FIELD EVALUATION OF MOBILE ROOF SUPPORT TECHNOLOGIES

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Abstract

This study presents a historic overview of the role of mobile roof support (MRS) technologies in improving stability and worker safety and presents the results of recent field evaluations of the MRS load rate monitoring device and other remote deformation-monitoring techniques. Field studies were implemented at two sites in cooperation among researchers from the National Institute for Occupational Safety and Health (NIOSH), Maleki Technologies, Inc., and J. H. Fletcher & Co. The objective of the field programs were to (1) study the interaction between MRS's and coal mine strata and (2) develop and test suitable monitoring systems for assessing roof and pillar stability. An MRS consists of a roof canopy, four hydraulic cylinders, a caving shield canopy, and associated electromechanical systems mounted on crawler tracks. The machines are controlled by radio from a remote location and operate on self-contained power units. Typically, MRS's have capacities of 5,340 and 7,120 kN (600 and 800 tons). In comparison to posts, an MRS is capable of maintaining the yield load after significant amounts of roof-floor deformation. Because the mining cycle is accelerated, MRS's help reduce the potential for time-dependent roof falls.

MRS performance has been monitored in the laboratory under controlled static loading conditions and in the field under deep, two-seam mining conditions. Laboratory studies have quantified support capacity and system stiffness as a function of machine height. Field investigations have focused on determination of optimum operating conditions and development of warning systems that indicate excessive load on the machine and/or impending roof-pillar stability problems. Analyses of field data show that roof instabilities are influenced by (1) pillar failure, (2) pillar yielding, (3) mine seismicity, (4) geologic structures, and (5) panel layout designs and mining practice. Pillar yielding and failure (unloading) and seismicity can be conveniently monitored by the load rate monitoring device, but for consistent detection of roof falls, additional deformation measurements directly within the cuts are needed.

INTRODUCTION

Room-and-pillar mining is one of the oldest methods used for the extraction of tabular ore bodies. In this method, a series of rooms are driven on advance using continuous miners and shuttle cars while the roof is bolted a short distance behind the face. During the retreat, the same equipment is used to mine the pillars, which allows roof rocks to cave behind the face. To control the cave line, a series of secondary support systems are installed as mining continues within the pillars.

The room-and-pillar mining method is at a disadvantage when compared to other mining techniques, such as longwall mining. Because of economies of scale, productivity using room-and-pillar mining is significantly lower. The longwall method is also much safer because the retreat is completed under the protection of self-advancing hydraulic support systems at the face. However, during the last two decades, federal laboratories, mining companies, equipment manufacturers, and geomechanics consultants have cooperated to improve the understanding of strata mechanics and develop a remotely controlled, self-advancing support system called a mobile roof support (MRS). This cooperation has resulted in improvements in the safety and productivity of room-and-pillar retreat operations.

Figures 1 and 2 illustrate generic panel layouts and pillar extraction sequences for two typical room-and-pillar retreat systems. The first is three-entry access and retreat to one side, while the second is nine-entry access with full retreat within the panel. In the first system, mining starts by driving a three-entry panel access to the boundaries of the room-and-pillar panel. A three-entry system using narrow rib pillars is developed to the side and retreated. After pulling one row of pillars, another row 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*A* presents the mine layout at four stages of pillar recovery. Figure 1*B* shows the sequence of the pillar cuts, typical position of posts, and the location of unmined stumps for the extraction of a pillar using the split-and-fender method.

In the second system, a nine-entry access is developed on advance to the panel boundaries. The pillars are then extracted until the entire panel is mined. Figure 2*A* presents a panel layout and the location of MRS's at three intermediate stages of pillar recovery using the "Christmas tree" method. Figure 2*A* shows the sequence of cuts taken from two pillars where MRS's are used as secondary support. Many variations in these two panel layouts and excavation sequences are

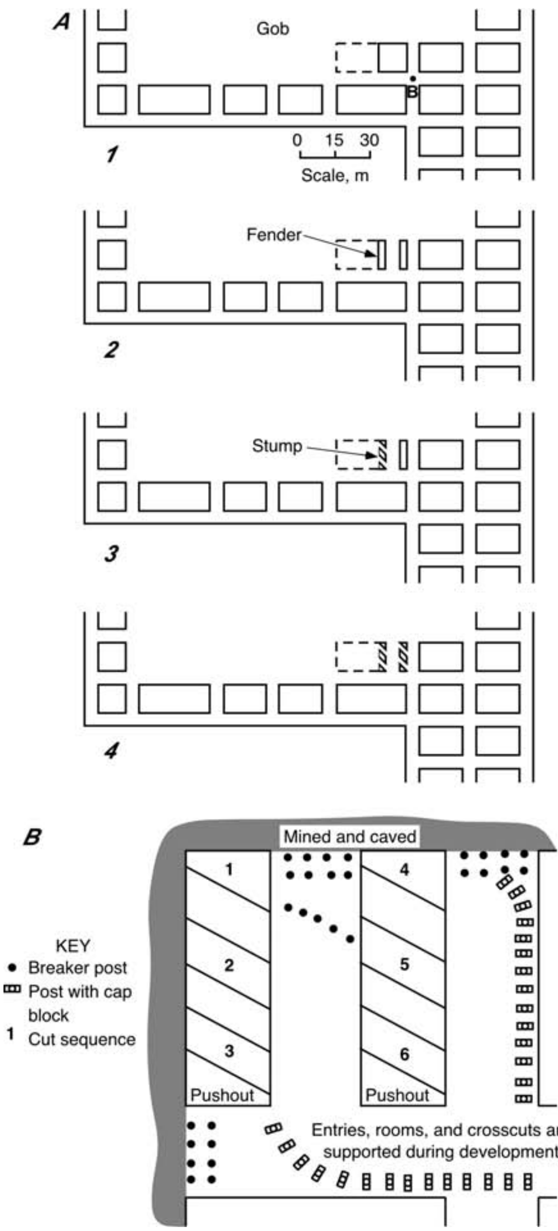

Figure 1.—Mine layout (*A*) and pillar extraction sequence (*B*) using split-and-fender method with posts.

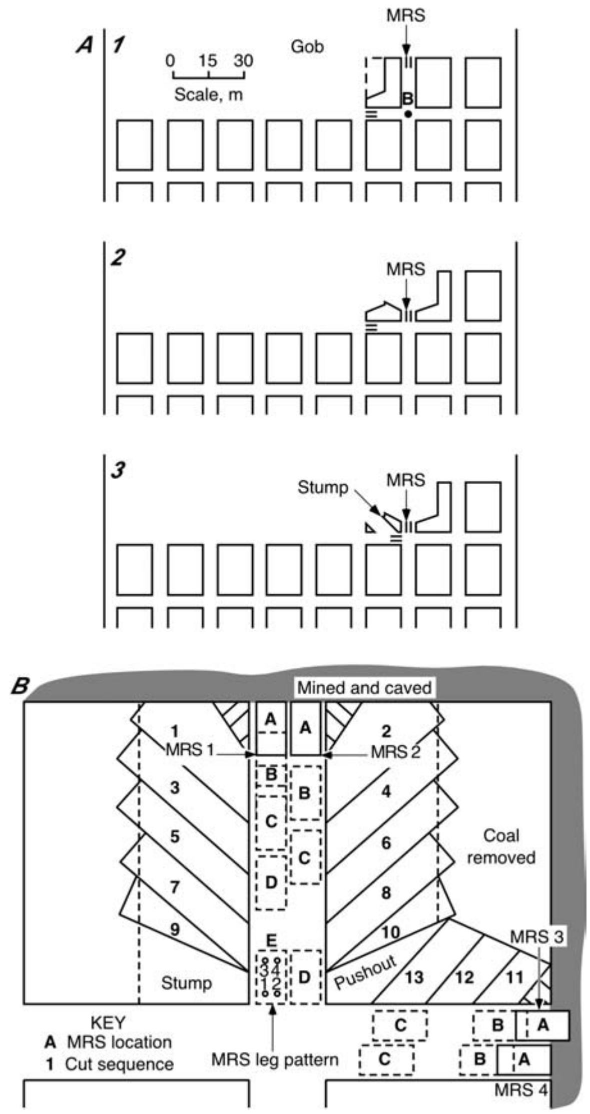

Figure 2.—Mine layout (*A*) and pillar extraction sequence (*B*) using Christmas tree method with MRS's as support.

practiced in U.S. coal mines. New applications of the three-entry system involve use of MRS's instead of posts and eliminates fenders completely.

After completing an analysis of the hazards of room-and-pillar retreat mining systems, it became apparent to the authors that safety could be significantly improved by considerations of (1) human factors, (2) remotely controlled MRS's, (3) mine layout designs, and (4) ground monitoring systems. A significant effort was directed to studying the above factors both in the laboratory and in the field. Recent geomechanics field evaluations focused on identifying failure mechanisms and critical levels of load and movement rates that are indicative of impending stability problems.

HUMAN FACTORS

Several human factors considerations were identified during an earlier geomechanics field study (Maleki 1981) in which the main objective was to identify causes of roof stability problems and develop practical monitoring techniques for detecting these problems (Maleki and McVey 1988). These factors were (1) the number of people required at the face, (2) the amount of time required to work at the cave line, (3) poor footing in entries, which influenced timely escape during a roof fall, (4) worker reaction at the time of a roof fall, and (5) the judgment-based methods used by miners to evaluate the stability of the roof and determine the optimum time for retrieving miners and equipment.

A large crew is required for conventional room-and-pillar retreat operations because posts must be delivered, cut to size, and installed. Each installation takes approximately 20 minutes and requires two to three workers. Debris on a mine floor can accumulate quickly and create poor footing. Miners must judge roof stability continually on the basis of observations of primary and secondary support behavior (bending of roof plates, crushing of posts, etc.). In the study mine, when the roof caved prematurely and trapped a miner in a cab, other miners rushed to help. A second rock fall could have resulted in serious injury to rescuers (Maleki 1981). This could have easily happened, considering that many posts had already been broken and some had been knocked down during the first fall.

DEVELOPMENT AND TESTING OF MRS

To improve the safety of room-and-pillar retreat systems, a two-step solution was proposed. First, the mechanics of strata behavior was studied through extensive field measurements, and practical techniques for assessing roof behavior were developed. Second, a prototype of a remotely controlled roof support system was developed to eliminate the need to install posts near the gob. The machine was equipped with a dozer blade so that floor debris could be cleaned routinely, which allowed easier travel and escape. The prototype unit was developed by the U.S. Bureau of Mines in cooperation with an equipment manufacturer and a mining company (Thompson and Frederick 1986).

Commercial units have since been developed by U.S. and Austrian manufacturers and are being used on two continents. The commercial MRS units are more rugged and have higher capacities (5,340 to 7,120 kN [600 to 800 tons]) (Wilson 1991; Howe 1998) than the prototype. They consist of a roof canopy, four hydraulic cylinders, a caving shield canopy, and associated electro-mechanical systems mounted on crawler tracks. The system has radio control and self-contained power units. Because of their greater mobility and because they allow higher resource recovery, they are currently being used in 36 U.S. coal mines, as well as a number of Australian mines (Shepherd and Lewandowski 1992; Habenicht 1988).

MRS performance has been monitored both in the laboratory and in the field by NIOSH and MTI personnel. Laboratory investigations focused on an evaluation of support stiffness and load-carrying capacity under controlled static loading conditions. The study quantified system stiffness as a function of machine height for both two- and three-stage hydraulic cylinders (Barczak and Gearhart 1997, 1998). The advantage of the three-stage cylinder design is greater operating range, but a disadvantage is reduced support stiffness. Each unit has the load-bearing capacity of six posts and the stiffness of two hardwood posts (Barczak and Gearhart 1997). The study also identified inaccuracies in hydraulic cylinder pressure measurements of roof loads when the bottom cylinder stages were fully extended.

The mechanics of load transfer from pairs of MRS's to the mine strata was analyzed using laboratory results, boundary-element modeling, and analytical solutions. The results showed that MRS's support roof rocks near the machines, but do not have the capacity to control overall roof-floor convergence and overall stress distributions because the MRS's are considerably less stiff than coal-measure rocks. In comparison to posts, however, an MRS is capable of maintaining the yield load after significant amounts of roof-floor deformation. Because the mining cycle is accelerated, MRS's help reduce the potential for time-dependent roof falls.

To study the influence of pairs of MRS's on the mine roof, the authors used analytical solutions for two pairs of MRS's positioned 5.5 m (18 ft) apart (figure 3) (Maleki and Owens 1998). Results showed that MRS's form a pressure arch in the immediate roof that reduces the potential for roof falls in the space confined by the MRS's. This is beneficial for protecting a continuous miner when it is operating within this space. It was also found that higher MRS capacities and setting pressures are useful for stabilizing the upper strata, but may contribute to differential loading on the immediate roof, failure of mechanical bolts, and reduction in the stability of the immediate roof.

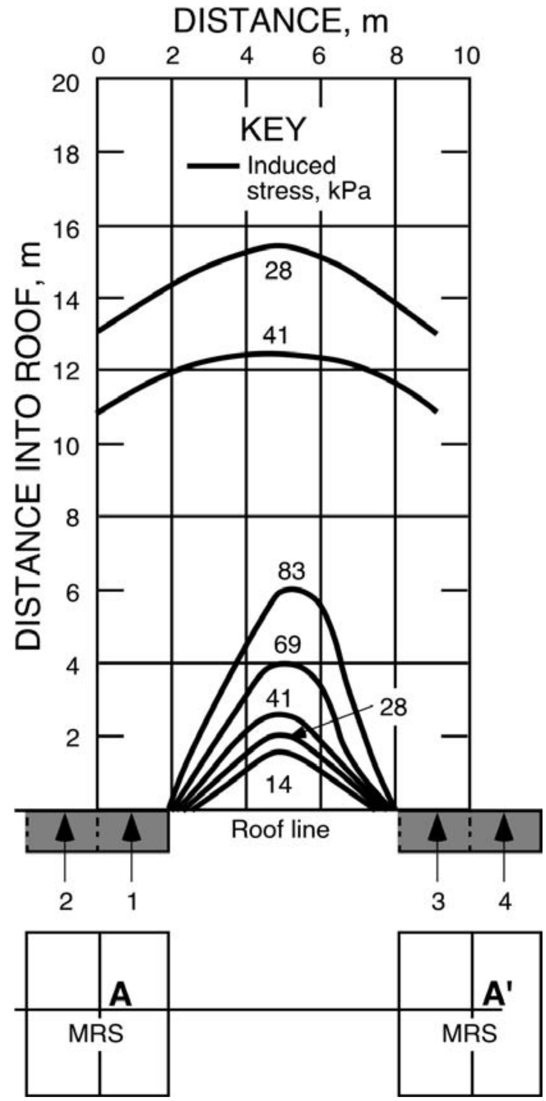

Figure 3.—Stress isobars along A-A' for two pairs of MRS's at 5.5-m spacings.

Early field evaluations focused on a comparison of ground movements in two room-and-pillar retreat sections using the split-and-fender method with posts (figure 1) and the Christmas tree method with MRS's as the secondary support system (figure 2). In addition, the history of hydraulic pressure was analyzed for all four MRS legs (Hay et al. 1995). Deformation measurements indicated generally higher strata movement at the intersections in the section using the Christmas tree method. Because of differences in geologic conditions and mining practices, it was not possible to make a direct comparison. We recommended that numerical modeling of these geometries address mine layout designs while keeping geologic conditions constant.

PANEL LAYOUT DESIGN

Early field studies identified the importance of mine layout designs and revealed the dangers of overconfidence concerning the ability of MRS's to support the entire area. Such overconfidence contributed to workers choosing unsafe operating locations. Thus it became apparent to the authors that to improve stability, layout designs that control convergence and stress should be developed. To illustrate this point, boundary-element analyses were completed in which stress distributions were calculated in both single and multiple seams. These analyses were also helpful in tailoring the type of monitoring required to assess changes in the stability of the mining system.

The first study compared stress distribution and convergence patterns for two pillar recovery plans: split-and-fender and Christmas tree. Model input was based on extensive laboratory and field measurements in one mine (Maleki 1981), and modeling procedures were based on a methodology developed for coal mine excavations (Maleki 1990; Maleki and Owens 1998). The analyses were completed for a typical depth of 305 m (1,000 ft).

Figure 4 presents the calculated roof-floor convergence for a point in the intersection for two pillar recovery methods (point B in figures 1A and 2A) and provides guidance for selecting monitoring systems. Note that calculated deformation significantly increases within a mining step, which is associated with the failure of fenders and stumps. MRS's will therefore experience an increase in both vertical and lateral support loading as fenders fail. Since fender failure induces differential movement in the mine roof, a roof fall may be triggered. Such a roof fall may be sensed through monitoring either roof movements or possibly MRS leg pressures. The change in convergence that occurs as a result of failure of the fenders is large enough to cause a change in leg pressure and can be conveniently detected by the load rate device. Obviously, changes in convergence and roof movements may best be directly detected by monitoring roof-floor movements (Maleki 1981) if inadequacies in measuring the hydraulic leg pressures of the MRS's are suspected.

Roof-floor convergence is at least 10% higher using the Christmas tree method, as illustrated in figure 4. To control convergence, a stump is left in the model (figure 2). Further improvements in stability and convergence can be achieved by changing the size of the stumps and pillars left behind while considering site-specific structural conditions (i.e., using engineered mine layouts and extraction designs).

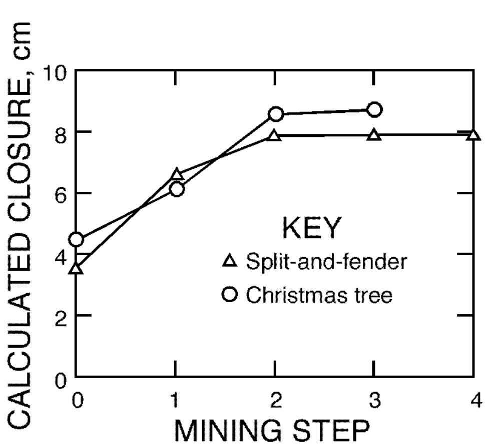

Figure 4.—Calculated closure for split-and-fender and Christmas tree methods at location B.

MRS's are used often when mining difficult reserves, such as where there are earlier workings in adjacent seams. In a second study in a cooperating mine described here, numerical modeling techniques and field data were used to show how two-seam layouts influence stability and support response. The mine uses the room-and-pillar technique to extract three-seam reserves in coal fields on the Wasatch Plateau near Huntington, Utah. These seams are located toward the base of the Blackhawk Formation and consist of the Tank, Blind Canyon, and Hiawatha. The Tank Seam is presently being mined in an area partially undermined by the Blind Canyon Seam, approximately 85 m (280 ft) below. Thus, mining layout and pillar pulling plans are complex. The test site in the Tank Seam is located in a graben bordered to the east and west by two major faults (figure 5). North-south-trending joints are common in the section and influenced by mining and caving process during extraction of the Blind Canyon Seam.

Figure 6 presents Tank Seam mining geometry and vertical stress distributions over a portion of the two-seam mining areas during the extraction of pillar 2. A stress profile was also prepared (figure 7) along an east-west cross section positioned toward the middle of the modeled area (away from the active face in the 1st North Mains). Modeled geometry in the Blind Canyon Seam was limited to the fully retreated 2nd East panel. This panel lies directly under the 1st Main North, but shifts some 24 m (80 ft) toward the east and so the last (most westerly) row of 1st North Mains pillars is not undermined. Modeled areas in the Tank Seam include a fully retreated room-and-pillar panel to the western boundary of the model (top of the page) and a 43-m- (140-ft-) wide barrier pillar between this gob and the 1st North Mains (figure 5)

Results indicate a nonuniform stress distribution over the 1st North Mains. Pillar stresses increase to the west across the 1st North Mains. Maximum stresses are concentrated over the last row of pillars (row 8) and the barrier pillar. This is in agreement with underground observations indicating large amounts of rib spalling and floor heave near pillar 8 in contrast with little (unnoticeable) movement to the east. This two-seam mining geometry created an opportunity to assess machine performance in the field under these two different loading conditions.

Based on this and other multi step stress analyses, it became apparent that pillar stresses exceeded pillar strength [21 MPa (3,000 psi)] (Maleki 1992) when approximately half a pillar was extracted. At this time, the pillar exceeded yield loads and was approaching the post-failure regime. Seismicity noticeably increased. Pillar unloading resulted in increased roof-floor convergence and load transfer to the MRS units nearby. This process was associated with an increase in the rate of loading on the MRS's. Roof falls may be triggered by additional movement, particularly if smooth joints are present.

DEVELOPMENT OF GROUND MONITORING SYSTEMS

During field tests in underground mines, the authors identified three factors that might adversely influence worker safety in an MRS section.

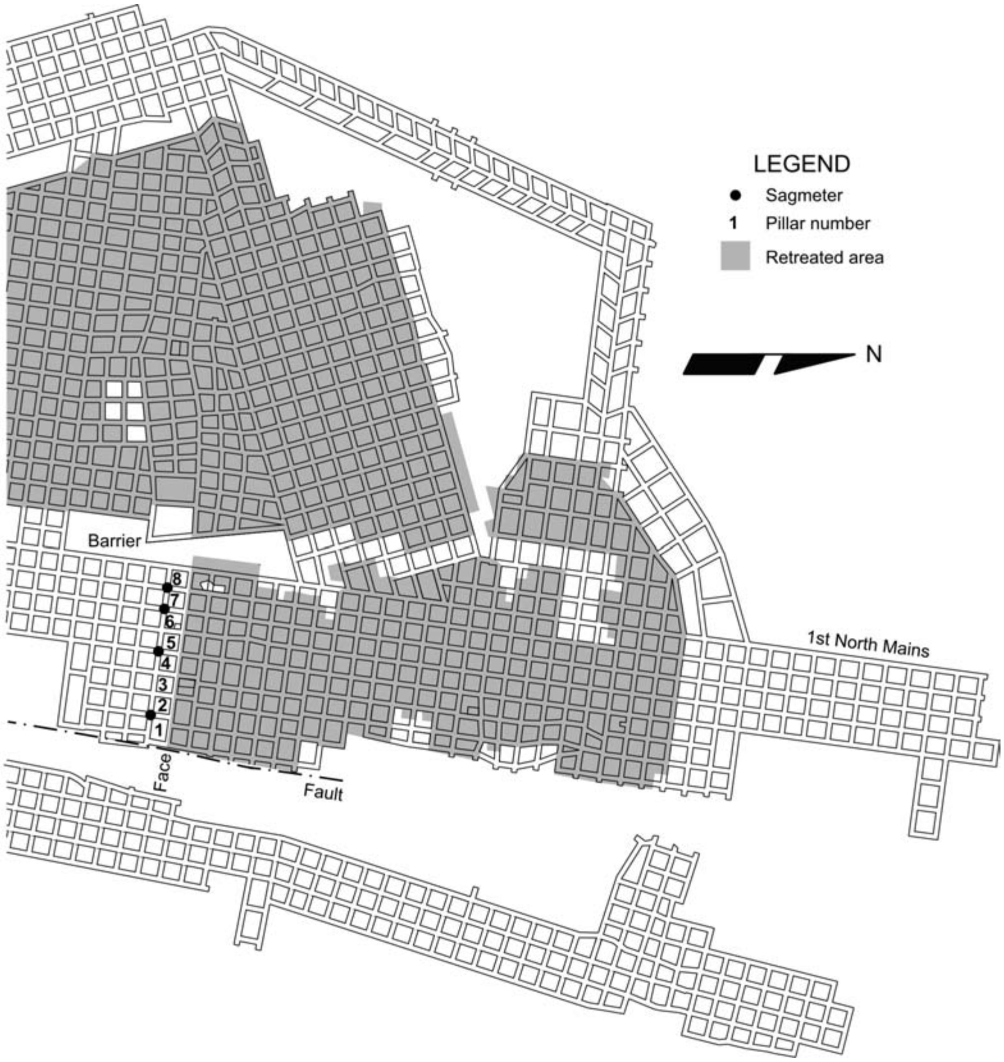

Figure 5.—Mining geometry and monitoring locations in Tank Seam.

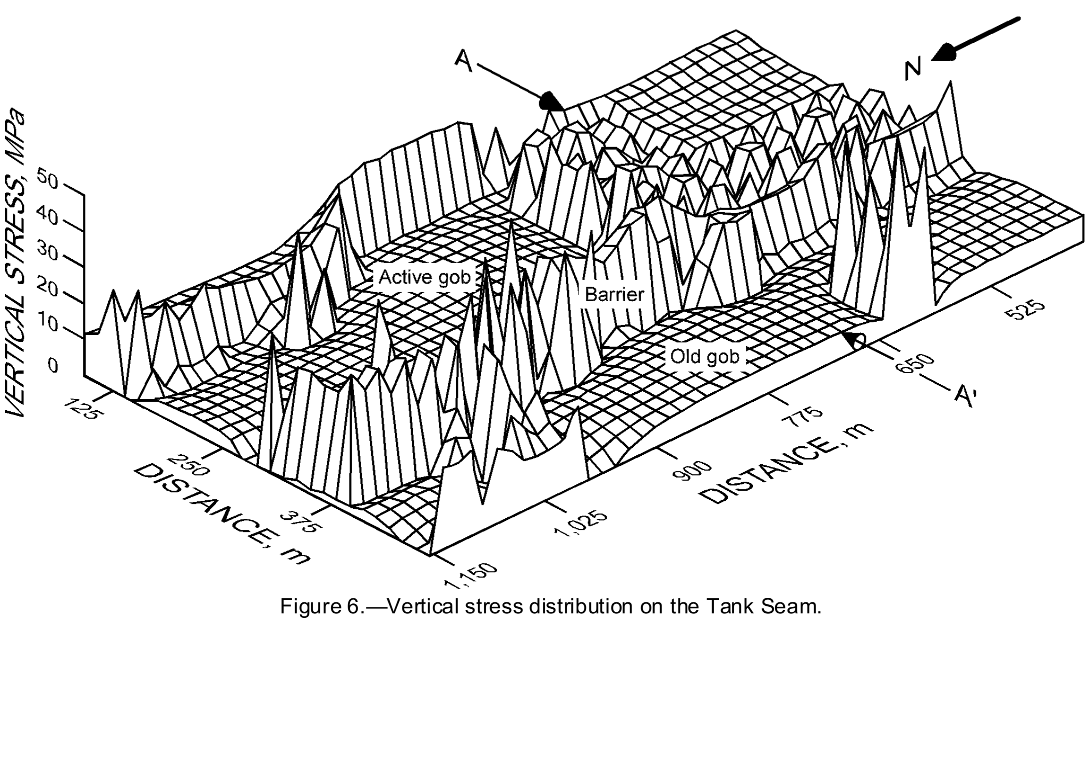

Figure 6.—Vertical stress distribution on the Tank Seam.

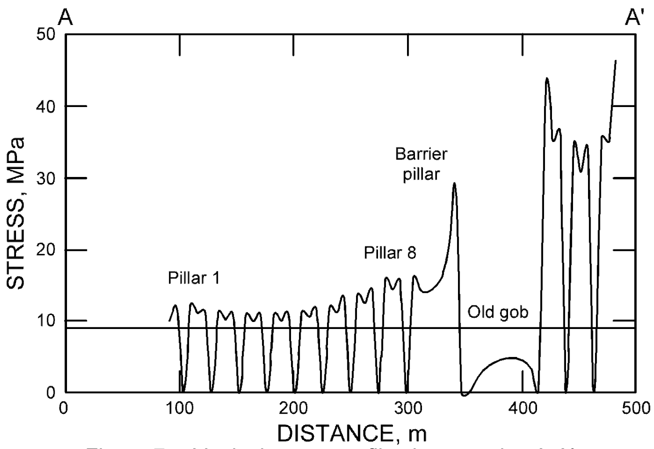

Figure 7.—Vertical stress profile along section A-A'.

- Elimination of posts reduced a worker's ability to assess roof conditions.
- Overconfidence in the ability of MRS's to support the entire area caused some miners to chose unsafe operating positions.
- Use of MRS's on a routine basis under adverse geologic and mining conditions to recover reserves that were otherwise unminable.

It became apparent to the authors that there was a need to develop a warning system that would alert workers to unstable roof conditions so that miners and equipment could be removed before a roof fall occurred. Two monitoring methods were chosen on the basis of mine measurements and numerical modeling considerations. These were load-rate monitoring on the hydraulic legs of MRS's and remote monitoring of roof movements using a theodolite. A reliable warning system needs to combine both ground deformation and load-rate data. Theodolite and spads have been effectively used for the remote measurement of roof movements and for the detection of roof falls in room-and-pillar operations (Maleki 1981). In this application, marked spads are installed in the area of interest during pillar recovery and ground movements are remotely monitored using a theodolite (or transit). By measuring the change in vertical angle, the rate of roof movement is calculated.

A load rate monitoring device was developed by NIOSH that monitors dynamic loading rates on an MRS in real time and displays warning signals. Hydraulic supports such as the MRS provide little or no discernible audible or visual indications of impending roof stability problems. In MRS retreat mining sections, miners rely on the hydraulic gauges on the MRS's to determine when to cease operations and leave the area of the active mining face before a roof fall. An imminent roof failure is sometimes preceded by a rapid increase in pressure on the dial gauges. However, these gauges are difficult to read, requiring miners to approach the MRS to monitor the gauges, which in turn requires them to be close to the active mining face, an area susceptible to roof falls, and in a location with a lot of equipment activity. As a result, miners do not check the pressure gauges often. Monitoring the rate of loading on MRS legs was shown to provide warnings about major events, such as failures of fenders and pillars. These events often trigger roof falls.

With the cooperation of the MRS manufacturer, J. H. Fletcher & Co., the device was installed and tested on MRS's in the laboratory and in the field. The system is MSHA permissible and operates as an integral part of the MRS. Research continues in analyzing the data from recent field installation and in identifying critical loading parameters associated with roof and/or pillar stability problems. Necessary calibration can be done prior to installation or periodically as mine conditions change, but need not be done by operating personnel at the mine. The operating parameters for the system are set by connecting the system to a laptop computer via an RS-232 null modem cable with the communication terminal emulator acting as the laptop client program. This allows a trained user to change the parameters for triggering the various load rate indicator devices easily to suit conditions at the mine.

FAILURE MECHANISMS AND MONITORING RESULTS

MRS performance was monitored during the extraction of one row of pillars. Hydraulic leg pressures were collected on all four MRS's using Campbell Scientific[1] data acquisition systems. Two loading rates are used to analyze the loading history of MRS's: (1) Instantaneous loading rate calculated by taking measurements every 2 sec and (2) average loading rates calculated by taking measurements following an acceleration in loading rates up to a period of 1 hour. The instantaneous rate is highly variable but useful when addressing seismically induced events. The average loading rate is more suitable for addressing overall changes in pillar stability.

Three time windows were selected to analyze failure mechanisms and machine response to applied load during pillar extraction. Mining geometry, MRS location, load histories, and roof fall locations are illustrated in figures 8, 9, and 10.

Pillar Failure Mechanism

Monitoring results during the extraction of the second half of pillar 1 clearly show the influence of fender failure and deterioration in roof stability. No roof falls occurred within the mining areas of interest while mining pillar 1 (figure 8). However, three roof falls occurred near the outside boundary of the excavation. These falls took place during and after extraction of cuts 11 and 12 when pillar failure was in progress as the effective pillar area was reduced. Maximum yield load was achieved on MRS 4 during excavation of the pushout cut, completing the pillar failure process. The instantaneous measured rates varied from 280 to 450 kPa/sec (40 to 65 psi/sec) during these events. Average load rates varied between 75 to 105 kN/min (17,000 to 24,000 lb/min) during this process.

Pillar Yielding Mechanism and Geologic Structure

Figure 9 presents mining geometry and roof fall locations during the extraction of pillar 2. Two roof falls occurred while completing approximately 50% extraction in the pillar. The first was outside of areas of active mining during mining cut 12. The second roof fall buried the continuous miner during mining of cut 14; this roof fall was structurally controlled by north-south-trending joints. At this time, the effective area of the pillar was reduced by approximately 50%, and thus the pillar approached yielding and the post-failure regime. This assertion is made based on stress analyses (figure 6) and loading

[1]Mention of specific products and manufacturers does not imply endorsement by the National Institute for Occupational Safety and Health.

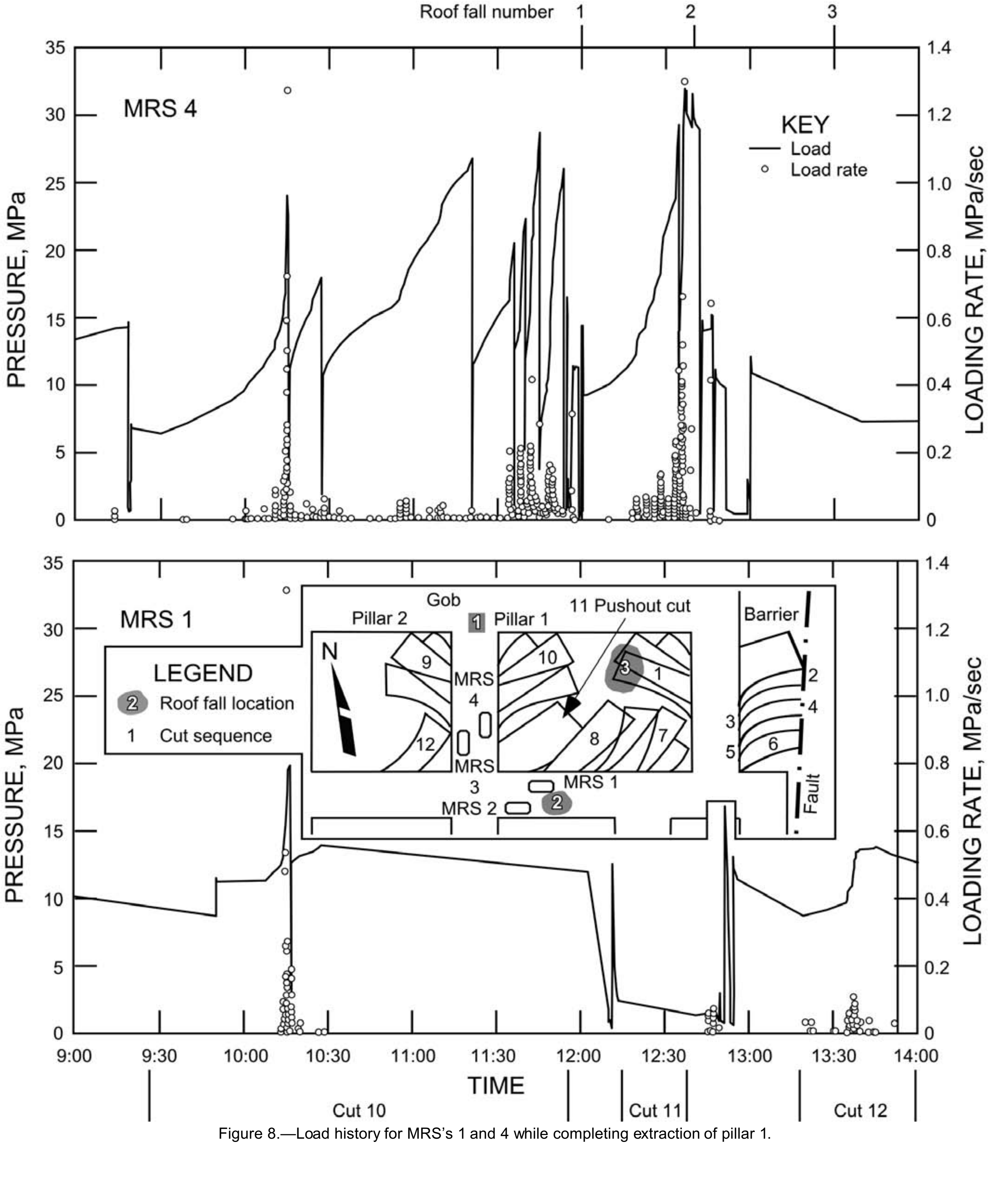

Figure 8.—Load history for MRS's 1 and 4 while completing extraction of pillar 1.

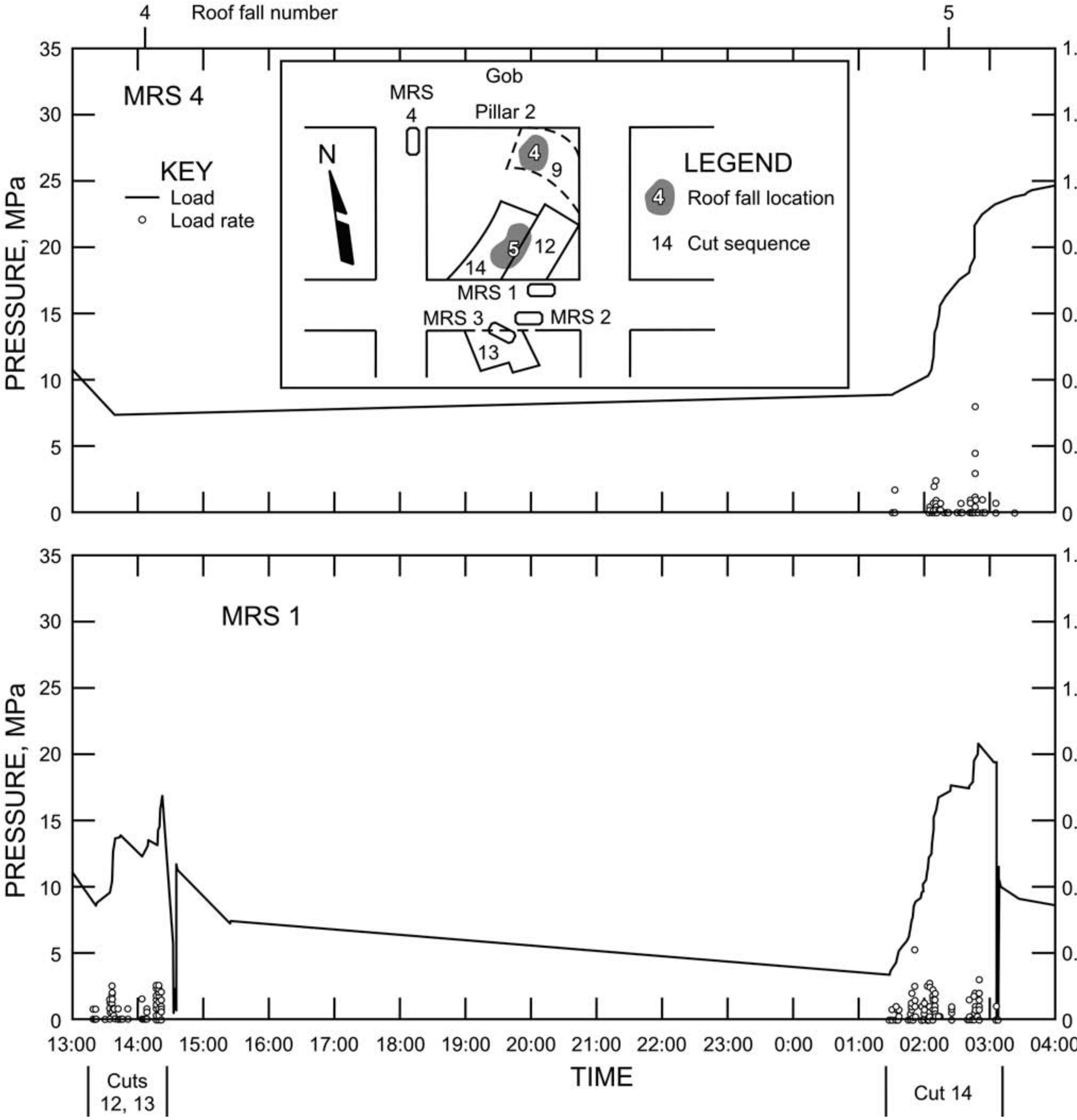

Figure 9.—Load history for MRS's 1 and 4 while completing extraction of pillar 2.

patterns on MRS's 1 and 4 (figure 9). Three minutes prior to this roof fall, load on both MRS 1 and 4 increased to approximately 21 MPa (3,000 psi) and instantaneous load rates varied from 120 to 200 kPa/sec (18 to 29 psi/sec) with an average load rate of 670 kN/min (15,000 lbf/min). In comparison to events for pillar 1, both load and load rates were lower because pillar 2 still provided sufficient resistance to limit roof-floor convergence. We suspect that pillar 2 was in a post-failure load deformation stage because there was a gradual load increase on MRS 4 during equipment recovery operations. At the termination of recovery operations, load was approaching 28 MPa (4,000 psi). Pillar yielding thus appear to have triggered movements in roof blocks outlined by preexisting joints.

Seismically Triggered Roof Falls

Figure 10 presents mining geometry and roof fall location during the extraction of pillar 8 and the barrier pillar. At this location, only MRS's 3 and 4 were used. One roof fall, a block of rock 1 by 1 by 3.7 m (3.3 by 3.3 by 12 ft), occurred during the extraction of cut 6. The block was structurally controlled by north-south-trending joints. At the time of failure, loads were moderate on both MRS 3 and 4 of about 21 MPa (3,000 psi) and instantaneous load rates were generally small, 76 kPa/sec (11 psi/sec) with average load rate of 36 kN/min (8,000 lbf/min). A large, instantaneous increase in the load rate of 390 kPa/sec (56 psi/sec) was measured on MRS 3 shortly before the block

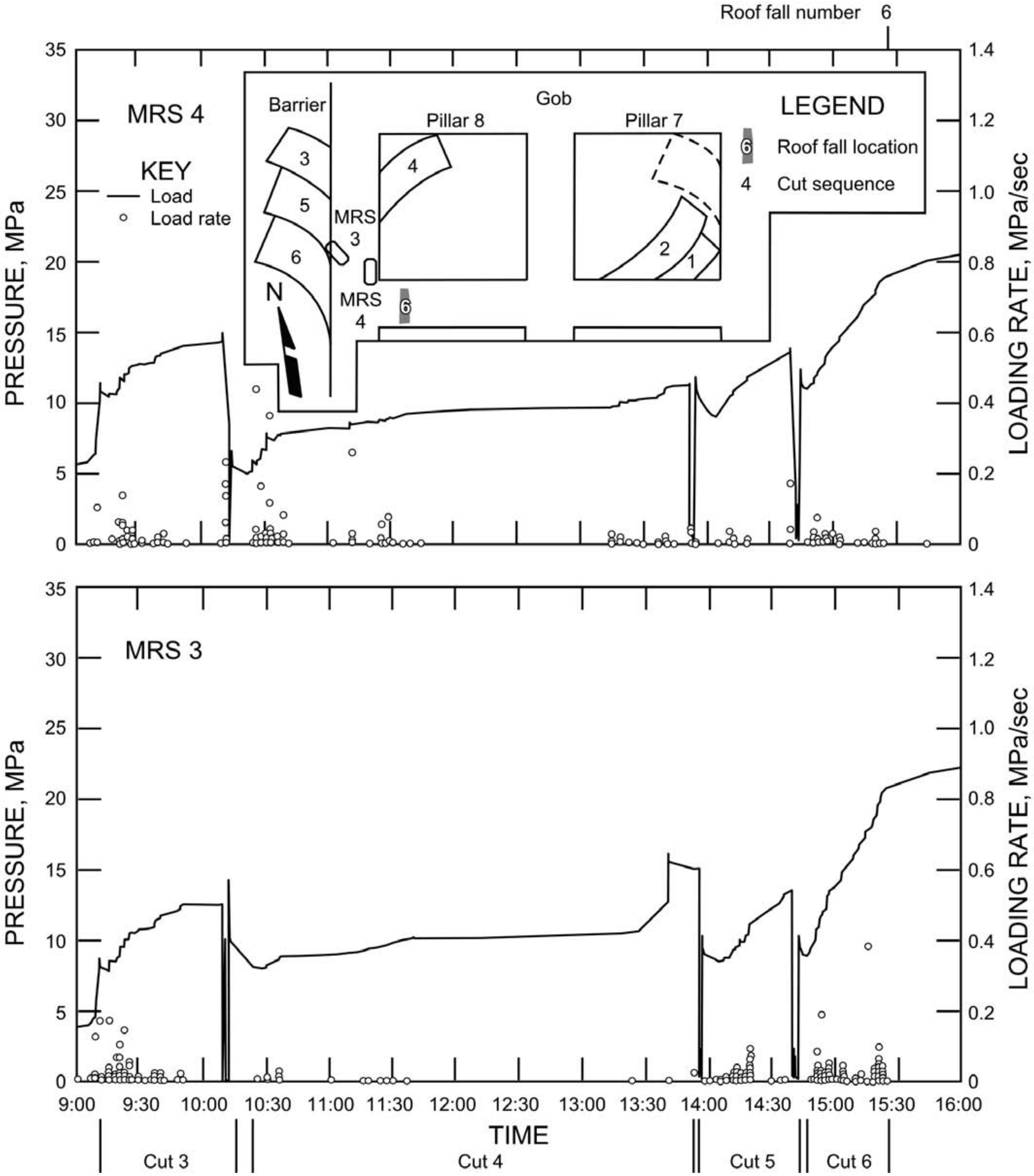

Figure 10.—Load history for MRS's 3 and 4 while extracting pillar 8 and barrier pillar.

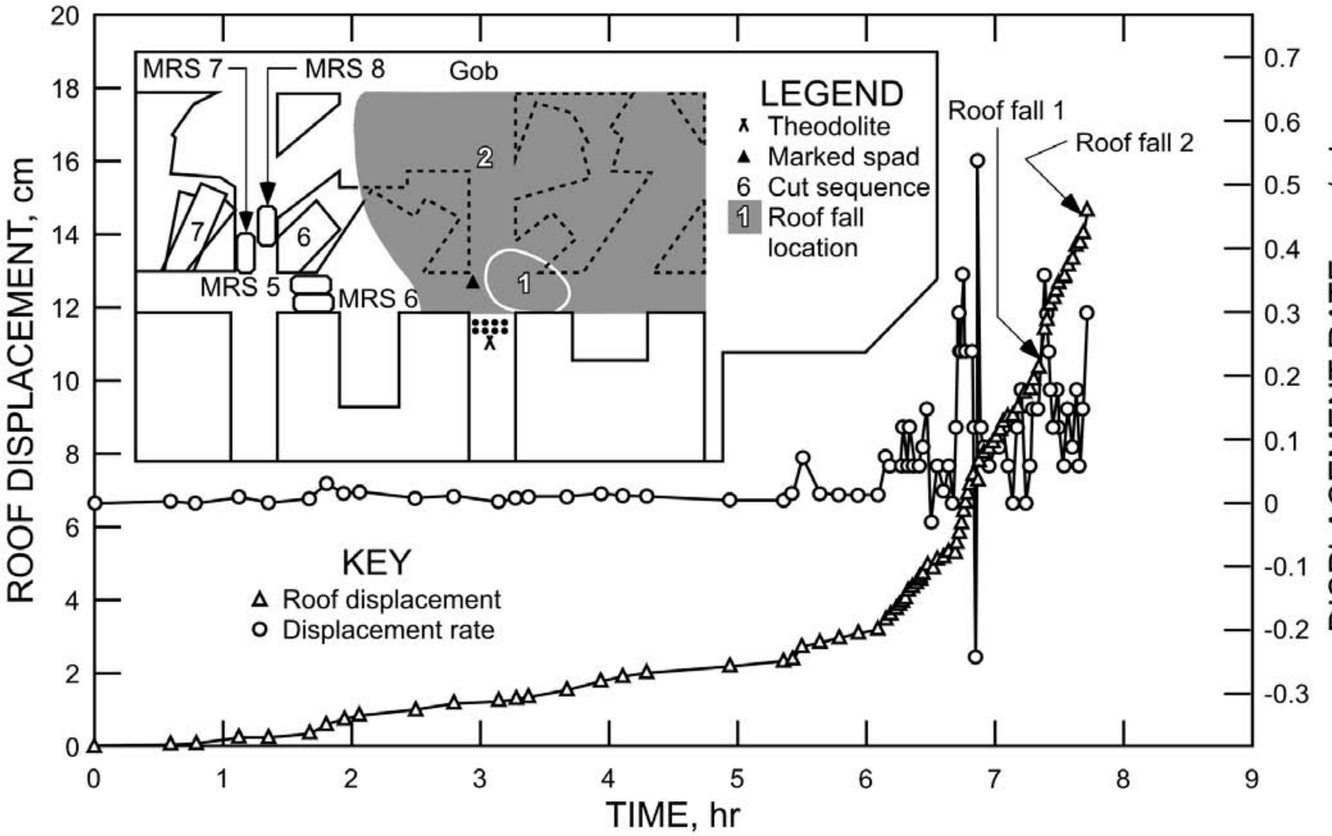

Figure 11.—Roof displacement history prior to major roof falls.

fell. The authors suspect preexisting structures to have contributed to this roof fall, which was triggered by higher-than-normal mine seismicity in this high-stress area.

Typical Deformation Monitoring Results

Reliable detection of impending stability problems requires monitoring both loading patterns on MRS's and roof movements. This is illustrated by presenting a roof deformation and major caving history approximately 30.5 m (100 ft) behind the face using a theodolite and marked spads at the study mine in the Blind Canyon Seam (figure 11). Note an increase in roof deformation and roof deformation rate prior to two roof falls. The deformation rate exceeded a critical rate of 0.5 cm/min (0.2 in/min) approximately 30 min prior to roof fall 1. This critical rate is in close agreement with other measurements of convergence in four other U.S. coal mines (Maleki 1981; Maleki 1988; Maleki et al. 1999). The second roof fall was associated with seismicity that was registered as spikes in the loading patterns on four MRS's.

CONCLUSIONS AND RECOMMENDED WORK

To eliminate setting and handling posts and reduce the number of miners required to work near the cave line and at other dangerous locations, a remotely controlled MRS has been developed and tested in the field. Optimum use of MRS's depends on careful panel designs, mine orientation, and primary support designs geared to expected geologic and stress conditions (Maleki and Owens 2001). 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.

An integrated ground monitoring system was tested in which the simplicity of deformation measurements were combined with more elaborate load rate monitoring on MRS leg cylinders. Analyses of field data show that roof instabilities are influenced by four mechanisms: (1) pillar failure, (2) pillar yielding, (3) mine seismicity, and (4) geologic structures. Pillar yielding and failure (unloading) and seismicity can be conveniently monitored by the load rate monitoring device, but to detect impending roof falls, additional deformation measurements directly within the cuts are needed.

Preliminary results show that roof falls occur when roof movements accelerate, reaching critical limits of 0.5 cm/min (0.2 in/min). Using average loading rates on MRS's at the study mine, there is a high potential for roof-pillar failure when the MRS loading rate increases beyond 44 kN/min (10,000 lbf/min). At such high loading rates, it is considered very likely for an MRS and/or the continuous miner to be buried during either mining or relocating the MRS. Between 22 to 44 kN/min (5,000-10,000 lbf/min), stability problems are still likely to pose some risk to equipment and worker safety. Structurally controlled instabilities play a bigger role at the lower end of this range, depending on mine seismicity, geology, and operating conditions. Below 22 kN/min (5,000 lbf/min), the likelihood of pillar stability problems is very low, and overall stability can be controlled through prudent support and excavation techniques.

Research continues in testing and evaluating MRS performance under dynamic loading conditions. The focus of future ground control research is to quantify and verify critical loading parameters that are indicative of impending stability problems under different geologic conditions.

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Figure 1.—Mine layout (*A*) and pillar extraction sequence (*B*) using split-and-fender method with posts.

Figure 2.—Mine layout (*A*) and pillar extraction sequence (*B*) using Christmas tree method with MRS's as support.

Figure 3.—Stress isobars along A-A' for two pairs of MRS's at 5.5-m spacings.

Figure 4.—Calculated closure for split-and-fender and Christmas tree methods at location B.

Figure 5.—Mining geometry and monitoring locations in Tank Seam.

Figure 6.—Vertical stress distribution on the Tank Seam.

Figure 7.—Vertical stress profile along section A-A'.

Figure 8.—Load history for MRS's 1 and 4 while completing extraction of pillar 1.

Figure 9.—Load history for MRS's 1 and 4 while completing extraction of pillar 2.

Figure 10.—Load history for MRS's 3 and 4 while extracting pillar 8 and barrier pillar.

Figure 11.—Roof displacement history prior to major roof falls.