ANALYSIS OF THE INTERACTION BETWEEN MOBILE ROOF SUPPORTS AND MINE STRATA

Hamid Maleki,
Maleki Technologies, Inc., Spokane, WA
and
John Owens,
Spokane Research Laboratory, National Institute for Occupational Safety and Health, Spokane, WA

ABSTRACT

Efficient and safe use of mobile roof supports (MRS) depends on the interaction between the MRS and coal strata. Of particular interest to this study are the mechanics of strata deformation as influenced by geologic conditions, pillar extraction methods, and MRS load-bearing capabilities. To provide a better understanding of the mechanics of strata deformation, the authors have collected and reviewed measurements of convergence and stress in one western U.S. mine and have completed pseudo-three-dimensional, boundary-element modeling for two typical pillar-pulling plans. Stress distribution in the mine roof above pairs of MRS's was calculated to demonstrate how MRS's contributed to the control of roof block movements.

It was shown that overall stress and roof-floor convergence patterns were most influenced by the stiffness of coal-measure rocks and by pillar-pulling sequences and layouts. MRS's and other support systems play a critical role in controlling the stability of both the immediate roof and the middle roof for a distance of up to 18 m (60 ft) above the seam. MRS's provide unique ground control advantages over other types of secondary support by significantly reducing the time between mining and installation of secondary support. Although MRS's are similar to posts in stiffness and capacity, they are more effective than posts under static loads because they can yield and still maintain loads at near-peak capacity, whereas posts fail and loose their ability to limit mine roof deformation.

INTRODUCTION

Mobile roof supports (MRS) consist of a roof canopy, four hydraulic cylinders, a caving shield canopy, and associated electromechanical systems mounted on crawler tracks. They are controlled by radio from a remote location and operate on self-contained power units. Typically, an MRS has a capacity of 5,340 kN (600 tons) (Wilson 1991). These supports are generally used in pairs during room-and-pillar retreat mining and replace conventional roadway, turn, and breaker posts. MRS's have been used successfully in more than 60 U.S. coal mines, as well as a number of Australian and South African mines (Shepard and Lewandowski 1992; Habenicht and Vrschitz 1986).

The former U.S. Bureau of Mines (USBM) developed a prototype unit in cooperation with an equipment manufacturer and tested this unit in cooperation with a mining company (Thompson and Frederick 1986). The goals were better control roof block movements in faulted and jointed mine settings and the reduction of crew exposure to unstable ground conditions. Commercial units have since been developed by U.S. and Austrian manufacturers and are being used on three continents.

MRS dimensions and designs vary depending on the manufacturer, and the way they are used depends on operator experience and ground control plans. The roof canopy area varies between 3.3 to 8 m^2 (35 to 85 ft^2) and operating height from 1.2 to 4 m (4 to 13 ft). Support capacity is typically 5,340 kN (600 tons), but several operations under deep cover are using MRS's having support capacities of 7,120 kN (800 tons). Support efficiency depends on the operating height. geology of the roof and floor, pillar-pulling method, and load-bearing capacities of the MRS's. Each support has the load-bearing capacity of six timber posts 20 cm (8 in) in diameter and the stiffness of two posts (Barczak and Gearhart 1997). Typical setting pressures are generally equal to one-third of the maximum rated support capacity. Yielding typically occurs after 2.5 cm (1 in) of entry closure. Unlike timber posts, an MRS is capable of maintaining the yield load after significant amounts of deformation (1 or 2 m of closure) under static loading conditions.

The mechanics of load transfer in room-and-pillar retreat mining is poorly understood, although the art of pillar extraction has evolved over the last century through trial and error, simple monitoring, and pillar-pulling experience in neighboring mines. Variations in geologic conditions and pillar-pulling methods and lack of comprehensive instrumentation programs for monitoring ground behavior during pillar pulling are among the factors that make it difficult to predict how strata will respond to pillar extraction.

Efficient use of MRS's depends on the interaction between the support and coal strata. Of particular interest to this study are the mechanics of strata deformation as influenced by geologic conditions, pillar-pulling methods, MRS load-bearing capabilities , and time-dependent deformation of the immediate roof and floor blocks. To provide a better understanding of the mechanics of strata deformation, the authors collected and reviewed measurements of convergence and stress in one western U.S. mine and completed pseudo-three-dimensional, boundary-element modeling (Crouch and Starfield 1990) for two typical pillar-pulling plans. Stress distributions in the mine roof above a typical MRS have also been calculated to demonstrate how the spacing of MRS's contributes to the control of roof block movements.

SITE DESCRIPTION

The mine is located within the Blackhawk Formation on the Wasatch Plateau, Utah. Both room-and-pillar and longwall mining techniques have been used for the extraction of the upper Hiawatha coal seam. Figure 1 presents the room-and-pillar layout and pillar-pulling sequence. Mining starts by driving a three-entry panel access to the boundaries of the room-and-pillar panels. A three-entry system using narrow rib pillars is developed to the side and retreated, as shown in figure 1. After pulling one row of pillars, another room is driven into the solid coal block, and the sequence is repeated until the panel coal is extracted. Pillar recovery operations consist of splitting the pillars and fenders (figure 1). The position of secondary support systems (either posts or MRS's) and the location of unmined stumps are shown in figure 1. Recent use of MRS's, however, have involved attempts to maximize resource recovery by extracting the pillar using a series of outside lifts.

The upper Hiawatha Seam is 4.3 m (14 ft) thick in the area of interest and contains two cleats oriented N 15°-20° W and N 75°-80° E. Faults and major joints strike N 20°-24° W, which is almost parallel to the direction of the face cleat. There is a secondary joint set oriented N 61°-73° E that dips 85° to the southeast. Room-and-pillar panels have been oriented 45° from the direction of the structures. Mining height varies from 2.5 to 3 m (8 to 10 ft), which leaves a meter or so of coal in the roof and floor.

Overburden consists of a series of thick-bedded sandstones and siltstones separated by thin-bedded claystones in the mine roof. Caving conditions are influenced by the position and thickness of the sandstones and siltstones within the Blackhawk Formation and the Castlegate Sandstone above. The cliff-forming Castlegate Formation is thick but of moderate strength. Regional data indicate a strength of 62 MPa (9,000 psi).

Considerable amounts of mechanical property data are available for the upper Hiawatha Seam and rocks of the immediate roof and floor (Maleki 1981). The coal seam is strong, with uniaxial compressive strengths varying from 21 to 33 MPa (3,100 to 4,800 psi). Uniaxial compressive strengths are 34 and 110 MPa (5,000 and 16,000 psi) for claystones and sandstones, respectively.

Far-field horizontal stresses are moderate and are oriented parallel to the direction of the structure. The minimum and maximum principal stresses are 4 and 7 MPa (700 and 1,000 psi), respectively. The coal seam is located under 275 to 365 m (900 to 1,200 ft) of cover.

MONITORING RESULTS AND FAILURE PATTERN

An extensive monitoring program was initiated in one room-and-pillar panel in the mine. Instruments are installed (1) in the gob to measure load transfer through the gob, (2) within the coal pillars to monitor pillar stress as pillars are split during the pillar-pulling operations, and (3) in the roof and floor to monitor strata movement. Analysis of load cells in the gob (Maleki and others 1985) indicated that caving conditions were periodic in nature, transferring significant loads to panel boundaries prior to the collapse of the main roof rocks. Analyses of pillar load measurements were used to determine the in situ strength properties for the upper Hiawatha coal seam (Maleki 1992).

An important part of the monitoring program was to develop simple methods for assessing roof stability and to warn against impending roof instability during pillar-pulling operations. In addition, the program was very useful in furthering the understanding of ground behavior prior to roof collapse. The analysis of convergence data identified critical rates of roof-floor convergence of 6 mm/min (0.25 in/min) beyond which roof and pillar stability problems would be likely. A warning device was subsequently developed at the Spokane Research Center of the USBM and used successfully for many years to detect roof stability problems (Maleki and McVey 1988). Similar monitoring techniques have been adopted by the Australian Coal Industry Research Laboratories and the Spokane Research Center in conjunction with pressure monitoring on MRS legs for assessing roof stability (Shepard and Chaturvedula 1992; Hay and others 1995).

Figure 2 presents typical monitoring results, the mining sequence, and the location of entry timber posts (excluding the location of timbers within the lifts). Marked spads and a transit were used at this location to monitor roof movements continuously as mining proceeded from the last fender in one pillar into a new pillar. There was no systematic roof bolting plan for this area, but mechanical bolts were installed locally near faults and/or joints.

Deformation data reflect several cycles of accelerated ground movement that indicate a change in the stability of the system. Note that there was slight increase in movement (2 cm [0.8 in]) during splitting of the fender (cuts A, B, and C) because the fender had yielded prior to initiation of monitoring and splitting. On the contrary, there was a significant increase in ground movement as the second fender was created and split (cuts G and H). At this mining step, the fender was being crushed, and ground movement was now controlled by the stiffness of unsplit pillars 6 to 9 m (20 to 30 ft) away. Changes in pillar stress confirmed that partially mined pillars remained stable before the last split was put into the pillar (Maleki 1981).

Figure 3 shows ground movement and mining activities prior to the roof falls. Prior to pillar splitting, overall stress distribution and ground deformation were influenced by the stiffness of the coal pillars, roof and floor rocks, and caved rocks. During pillar splitting, spans were increased, contributing to increased roof movement. These movements are generally small in a well-designed mining system. As fenders are split, the resistance provided by the fenders is reduced, resulting in a significant increase in convergence (time-dependent failure of stumps left in the gob has similar effects) (figure 3*B*). Crushing of the stumps increases bed separation in the roof, leading to failure of rock bolts (figure 3*C*), which then results in a roof fall. Supplementary support, such as timbers and MRS's, control the location and timing of roof falls.

STRESS ANALYSIS OF TYPICAL ROOM-AND-PILLAR LAYOUTS

Since the stiffness of coal-measure rocks is significantly higher than the stiffness of supports (including posts, bolts, and MRS's), overall stress distributions and strata movement are most influenced by geologic conditions, mine orientation in relation to discontinuities and stress fields, and pillar-pulling methods. Thus, to optimize roof stability and to improve productivity, it is important to have careful mine layout designs and proper mine orientations (Maleki and others 1991).

Calculated entry closure and stress distributions were compared for two pillar-pulling plans using the material property values measured in the study mine (Maleki 1990). Table 1 presents model input. Figures 1 and 4 show the pillar mining sequence, which consists of up to four mining steps. Pillar core was modeled elastically, and fenders were assumed to remain elastic until peak strength was reached, after which pillars unloaded to a residual strength (Maleki 1992). Figure 5 presents stress distributions for the split-and-fender method.

Table 1.—Pillar strength values and model input

	Peak residual strength			Young's modulus	
	MPa	psi		MPa	psi × 10^6
Pillar ribs . . .	13.2 - 26.3	1,910 - 3,820	Roof and floor . . .	6,820	0.99
Pillar core . . .	Elastic	Elastic	Coal	1,380	0.20
Fenders	2.8 - 10.3	400 - 1,500	Gob	1,030	0.15
MRS	0.6	90	MRS	276	0.04

Figure 6 shows calculated roof-floor convergence for a point (B) located in the intersection for two pillar-pulling plans (figures 1 and 4). Note that calculated deformation significantly increases within a mining step and is associated with pillar unloading to residual strength. Pillar unloading events are thus associated with a significant increase in loading (both vertical and horizontal) of the secondary support systems. MRS's will therefore experience an increase in both vertical and lateral support loading as fenders unload. Because fender unloading induces differential movement in the mine roof, a roof fall may be triggered, which may be sensed through monitoring either convergence rate or possibly leg pressures on the MRS. Calculated deformation depends on the pillar-pulling method. The Christmas tree method is associated with greater extraction and greater entry closure.

LOCALIZED STRESS DISTRIBUTION IN THE MINE ROOF

Since MRS's control the stability of the immediate roof rocks, it is important to examine stresses in the mine roof induced by the MRS canopy. Analytical solutions are available to determine induced stresses in the mine roof for flexible loading plates (Das 1994). Figure 7 shows the so-called pressure bulb above the centerline of a pair of MRS's set side by side in an entry at an effective load of 4,440 kN (500 tons). This analysis assumes a single layer of roof rock and excludes pillar reactions.

Results indicate that pressure applied to the roof reaches a maximum near the opening and becomes insignificant by a distance of 18 m (60 ft) into the roof. Because MRS's have a limited area of support influence, it is important to place them under supported roof during pillar-pulling operations. Note that induced stresses are quite small in comparison to the strength of typical coal mine roof rocks (55 to 110 MPa [8,000 to 16,000 psi]), and thus the best method of inducing a cave is through proper mine orientation with respect to geological discontinuities.

Figure 8 shows the induced stresses in the mine roof for two pairs of MRS's at 5.5-m (18-ft) spacings. This condition typically results during the pushout mining cycle where pairs of MRS's are used while a continuous miner works between the supports. Note that the MRS pairs are helpful in applying upward force to the upper roof, but contribute least to the stability of the immediate 1.5 m (5 ft) of roof between the two pairs of MRS's. This very immediate roof should be supported with roof bolts, and the roof bolts should not fail because of excessive ground movement and/or high setting pressures against the roof.

SUMMARY AND RECOMMENDATIONS

The mechanics of load transfer has been analyzed in this report using analyses of field data, boundary-element modeling, and analytical solutions. It was shown that overall stress and roof-floor convergence patterns are most influenced by the stiffness of coal-measure rocks and pillar-pulling layouts. MRS's and other support systems play a critical role in controlling the stability of both the immediate roof and the middle roof for a distance of up to 18 m (60 ft) above the seam. MRS's provide a unique ground control advantage over other types of secondary support by significantly reducing the time between mining and installation of secondary support. Although MRS's are similar to posts in stiffness and capacity, they are more effective than posts because they can yield a meter or so but still maintain loads at near peak capacity, whereas posts fail under less than 2.5 cm (1 in) of convergence and lose their ability to limit deformation of the mine roof.

Optimum and safe use of MRS's depends on careful mine layout designs, mine orientation, and pillar-pulling methods, and prudent selection of primary support designs for the expected geologic and stress conditions. MRS's have a limited zone of influence around them and thus can best be utilized in combination with other MRS's and in conjunction with ground monitoring systems. Higher MRS capacities and setting pressures are considered useful for stabilizing the upper strata, but high setting pressures may contribute to differential loading of the immediate roof, failure of mechanical bolts, and a reduction in the stability of the immediate roof. The existing industry setting pressure standard of 10 MPa (1,500 psi), one-third of capacity, is reasonable because MRS's work in areas where significant deformation occurs.

REFERENCES

Barczak, T., and D. Gearhart, 1997. Full-Scale Performance Evaluation of Mobile Roof Supports. Paper in *Proceedings: New Technology for Ground Control in Retreat Mining*, comp. by C. Mark and R. Tuchman (Pittsburgh, PA). NIOSH IC 9446, pp. 99-126.

Crouch, S., and T. Starfield, 1990. *Boundary Element Methods in Solid Mechanics*. Routledge Chapman and Hall.

Das, M. Braja, 1994. *Principles of Geotechnical Engineering*, 3rd ed., PWS Pub., 672 pp.

Habenicht, H., and E. Vrschitz, 1986. Rib Pillar Extraction: An Alternative to Long Walling and Short Walling. SME Preprint 86-65, SME annual meeting, New Orleans, LA, March 2-6, 1986, 14 pp.

Hay, K. E., S. P. Signer, and M. E. King, 1995. Monitoring Mobile Roof Supports. Paper in *Proceedings of 14th International Conference on Ground Control in Mining*, ed. by S. S. Peng (Morgantown, WV, Aug. 1-3, 1995). Dept. of Mining Engineering, WV Univ, 1995, pp. 55-62.

Maleki, H., 1981. Coal Mine Ground Control. Ph. D. dissertation, Colorado School of Mines.

Maleki, H., 1990. Development of Modeling Procedures for Coal Mine Stability Evaluation. Paper in *Rock Mechanics Contributions and Challenges: Proceedings of the 31st U.S. Symposium*, ed. by W. A. Hustrulid and G. A. Johnson (CO School of Mines, Golden, CO, June 18-20, 1990). Balkema, pp. 85-92.

Maleki, H., 1992. In Situ Pillar Strength and Failure Mechanisms for U.S. Coal Seams. Paper in *Proceedings of the Workshop on Coal Pillar Mechanics and Design*, comp. by A. T. Iannacchione, C. Mark, R. C. Repshar, R. J. Tuchman, and C. C. Jones (Santa Fe, NM, June 7, 1992). U.S. Bur. Mines IC 9315, pp. 73-77.

Maleki, H., R. Acre, and A. Weaver, 1991. Stress-Induced Stability Problems. A Coal Mine Case Study. Paper in *Rock Mechanics as a Multidisciplinary Science: Proceedings of the 32nd U.S. Rock Symposium*, ed. by J-C. Roegiers (Univ. OK, Norman, OK, July 26-28, 1991). Balkema, 1991, pp. 1057-1054.

Maleki, H., W. Hustrulid, and D. Johnson, 1985. Pressure Measurements in the Gob. In *Research and Engineering Applications in Rock Masses. 26th U.S. Symposium on Rock Mechanics* (SD School of Mines and Technology, Rapid City, SD, June 26-28, 1985). Balkema, pp.

Maleki, H., and J. R. McVey, 1988. Detection of Roof Instability by Monitoring the Rate of Movement. U.S. Bur. Mines RI 9170, 12 pp.

Shepherd, J., and K. Chaturvedula, 1992. Strata Mechanics of Pillar Extraction Goaf Edges. Paper in 11th International Conference on Ground Control in Mining, Proceedings, ed. by N. I. Aziz and S. S. Peng (Univ. of Wollongong, Wollongong, Australia, July 7-10, 1992). Australasian Institute of Mining and Metallurgy, Wollongong, New South Wales, Australia, pp. 345-350.

Shepherd, J., and T. Lewandowski, 1992. Modified Wongawilli Extraction with Mobile Breaker Line Supports: Preliminary Geomechanics. *Aust. Coal J.,* No. 38, pp. 41-47.

Thompson, R., and J. Frederick, 1986. Design and Field Testing of Mobile Roof Support for Retreat Mining. Paper in *Proceedings, 5th Conference on Ground Control in Mining* (Morgantown, WV, June 11-13, 1986). WV Univ., pp. 73-79.

Wilson, H. G., 1991. Mobile Roof Support for Retreat Mining. Paper in *10th International Conference on Ground Control in Mining, Proceedings,* ed. by S. Peng (Morgantown, WV, June 10-12, 1991). Dept. of Min. Eng., WV Univ., pp. 103-114.

Yoder, E. J., and M. W. Witczak, 1975. *Principles of Pavement Design.* John Wiley and Sons.

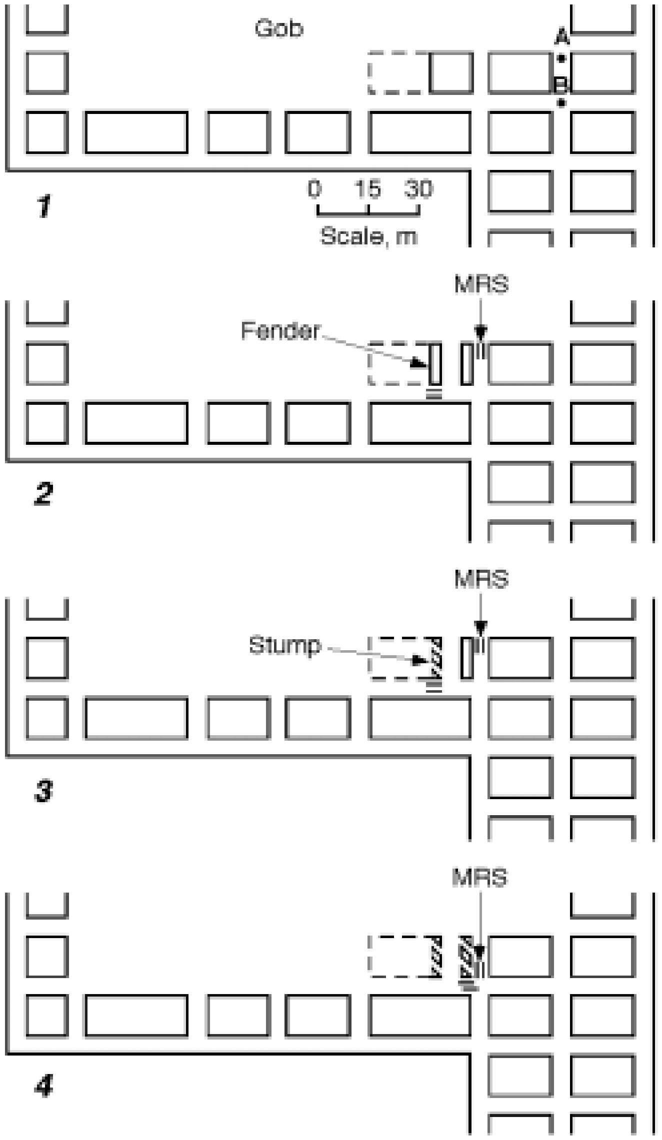

Figure 1.—Mine layout and pillar-pulling sequence for Wasatch Plateau mine, steps 1-4.

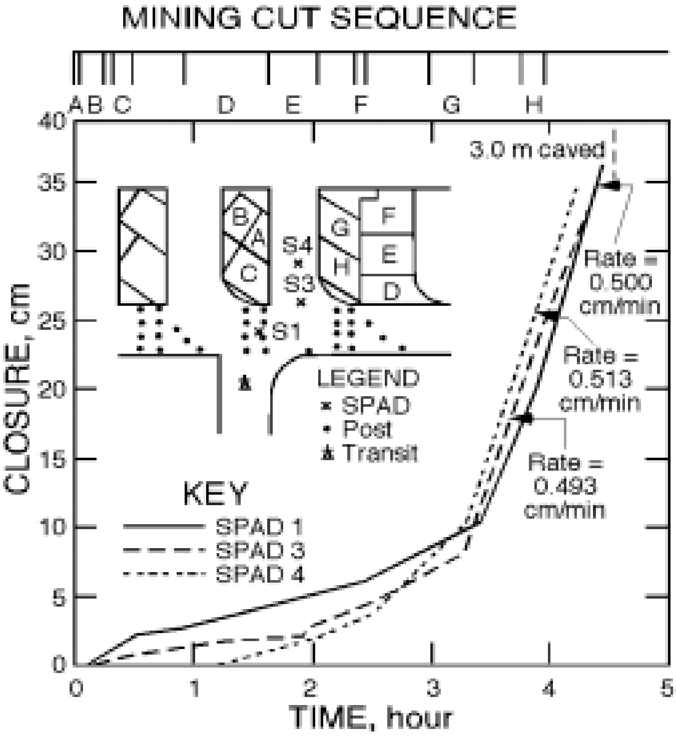

Figure 2.—Roof-floor convergence versus mining face position.

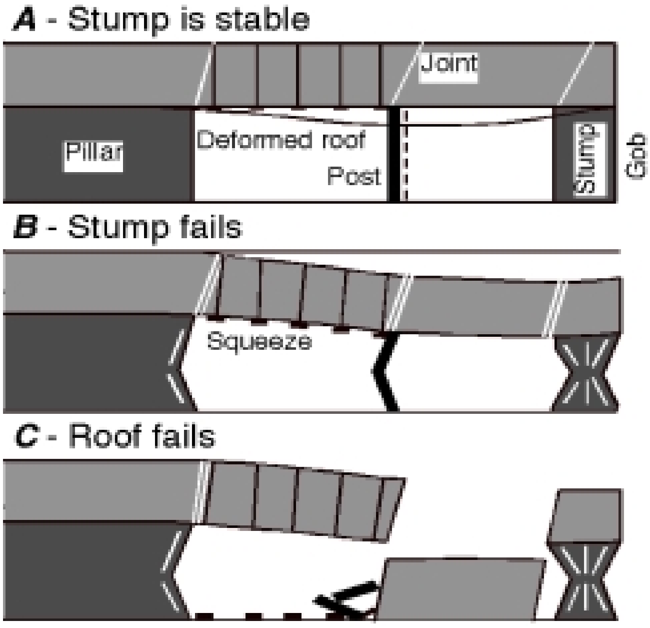

Figure 3.—Schematic of strata movement and roof failure.

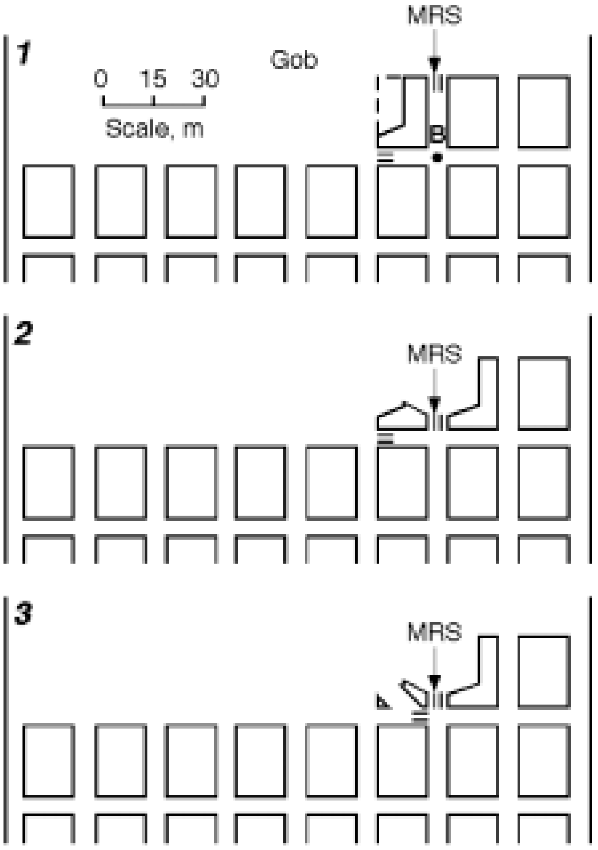

Figure 4.—Mine layout and pillar-pulling sequence using Christmas tree method, steps 1-3.

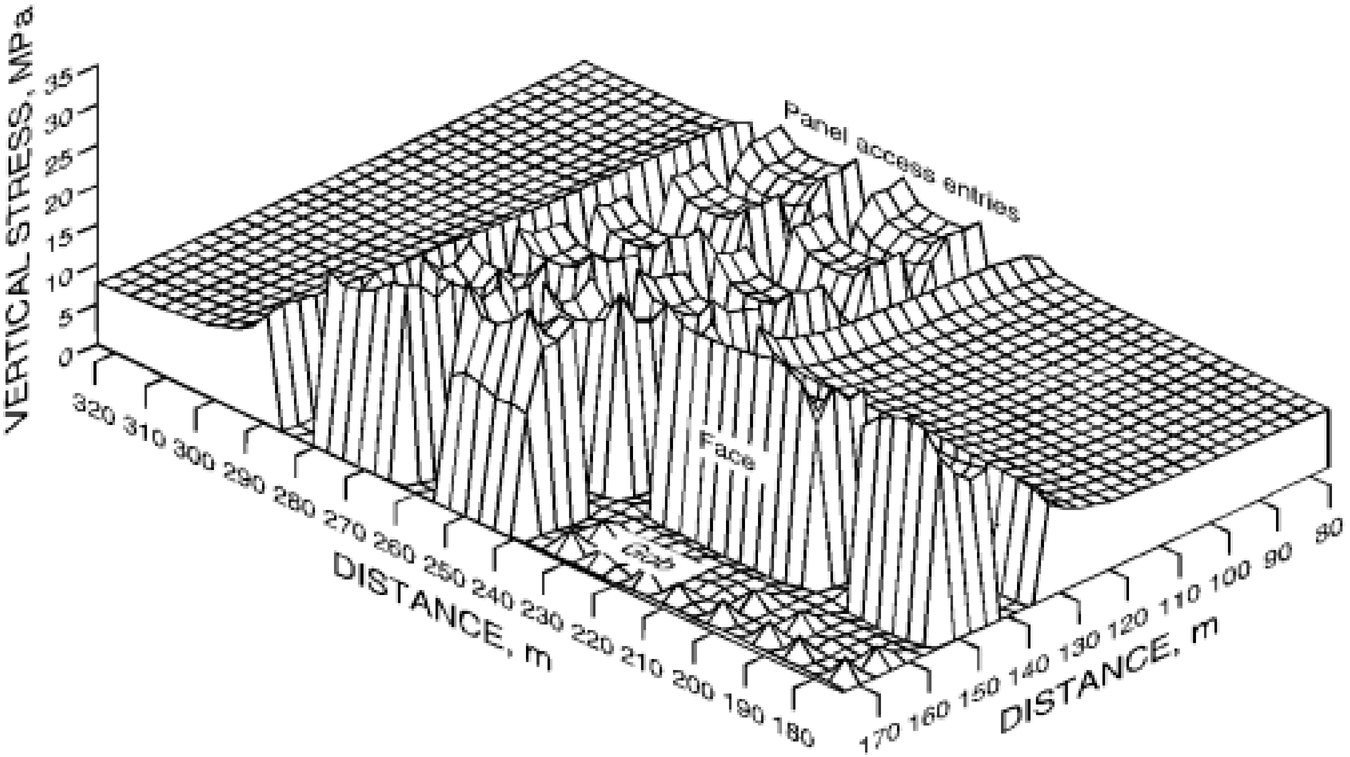

Figure 5.—Vertical stress distribution for split-and-fender method, step 4.

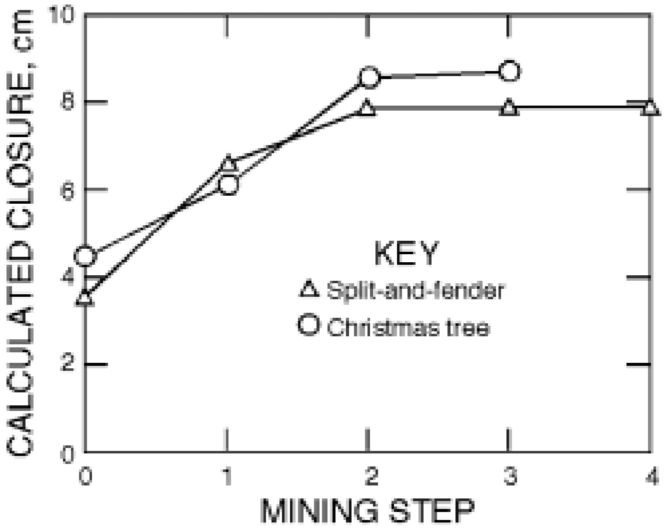

Figure 6.—Calculated closure for split-and-fender and Christmas tree methods at location B.

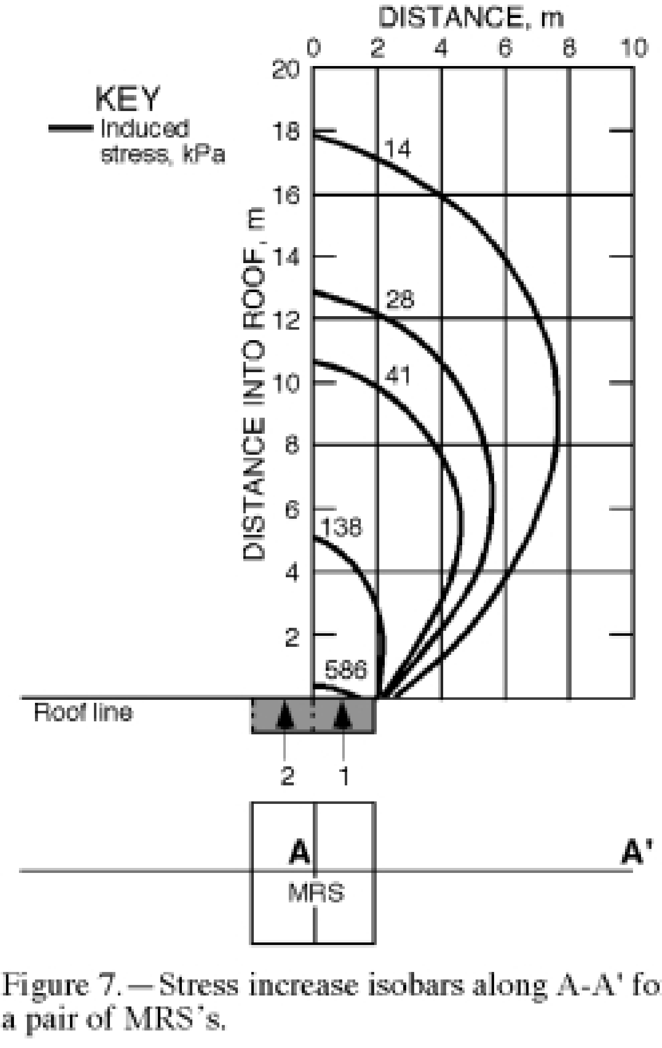

Figure 7.—Stress increase isobars along A-A' for a pair of MRS's.

LIST OF FIGURES