ratio
A	0.75	74	1.05
B	0.84	77	1.00
	0.96		1.00
B	0.82	77	1.00
B	1.46	77	2.00
	1.30		3.00
C	0.94-1.15	64	1.00
C	1.15	64	3.00
D	1.15	81	1.82
	1.45		2.73
Not Indicated (6) . .	1.03	N/A	2.50
Roadside (1) . .	0.57	N/A	1.57
Coalbrook North	1.26	N/A	2.86

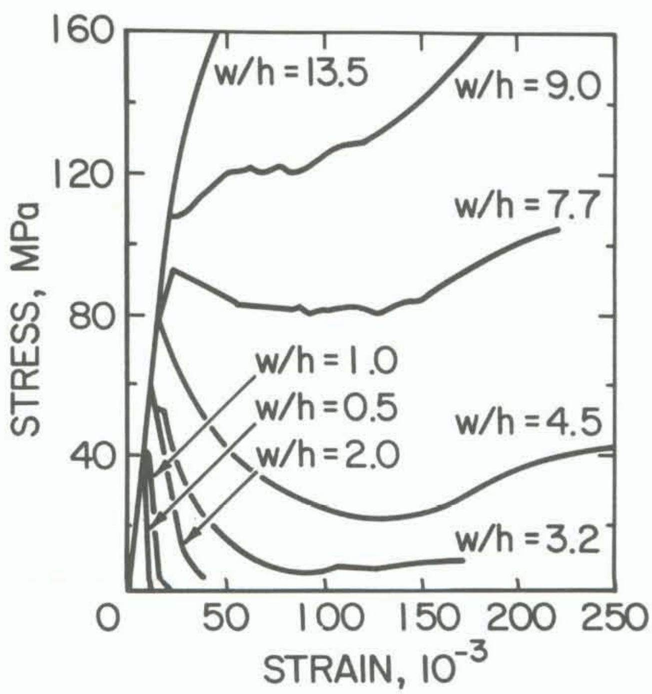

Figure 8. Complete stress-strain curves for Indian coal specimens, showing increasing residual strength with increasing w/h ratio (Das, 1986).

the failure is sudden and violent. We use a variation of the original theory to explain failure characteristics by considering the local mine modulus (K_{LMS}) relative to the postfailure modulus of the pillar (K_P). For K_{LMS} less than K_P the failure is stable and gradual; however, for K_{LMS} greater than K_P the failure is sudden and violent.

Figure 9 summarizes available postfailure modulus data for large in situ coal specimens and full-scale coal pillars. The dashed line indicates a conservative envelope for this limited in situ data. Also included in this figure are results from recent laboratory tests on Indian coals as reported by Das (1986). In general, the laboratory postfailure moduli exceed the large scale test values in magnitude. The laboratory data also suggests that beyond a w/h ratio of about 10, the postfailure modulus is always greater than zero. Since violent failure should be impossible for such strain-hardening materials, this observation may have important mine design consequences for avoiding catastrophic pillar collapses.

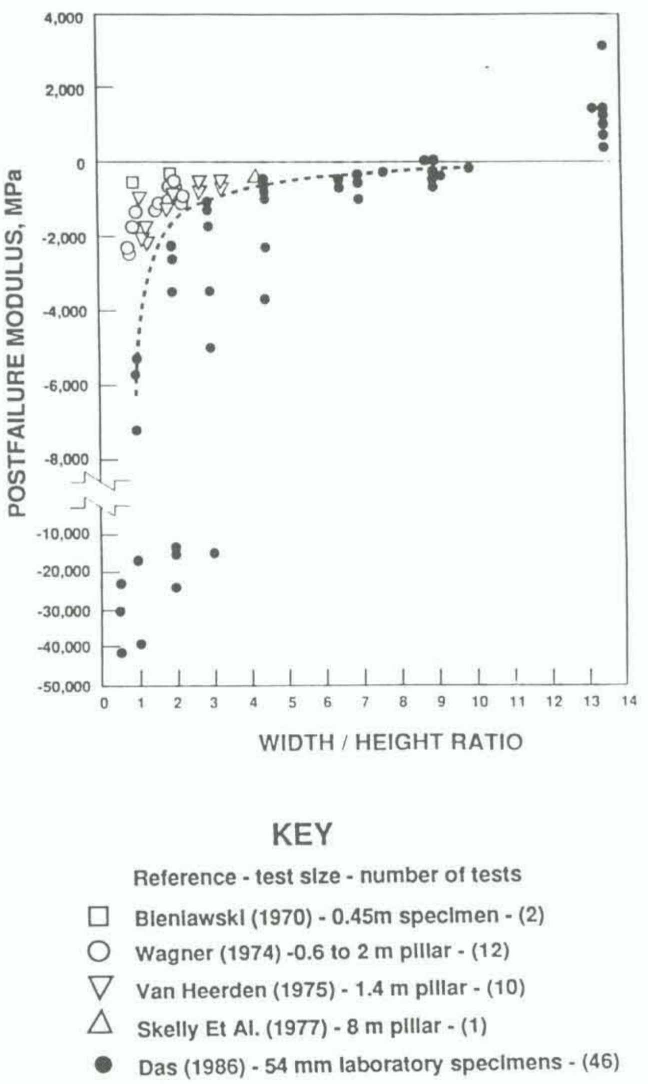

Figure 9. Postfailure modulus of coal pillars, in situ coal specimens, and laboratory samples.

NUMERICAL SIMULATION OF MASSIVE PILLAR FAILURES

Using a boundary-element-method (BEM) program similar to the USBM's MULSIM/NL program, it is possible to simulate sudden, massive pillar collapses and stable, progressive pillar failures. The collapse at Mine A, shown in figure 1, was used in these analyses to illustrate the mine stability theory. Since data on the postfailure modulus of the pillars (K_P) and the local mine modulus (K_{LMS}) is unknown, these analyses use assumed values, again, in order to illustrate the essential mechanics of massive pillar failures. For the stable case, the properties of the 3 m (9.5 ft) coal fenders with a w/h ratio of 1.05 were assumed to be an initial elastic modulus of 2,800 MPa (400,000 psi), a compressive strength of 11 MPa (1,600 psi), a residual strength after failure of 2.5 MPa (360 psi), and a postfailure modulus, K_P, of -833 MPa (-120,000 psi). This magnitude of K_P is high as suggested by the data in figure 9. The assumed compressive strength value for the pillars is slightly higher than the average stress of 9.4 MPa (1,360 psi) on the remaining fenders predicted by the tributary area theory. No field data is available to justify the assumed value for residual pillar strength after failure, although, experience suggests that this assumption is reasonable. The assumed rock mass modulus is 12,500 MPa, which means that the K_{LMS} approaches -12,500 MPa (-1,800,000 psi). Therefore, as shown in figure 10, this case satisfies the mine stability criterion since K_{LMS} is less than K_P. The BEM model should produce a stable failure.

Figure 11 shows calculated stresses and displacements after mining 4 and 9 rows of pillars, respectively. Pillars to the right of the peak stress line have not failed, while those to the left are in the process of failing. In other words, pillars to the right of the peak stress location line are on the ascending portion of the stress-strain curve shown in figure 10, while those to the left of that line are on the descending portion of the curve. Failure progresses gradually, and the stresses within pillars gradually decrease to the residual

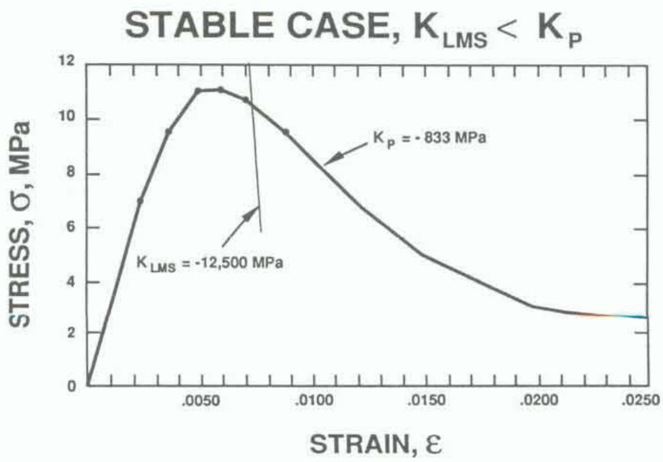

Figure 10. Pillar characteristics and Local Mine Stiffness used in the stable case BEM analysis.

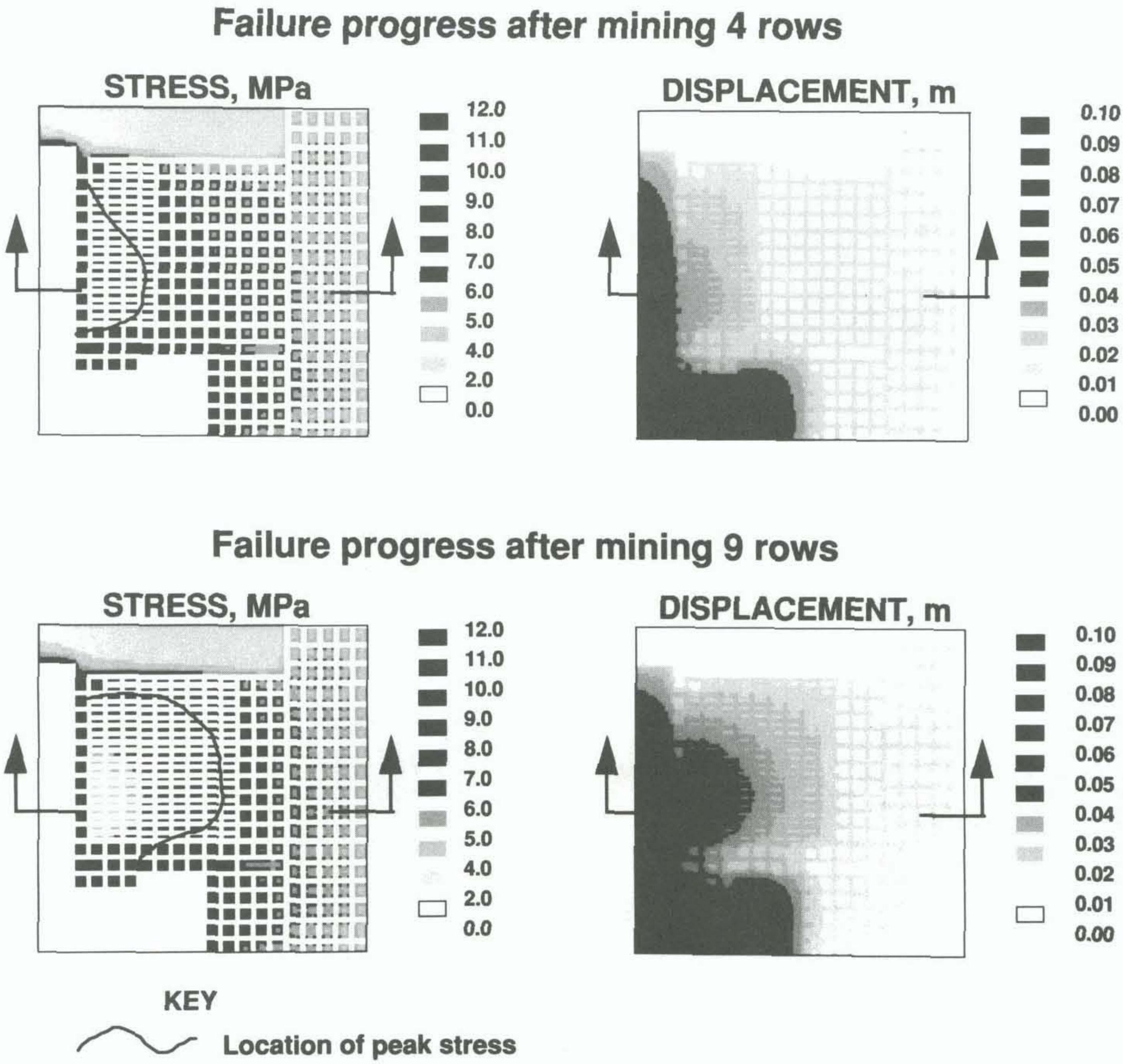

Figure 11. BEM results for the stable case.

stress level of 2.5 MPa (360 psi). Also, as shown in figure 11, displacements (convergence) in the panel increases gradually with additional mining. The failure progress follows the extraction progress, with each increment of mining leading to an approximately equal increment of additional failure. This illustrative BEM analysis closely approximates the desired behavior in room-and-pillar retreat mining, and unfortunately did not occur at mine A.

By assuming slightly different material properties, and thereby violating the mine stability criterion, the behavior of the panel takes on a completely different character. In the unstable case, the K_P of the coal fenders with w/h ratio of 1.05 was assumed to be -9,000 MPa (-1,300,000 psi) which is slightly high according to the postfailure modulus data shown in figure 9. A different rock mass value of 5,500 MPa (800,000 psi) is also assumed, which means that the K_{LMS} approaches -5,500 MPa (-800,000 psi). Therefore, as shown in figure 12, this case violates the mine stability criterion since K_{LMS} is greater than K_P. The BEM model should produce an unstable failure.

Figure 13 shows calculated stresses and displacements before and after the simulated massive pillar collapse.

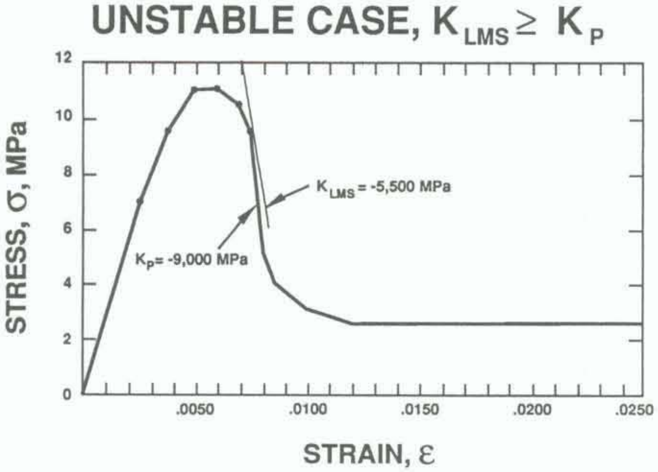

Figure 12. Pillar characteristics and Local Mine Stiffness used in the unstable case BEM analysis.

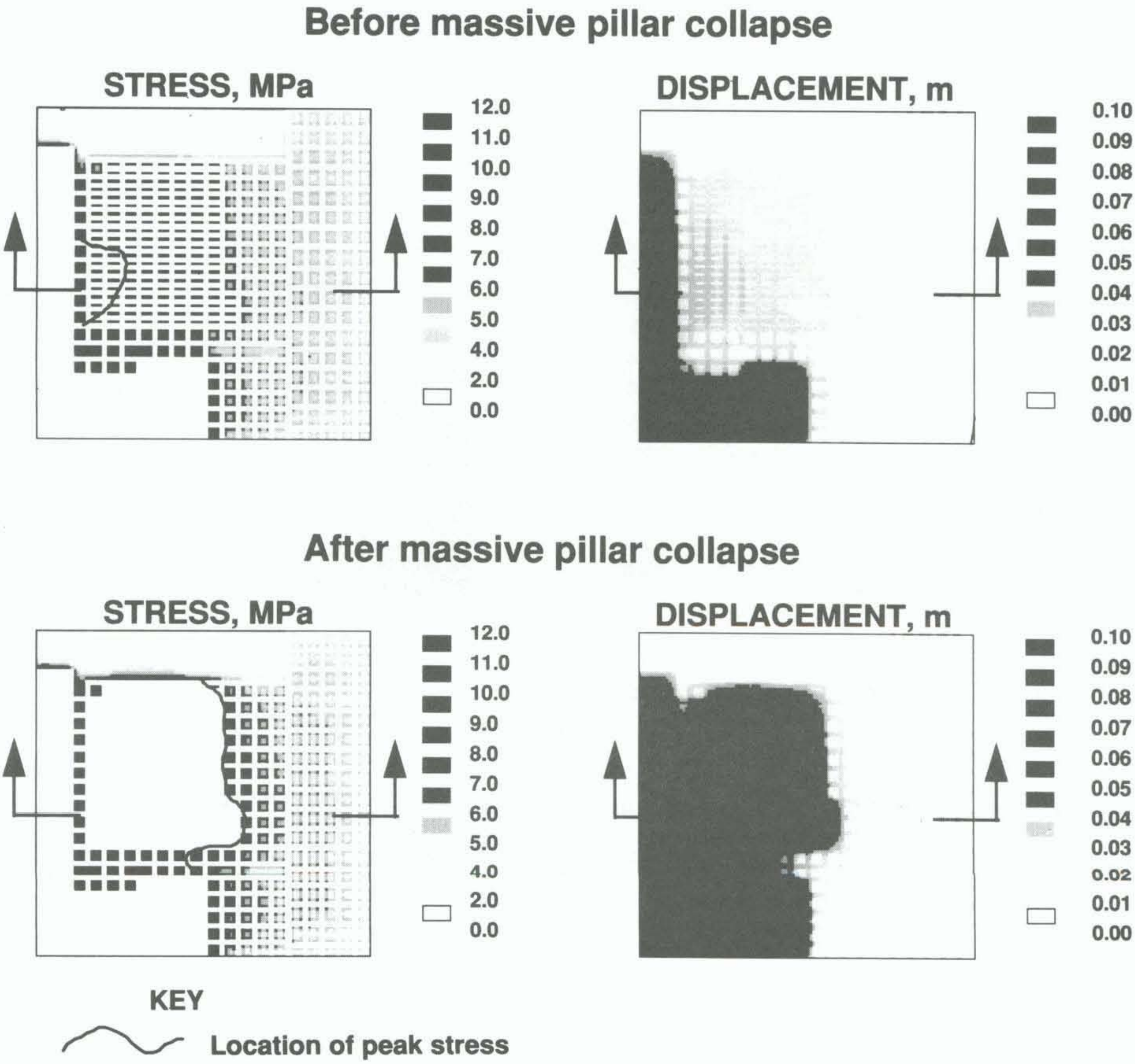

Figure 13. BEM results for the unstable case.

Before the failure, pillar splitting has been completed in 8 rows of pillars plus 2 pillars in the 9th row. Close examination of the stresses indicates that most of the fenders are approaching the peak stress of 11 MPa (1,600 psi). Again, pillars to the right of the peak stress location line are on the ascending portion of the stress-strain curve shown in figure 12, while those to the left of that line are on the descending portion of the curve. Splitting just one more pillar in the 9th row triggers disaster. An unstable "chain reaction" develops. As one pillar fails, it transfers load to adjacent pillars which in turn causes them to fail. Stress levels in the failed pillars decrease immediately to the residual stress level of 2.5 MPa (360 psi), as prescribed by the unstable stress-strain curve. The remaining stresses transfer to the fringes of the failed panel. Displacement (convergence) in the panel increases dramatically after the failure. Failure does not follow the mining progressively. The BEM analysis shows that a small increment of additional mining leads to a much larger increment of additional failure.

CONCLUSIONS

Massive pillar collapses, especially those which generate airblasts, can be devastating events. This study indicates that mines which have experienced collapses have similar characteristics, including competent roof strata, pillar w/h ratios of 3.0 or less, and ARMPS SF of less than 1.5. The cases cited from the literature also tend to confirm these findings.

Information collected at mines which have experienced air blasts, suggests that different strategies may be successful in preventing massive pillar failures under competent roof conditions. If partial pillar extraction must be conducted, increasing the extraction percentage and/or leaving less stable remnant pillars in the gob, as was the case with diagonal pillar splitting and the Virginia 3 Cut methods, might allow the roof to cave. If traditional pillar splitting is practiced and the roof will not cave, the amount of coal extracted can be limited with the intention of designing for long-term panel stability. This might be accomplished either by increasing the size of the remnant pillars, or by leaving rows of unsplit pillars as barriers between smaller areas of split pillars. Another strategy which has worked is to go to full pillar extraction. By removing the support provided by the remnant fenders left during traditional pillar splitting, the bridging capacity of the roof should be substantially reduced. If the roof does not break during full pillar extraction, caving can be induced through explosives as documented by Unrug (1991). Concerns on production time lost in high coal conditions setting turn posts into lifts can be alleviated by the employment of mobile roof supports.

The Boundary-Element-Method (BEM) model in conjunction with Salamon's (1970) mine stability criterion provides a tool to distinguish between unstable, violent pillar collapses, and stable, controlled pillar crushing. The BEM calculations show that when the mine stability criterion is violated, a small increment of additional mining can lead to a much larger increment of additional failure. With a realistic model, it is possible to examine different pillar geometries and different extraction sequences that might prevent a massive pillar collapse. The numerical models might enable us to predict situations when the risk of an unstable, massive pillar collapse is high. Presently, the biggest unknown in this kind of analysis is the shape of the complete stress-strain curve for a full-scale pillar. Back-analysis of other massive pillar collapses might provide some additional information.

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