STRESS MEASUREMENTS FOR SAFETY DECISIONS IN LONGWALL COAL

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ABSTRACT

Researchers at the Spokane Research Laboratory of the National Institute for Occupational Safety and Health, Spokane, WA, have collaborated with three Western longwall coal mines in an ongoing effort to develop technologies that will aid in providing safe and stable working areas. The goal of the research described here is to develop a stress monitoring system that will provide immediate information to mine managers for making daily safety decisions as areas of poor ground are mined through.

Initial work has focused on answering preliminary questions regarding the reliability and use of stress change patterns. Research is concentrated on monitoring horizontal stress because horizontal stress is transmitted over long distances through stiff strata, thus allowing an extended length of entry to be monitored.

This paper presents an explanation of the concept, key results from field tests at two mine sites, and a proposed process for implementing a monitoring system. System design layouts, instrument use, data collection and interpretation methods, and processes to present findings to mine staff are described. Additional validation and correlation with actual failure mechanisms are required before this approach can be recommended at ongoing operations. However, initial results indicate that this approach shows promise in mines prone to bumps and roof falls associated with large stress changes. In particular, analyses of measured changes in horizontal stresses appear useful.

BACKGROUND

Researchers from Spokane Research Laboratory (SRL) of the National Institute for Occupational Safety and Health (NIOSH), Spokane, WA, have been developing an approach to better assess the stability of underground openings and reduce the risk of ground falls to miners. Information from the accident database compiled by the Mine Safety and Health Administration (MSHA) (figure 1) reveals that for the 5-year period of 1996 to 2000, ground falls caused 48% of the 143 fatalities in underground mines. Injuries from falls of ground for the same period accounted for 16% of the 22,437 lost-time injuries.

It is well understood that underground mining conditions will become more difficult and will present a greater risk to workers as companies are forced to mine at greater depths in less stable ground. Mines that now operate in good conditions are likely to encounter areas where roof conditions are poor and be faced with additional risk that cannot be explained by geology or calculated stress conditions. To reduce the risk to longwall miners, SRL researchers are developing a system that will continuously monitor stress changes in work areas as mining progresses. The system is being designed to provide mine personnel with additional information for making safety decisions, particularly when mining through difficult ground control conditions.

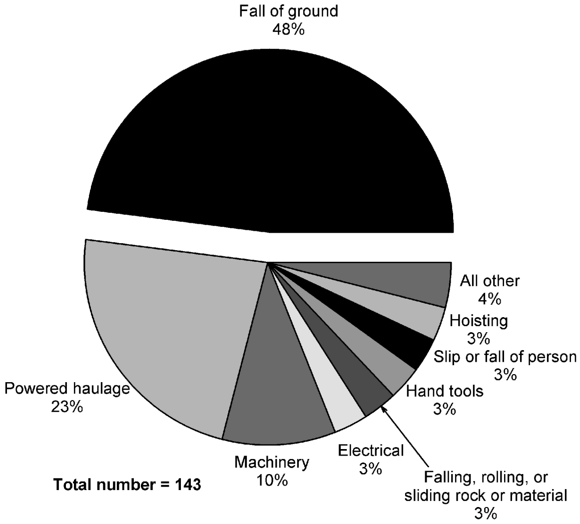

Figure 1.—Distribution of fatalities by accident class, underground mining 1996-2000 (MSHA database).

MONITORING SYSTEM CONCEPT

The long-term goal of this research is to develop monitoring systems to measure changes in stress and displacement in the surrounding rock to acquire information on the stability of high-use work areas near the longwall face. Data trends from these systems can then be used to quantify the overall level and nature of stress increases to determine if preventative safety interventions are warranted as mining progresses and to better understand stress change dynamics during mining.

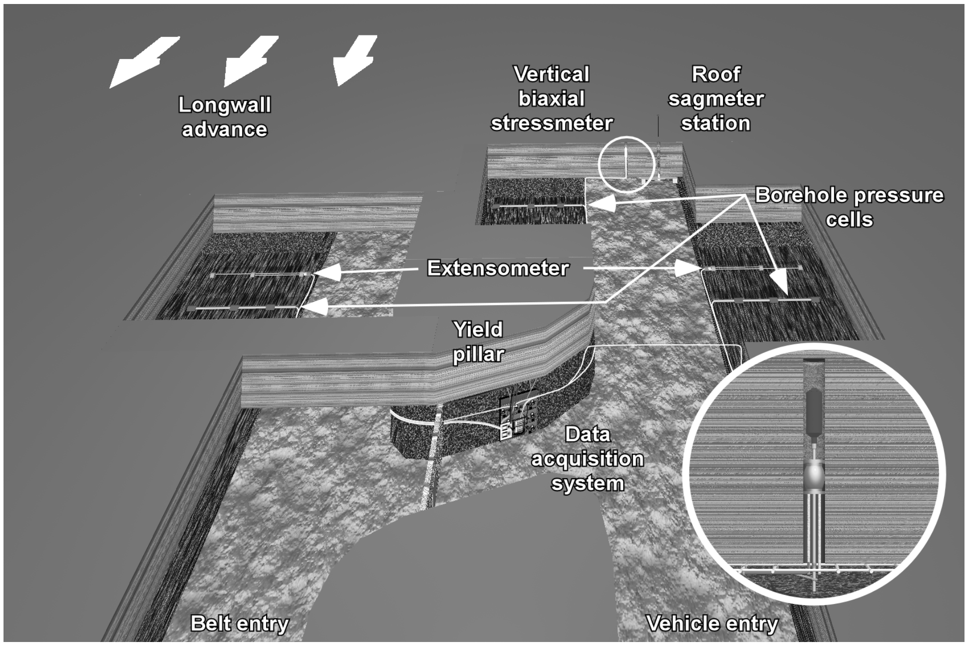

Figure 2.—Cutaway view of longwall panel and gate roads illustrating the concept of measuring stress change and displacement in the roof and rib ahead of mining

Development of the concept described in this paper was inspired by advances in measurement technologies not previously exploited for use in coal, notably the biaxial stressmeter (*1-3*) and increased understanding of the role that horizontal stress plays in coal mine stability (*4-6*). Based on these developments and the continued need for safety improvements, researchers at SRL are developing stress monitoring systems (figure 2) that utilize measurements of both displacement and stress changes in the roof, rib, and floor along entries near an active panel. These systems are designed to collect data from an array of instruments during mining operations. The data are then plotted and, along with underground observations and information from other data collection systems, made available for daily safety decisions. Results may also help in the interpretation of large seismic events and gas outbursts.

Researchers are developing ways to capitalize on previous experience with biaxial stressmeters (BSM's). Such experience suggests that mining-induced stress changes may be detected over 500 m (1650 ft) away (*7-8*). A key element is the measurement of horizontal stress changes using BSM's installed in the stiffest rock horizons above or below the coal seam. Experience has shown that horizontal stress changes are preferentially carried in zones with the highest modulus of elasticity (*9*). Plots of stress-versus-time from these horizons are analyzed and compared to actual events to determine if recognizable patterns of stress change exist that may be indirect indicators of roof and rib failure. The idea is that rapid and/or large changes in horizontal stress have a cause-and-effect relationship with failures.

Once researchers establish that these monitoring systems can yield recognizable patterns, the goal will be to determine if this approach is reliable enough to assist in making decisions to take preventative action. To increase reliability, measurements from other instruments in the array and observations from miners are used to determine the source of anomalous BSM patterns. Analysts need to be able to identify patterns that mimic those indicating an increased risk of failure, but that are actually caused by events not affecting safety (e.g., normal pillar yield, roof sag near instruments, or electronic interference from repositioned transformers).

While evaluating these stress change plots, it must be understood that the values of p, q, and θ are not absolute, but are measured from a zero datum that was established when the BSM came to equilibrium after it was installed in a pre-existing stress field. BSM stresses are measured in the horizontal plane; p is the change in major principal stress; q is the change in minor principal stress; and θ is the angle measured from the line of longwall advance counterclockwise to the direction of p (in plan view).

It was unreasonable to expect to find a mining operation in which the number of roof and rib failures were sufficient to test this concept. Hence, researchers tested the concept in operations in which conditions and events would produce large and/or rapid changes in stress, even if such changes created little safety risk. With this approach we could (1) determine if the patterns of stress changes associated with these major events had characteristics necessary for use as indicators, (2) evaluate the performance of instruments and data collection systems, adapting them as needed, and (3) develop effective ways of integrating the whole process into daily longwall operations.

Development of this system has made it clear that using these instruments for this application is significantly different from their traditional use in studies to better understand rock mechanics principles. Designing the system to conform with the rigors of daily operations has required researchers to develop a monitoring system configuration and information delivery process at the same time the capabilities of these new systems are being explored. The expectations of what these types of monitoring systems can offer has changed as research progressed, but is based on the following design requirements.

1. Results should provide useful information to assist in making safety decisions. Types of decisions could include adding support, restricting access to specific areas during high-risk times, de-stressing critical areas, altering face advance rate, and evaluating support types and configurations and effects of panel orientation.
2. The data delivery process should allow time for mine foremen to implement preventative actions.
3. Installation and operation should cause a minimum disturbance to coal production processes.
4. The system should be robust with built-in redundancy.
5. Simplicity and reliability of results should make it cost effective.
6. Mine coordinate system, time reference, and software formats should allow engineers, geologists, and foremen to compare results with data from other operational systems at the mine.

FIELD TESTING

Initial development of a stress monitoring system (*8*) was conducted at a longwall operation in mine A (figure 3). Subsequent field tests were conducted at two other Western longwall operations (mine B and mine C). At mine C, researchers tested and evaluated grouting and placement methods for installing BSM's; however, no installations were deemed fit for collecting data, and results are not presented here.

Mine A

The coal seam being mined was contained in a 200-m- (660-ft-) thick Cretaceous formation consisting of a heterogeneous sequence of thin, lenticular mudstones, siltstones, sandstones, shales, and numerous other subeconomic coal seams. Ground control was a primary concern because of the history of coal bumps in the mining district, a very stiff upper stratum, and very steep topography with overburden varying from 450 to 900 m (1500 to 3000 ft). Coal was mined in a two-entry configuration where panels were oriented to minimize ground control failures from high horizontal stresses. Upper strata contained a very strong, 180- to 200-m- (590- to 660-ft-) thick sandstone formation that created a condition where caving behind the face shields was significantly delayed. Because caving was incomplete, overburden loads normally transferred through the gob into the floor were transferred onto adjacent abutments and forward into rock surrounding active work areas. Mine planners were concerned that these stress buildups could not be relieved safely and could possibly result in violent coal bumps that could kill workers or trigger the release of large volumes of explosive methane gases.

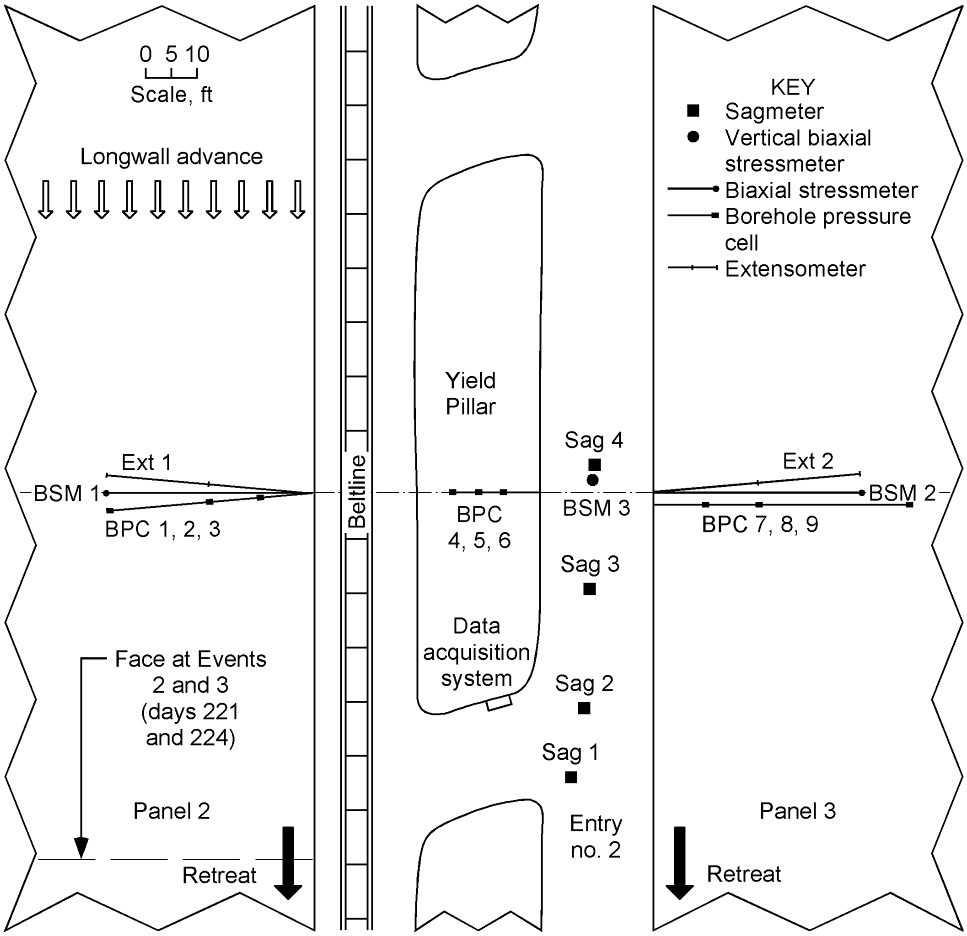

Figure 3.—Plan view of monitoring system with instrument layout with BSM 3, mine A

A stress monitoring system was designed and installed where instruments were clustered in two panels, a yield pillar, and the immediate roof and floor (figure 3). Data were gathered continuously for 6 months from a variety of stress- and displacement-measuring instruments as longwall mining proceeded from the start-up room 700 m (2300 ft) away and moved toward and past the instrument site. With the aid of mine staff, researchers started developing methods to integrate the whole process into daily longwall operations. Following are activities that were done in that context.

- Developed a method for placing BSM's into a roof for measuring horizontal stresses.
- Tested and evaluated instruments and placement strategies in relation to the operating face.
- Performed numerical analyses to evaluate placement strategies.
- Acquired geotechnical information (e.g., rock stiffness, in situ stress measurements).
- Tested and evaluated methods to interpret and disseminate results among mine staff.

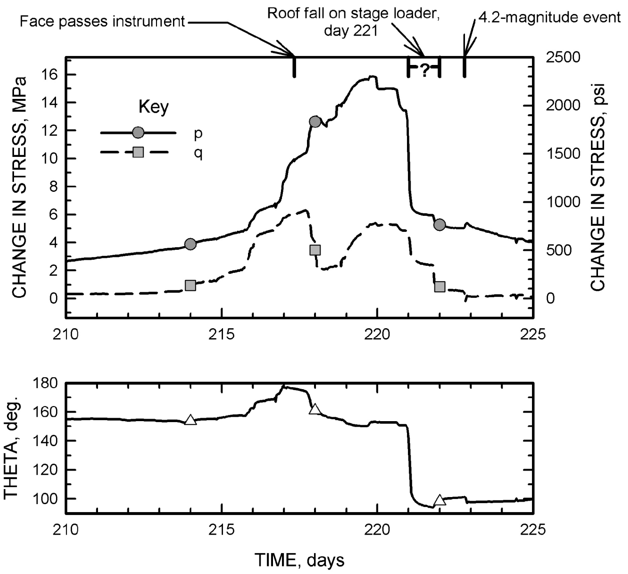

Figure 4.— Horizontal stress change measured in roof of gate roads by BSM 3 during days before and after three events, mine A. Symbols indicate lines, not events.

During the initial tests, researchers wanted to determine if stress change patterns emerged that could be useful in decision making. Some form of stress change anomoly was anticipated surrounding events. Hence researchers used the monitoring system to determine if magnitudes and profiles were unique enough to warrant further development and if stress change patterns could be associated with actual events. To accomplish this, plots of stress-versus-time were evaluated after the fact by comparing them with events noted by researchers and recorded in a foreman's log and with a NIOSH seismic system operating at the site. Figure 4 shows such a plot and illustrates stress change patterns surrounding three events (identified at the top of the plot and on Figure 3). In the first event, note the correspondingly large drop in q as the longwall face passes the instrument site. Stress in that direction could have been quickly relieved as mining cut through the nearby stress field, but then built up again as gob formed. The second event was the roof fall on the stage loader corresponding to the dramatic drop in stress during day 221. This event could have caused a simultaneous decoupling of the BSM from the stress field, which would also explain why a nearby 4.2-magnitude seismic event (third event) created such a small stress change pattern at day 222.

Note that in this plot, stresses leading up to the first two events rose quickly by many megapascals for a few days. Stresses then leveled off for a few more days, suggesting rock yielding mechanisms at work, before a dramatic drop. In this field test, the events happened when the face was so close to the instrument site that local effects were added to the stress profile, thus complicating the effects of the global stress changes the monitoring system was targeting. The field test at Mine B was designed to eliminate this condition.

Mine B

Mine B is in a coal seam 3.5 to 4.5 m (12 to15 ft) thick. The overburden consists of soft carbonaceous mudstones and siltstones. Three-entry gate roads are developed to mine coal panels under 100 to 120 m (325 to 400 ft) of overburden in the vicinity of the instrument site. The immediate floor is composed of mudstones and siltstones with a 2- to 3-m- (7- to 10-ft-) thick sandstone member located 2 to 3 m (7 to 10 ft) below the coal seam. This sandstone was identified as the stiffest strata above or below the coal seam and was best suited for instrumentation. Three BSM's were installed in this formation, and a two-point sag station was installed in the roof directly over each BSM to evaluate local changes affecting stress measurements (figure 5).

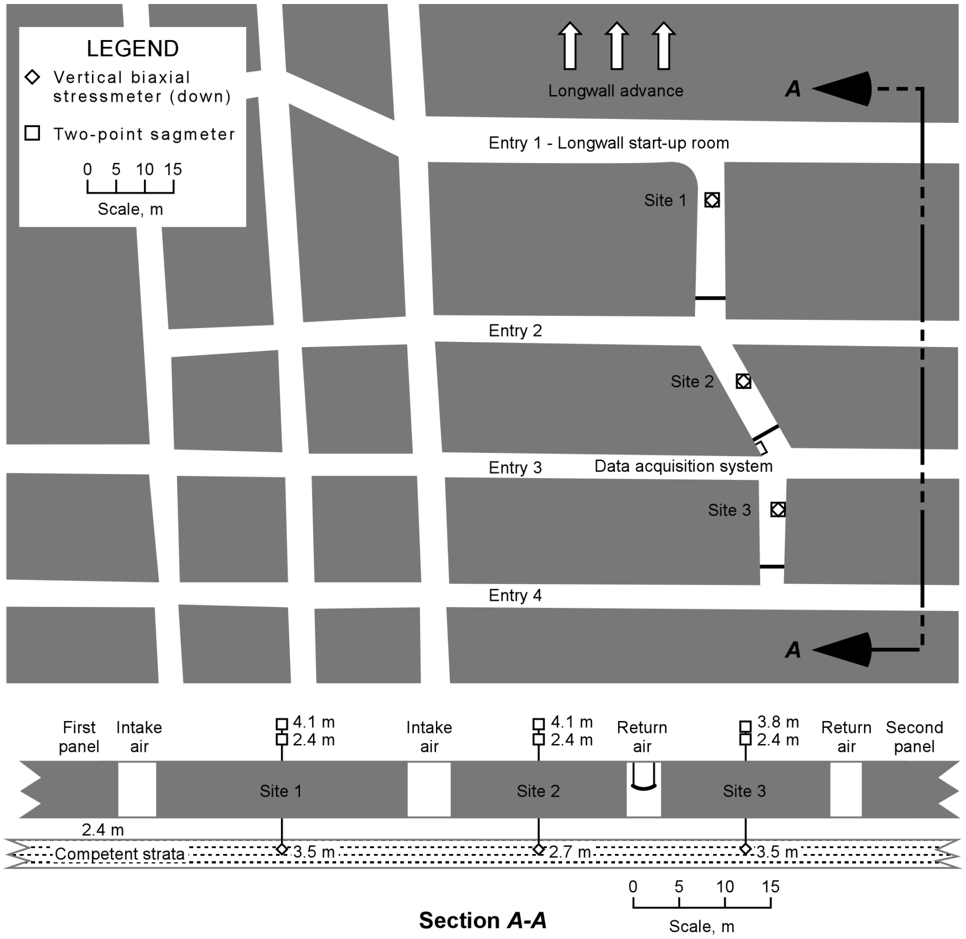

Figure 5.— Plan view and vertical section of monitoring system with instrument layout and datalogger, mine B.

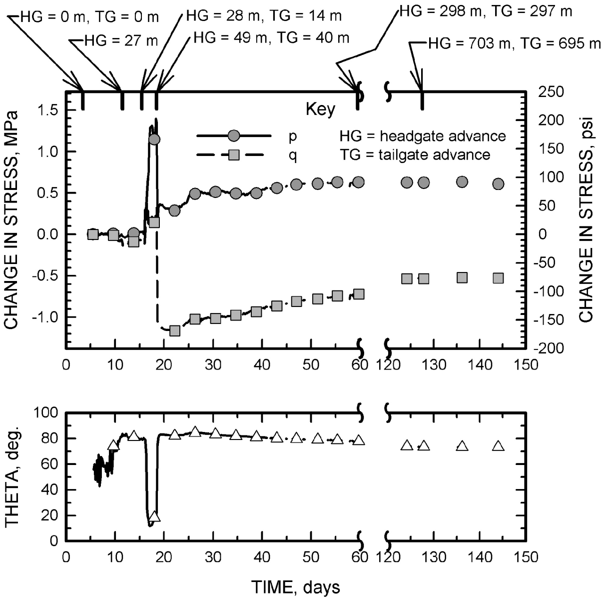

Figure 6.—Horizontal stress change and direction versus time as measured by BSM 1, mine B. Theta zero direction is direction of longwall advance, and counterclockwise is positive in plan view.

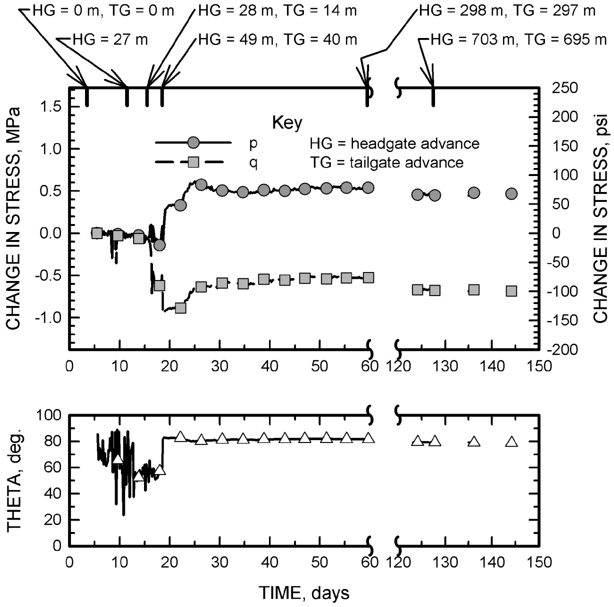

Figure 7.—Horizontal stress change and direction versus time as measured by BSM 2, mine B. Theta zero direction is direction of longwall advance, and counterclockwise is positive in plan view.

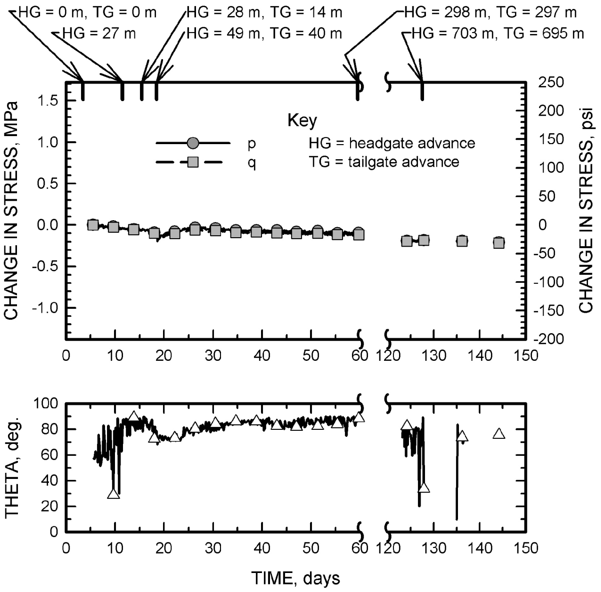

Figure 8.— Horizontal stress change and direction versus time as measured by BSM 3, mine B. Theta zero direction is direction of longwall advance, and counterclockwise is positive in plan view.

The monitoring system was designed to evaluate system response to a single event, the initial cave. Instruments were placed at various distances behind the start-up room to provide redundancy as well as evaluate horizontal stress change patterns and the effectiveness of instrument placement. A comparison of figures 6, 7, and 8 shows how stress change patterns from instruments placed further within the abutment became attenuated. Stress changes at the time of the caving event were greatest at BSM 1, which was 15 m (50 ft) from the start-up room and gob. As expected, the stress change dropped off according to how far away the BSM's were installed from the start-up room. (BSM 2 was 45 m [150 ft] and BSM 3 was 65 m [210 ft] from the start-up room.) However, the stress change was nearly zero at BSM 3. Such readings provide researchers with information on the sensitivity of instrument placement. It is also notable that the stress change pattern from BSM 2 varied significantly from the pattern obtained from BSM 1, possibly indicating the complexity of stress change dynamics.

Analysis of figure 9 (a close-up of data surrounding the first-cave event from BSM 1) provides insight on stress change patterns and whether this type of monitoring has any fatal flaws. Most significantly, the stress change patterns are similar to those in mine A, with the features of having a few days of sharply rising stresses followed by a few days of leveling off just prior to the cave event. Note that stresses remained somewhat constant for many days while mining was progressing up to the headgate position at 28 m (93 ft), but changes occurred quickly after that. This type of response pattern would be easy to identify before an event. Further evaluation of p, q, and θ provides quantitative measurements from which caving dynamics can be deduced that could be helpful in operational safety decisions. Such types of patterns encouraged researchers in their belief that measurements can be identifiable and can be recorded long enough before an event to allow preventative actions to be taken.

INFORMATION-GATHERING PROCESS

Implementation of a successful monitoring system will require attention to integrating many details into the daily operations at a mine. It is anticipated that each monitoring system will vary

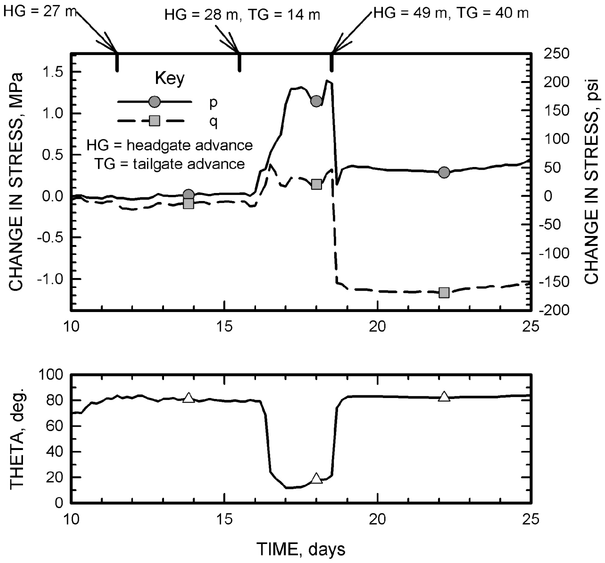

Figure 9.—Horizontal stress change measured by BSM 1 in floor near start-up room of a longwall panel in days before and after first major cave of roof, mine B. Symbols identify lines, not events.

depending on the ground control hazards of a specific operation. The details of installing and using a monitoring system will become more explicit on further development and experience in different mine settings.

While testing various reporting methods at these mine sites, the authors became aware that communicating the basic elements of this concept to those who will be using it on a daily basis is critical. The following discussion of activities and rationale was developed to illustrate a proposed process of instrument installation, data delivery, analysis, and decision making. Mine engineers, geologists, longwall foremen, and other selected mine staff can use their knowledge of site-specific conditions to install and utilize such a monitoring system successfully . Nothing is suggested here that has not been tested in field trials. In today's competitive coal markets, mining operations are continually testing and implementing improvements. Hence, the process described here is proposed for purposes of encouraging discussion for future research and application. However, in no way can the authors state that the monitoring system has been validated or that it is recommended for use at any other longwall operation.

Installation

The first activity is that of identifying a potentially hazardous segment of the coal panel. Typically, this would include areas where geologic anomalies, ground conditions, or previous experience indicate that it is appropriate to use this type of monitoring system. The system monitors stress changes over an interval of a few hundred meters of entry, where large stress changes are associated with coal bumps, roof falls, or other safety-related ground control problems.

Once the potentially hazardous area has been identified, a monitoring site is established immediately outby that area. This is done to take advantage of monitoring the entry when it is used both as a headgate and a tailgate. Experience has also shown that stress changes are not detected as well in the roof after the face has passed the instruments. This is most likely a result of normal caving, which can create a free (or strain-relieved) face parallel to the panel (along the line of caving, parallel to the gateroad entry) through which stress changes are not easily transferred. Results from existing or additional physical property tests are used to determine which strata in the immediate roof or floor are stiffest and which are most continuous between the instrument and the face.

An instrumentation site is designed with the key being instrument selection and placement. Strata directly above or below the coal seam with the highest modulus of elasticity and the greatest continuity between the site and the operating face are identified for placement of BSM's. Not having BSM's in the right zone can severely compromise the ability of the system to detect stress changes. Numerical modeling can be used to determine zones where stress changes are likely to be greatest. Additional tests to determine the stiffest zones can be done with a Goodman jack. Installing a number of BSM's about 15 to 45 m (50 to 150 ft) apart provides redundancy and allows interpretation of local stress changes. Additional instruments are used to help determine whether stress changes are due to normal yielding in the vicinity of the site, which should not be considered a hazard. These instruments include displacement-measuring devices, such as sagmeters and extensometers, as well as stress-measuring devices for coal, such as borehole pressure cells and flatjacks.

Once the instrument array and site configuration have been determined, the instruments and datalogger are installed. Usually the site is located in the roadway used in ongoing operations, so coordination between miners and installation crews is essential.

Data Delivery

Designing, maintaining, and upgrading a data delivery system requires special considerations. Decisions must be made on the frequency that instrument readings are to be taken. Reading frequency can be changed as desired when conditions change. Some considerations are anticipated rates of stress change for the monitoring period, level of redundancy needed, level of concern about conditions or need for the data, concerns about clogging data analysis with too much data, and the drain on a datalogger's battery power.

Once the datalogger has been designed, installed, and connected to the instruments, rigorous tests need to be performed to ensure the data are reliable. Good testing limits problems with instruments, wiring, components, programming, or external interference, such as high-voltage lines, motors, and nearby mobile equipment operations.

Analysis and Decision Making

Teamwork and communication are critical because this process is dynamic and includes people with varying specialties. Initially, a selected team needs to define routine tasks, determine who is responsible for each task, and schedule tasks so the data collection and delivery process becomes operational. In teams or in individual efforts, the process needs to be reviewed continually and changed to ensure that the generated graphs and reports are best designed to aid in making sound decisions. These changes will reflect the staff's need for information, which changes as mining progresses through the area being monitored.

Experience also indicates that there are only a few days from the time that stress change patterns appear until an event actually occurs. Therefore, quick data delivery and analysis are critical. For example, the system could be taking baseline data for weeks before an engineer sees a sharp rise in stress. At this time, the engineer could produce more-detailed graphs and reports and present them at the daily foreman's shift meeting. The team could determine if (1) these trends indicate a need for action or are explained by some other cause, (2) if the geologist or foreman needs to conduct special inspections, (3) if reports from other data collection systems need to be evaluated, or (4) if conditions warrant adding secondary support or some other action.

This process is quite flexible, so it can easily be adapted into the creative problem-solving culture prevalent at mining operations. Some activities that mine staff may consider are training the team on the capabilities of the system, determining the content of and scheduling routine reports for individuals or meetings, making special reports, and making results readily available to staff on dedicated monitors.

CONCLUSIONS

The concept of using stress monitoring systems for recognizing hazards during production is based on a number of research questions (*8*). The authors proceeded with the development of this concept by systematically testing these questions in the field. In general, additional research is needed to develop models for associated failure mechanisms and validate stress change patterns.

- *Can horizontal stress changes be measured accurately during a mining operation?* Results from two mines show that stress changes associated in time with observed ground control events can be measured. Trends and patterns in the data peaks seam reasonable and give a basis on which to compare future models. Further validation is needed to determine if these stress changes accurately reflect actual stress changes between the instrument and the face and whether patterns in stress change are of value in making safety decisions.

- *Are catastrophic events initiated by poor gob caving or by some other mechanism that (1) develops slowly enough to be detected and resolved before the event, (2) is not masked by changing geologic properties through which stresses are transferred, and (3) produces horizontal stress changes at the instrument site?* Results indicate that this system is best used for detecting stress change due to load redistributions during gob formation as the longwall advances. Results suggest catastrophic events may be triggered by the additional stresses transferred to work areas by gob formation events. They also suggest that measured stresses rise rapidly and then level off and indicate yielding before a global stress rise event such as first cave. This process has taken from about 3 to 7 days in the two tests to date. The monitoring system concept has value only to the extent additional tests confirm that these patterns are consistent. Three to seven days is reasonable for most types of preventative actions to be considered. However, more research is required to investigate differences between typical stress change response to mining and that which is characteristic of failure mechanisms leading to catastrophic events.

- *Can irrelevant factors influencing horizontal stress measurements be filtered out so as not to distort data trends in a way that does not interfere with detecting imminent catastrophic events?* Examples of such irrelevant factors are (1) stress redistribution due to normal yield pillar dynamics, (2) large changes in ventilation air temperatures or pressures, and (3) typical delamination or sagging of the immediate roof strata over entries. Experience has shown that characteristic stress trends before a major event were large and unique enough that local events have been eclipsed. However, validation of these patterns requires replication through additional field testing and correlation with established models of failure mechanisms.

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