GEOLOGICAL SENSING - THE KEY TO INCREASING MINER SAFETY

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ABSTRACT

The U.S. Bureau of Mines is involved in research to improve geological sensing (or geo-sensing) techniques. This paper presents results from field trials of two research projects concerned with new technologies for geo-sensing. The goal of the first project was to develop a "smart" roof bolter drill so that it could probe into roof rock to evaluate rock conditions. The goal of the second project was to modify an existing mine-wide monitoring system in a continuous mining operation so that the system could interface with geotechnical instruments to provide near real-time geo-sensing. Integration of this mine-wide monitoring system with the smart roof drill to collect, reduce, and analyze geotechnical data, and the potential applications of the resulting technology in mining, are described.

INTRODUCTION

For any engineering project to be effective, there must be a continual flow of data from the observed process or object to the observer. In ground control, this involves gathering information on the physical condition of the rock mass, the in situ stresses acting upon the rock, and those geological features that control rock mass behavior. Both analytical and empirical methods are now used to develop design alternatives. The effectiveness of a design is evaluated by feedback from monitoring instruments so that the stability of the rock surrounding an opening can be maintained.

Mining is much different today than it was just 10 years ago. There are fewer underground coal miners in the United States and also fewer miners, yet these mines and miners are producing more than ever before. Underground bituminous coal production reached almost 400 million short tons in 1989, the highest amount ever.

and this was accomplished with fewer underground miners (25,000 in 1987, down from 141,000 in 1980). Between 1980 and 1989, production per miner per hour rose from 1.45 to 2.72 tons.

Although the number of underground coal mine fatalities decreased from about 465 during the period 1980-1984 to about 210 during the period 1985-1989, falls of roof, face, and rib still accounted for about 42% of the fatalities. This percentage is relatively unchanged from year to year (Keystone Coal Industry Manuals, 1980-1989).

Part of the reason for increased coal production is that mining equipment has become larger and faster. However, as the rate of mining increases, there is less time to inspect ground for geologic hazards. Because of machine noise, rock sounds are hard to hear, and the fast mining rate makes hazardous geologic conditions difficult to see. Machine vibrations can mask a miner's ability to sense rock movement. As a result, a miner's ability to anticipate the development of potential hazards is seriously impaired.

The time has come to address the root cause of these fatalities and injuries. Miners must be given the tools that allow them to sense changes in the dynamically changing geological environment in which they work. They must receive information in time to take corrective action, whether this action consists of leaving an area, modifying the rock mass, or continuing to work with the confidence that the geological environment is safe.

Geo-sensing not only refers to the ability to detect changes in the geological environment, but also to the ability to predict how these changes affect ground stability. The first step in developing an effective geo-sensing program is to provide real-time displays of the factors affecting rock and roof stability, e.g., the engineering properties of rock, in situ field stresses, and geological discontinuities. Given this information, it is

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possible to begin to formulate hypotheses concerning ground stability. The next step is to understand the critical precursors to rock mass failure as derived from engineering data collected through geo-sensing.

The National Research Council report on Competitiveness of the U.S. Minerals and Metals Industry identifies geo-sensing as the first priority for research in mining technology in the United States (National Research Council Committee on Competitiveness of the Minerals and Metals Industry, 1990). This report defines geo-sensing as the ability to (1) predict variations in rock, coal, and ore grades of the working face, (2) sense the closeness of geological disturbances such as faults, joints, and water-bearing formations, and (3) obtain in situ measurements of ore grades.

Geo-sensing uses advanced technology to forecast changes in geologic environments. Several techniques exist to determine the quality of the geologic environment surrounding a mine opening. One technique is to transmit a source signal nonintrusively through the rock mass; such a signal is reflected back when it encounters geologic anomalies. This technique works well if time and technological resources are available and the reflective target boundaries are distinct and well defined so that interpretation can be made easily and rapidly. In most mining operations, this is not the situation, hence use of this technique has been limited primarily to identification of abandoned mine workings or potentially hazardous bodies of water that may cause inundation of a mine.

Another geo-sensing technique to gain knowledge of geologic structure is to probe a rock mass through sample and core interpretation or through changes in machine drilling parameters which vary with rock type and competency. Using such techniques, the Bureau of Mines has completed a series of field trials that suggest significant geologic information can be derived from the physical responses of a roof drilling machine. Information is collected in near real time; rapid data interpretation is possible through applications of rather simple artificial intelligence (AI) software.

A third and perhaps the most widely used geo-sensing technique is to measure changes in geologic environments to forecast rock mass behavior. Miners have long assessed rock mass stability by observing the condition of the roof, floor, ribs, supports, etc. They have also listened for telltale signs of rock mass movement. Recently, the Bureau has been involved in research to integrate mine-wide monitoring systems with geotechnical instruments that measure critical ground conditions in much the same manner as a miner would. In this research, a mine-wide monitoring system was used to measure continuously roof layer movement and roof-to-floor closure and display rates of roof-to-floor closure on a computer screen.

### Advanced Geo-sensing Techniques

The Bureau's ground control research program is broad and multifaceted; however, recent emphasis has been placed on developing techniques for geo-sensing. The objective of this new focus is to develop rapid, easy-to-use methods and techniques for capturing and interpreting geotechnical data. The use of simple AI software packages for analysis and interpretation of large amounts of geotechnical data is proving to be invaluable as a mining tool. Together, advanced technology in geo-sensing and AI provide the mechanisms for geotechnical decision-making in near real time. Two examples of current geo-sensing research are the smart roof drill and the mine-wide monitoring system for ground control.

### The Smart Roof Drill

It has been theorized that a direct relationship exists between the energy expended while drilling a given rock and the competency of that rock (Teale, 1965). Research has indicated that this hypothesis is true and that a close correspondence exists between the compressive strength of the drilling medium and specific energy of drilling as a function of torque, thrust, penetration rate, rotation rate, and the area of a hole.

In the late seventies, the Bureau of Mines tested drilling machine instruments as means of detecting hazardous roof conditions (Lusignan and Maser, 1978). It was concluded that it was possible to use drilling parameters to measure specific energy and that development of a system that measured such parameters could, within certain limits, identify rock strength. The long-term research objective was to develop a system that enhanced and supplemented operator senses by applying modern sensing and instrumentation techniques to measure drilling parameters and relate these parameters to roof conditions. Roof conditions could then be interpreted as they were encountered during drilling. The data would be supplied to modifying roof control planning. The system developed, shown in Figure 1, was referred to as the smart roof drill.

At the present time, the instrument system on the drilling machine consists of three components. A personal computer (PC) is used during program development and data retrieval and analysis. The PC is located outside the
mine environment and is not subjected to the adverse conditions underground. A second component consists of a mine-permissible, safe enclosure that houses the measurement and control systems and other signal-conditioning circuits. All lines running into and out of this enclosure are protected by barriers to prevent the transfer of unsafe currents to the transducers of the control panel. These lines are enclosed in flexible hose conduit. A third component is a control and display panel that includes all the external transducer circuits and a data transfer device (DTD).

The measurement and control section is mounted on the left rear side of the drill in an area previously occupied by the duct collection system. The duct collection system is not needed because drilling dust is now controlled by water-washing.

The control and display panel is mounted on the front of the drilling machine next to the control levers, which are used during the drilling and bolting sequences. This location is best to provide maximum visibility and access for the drill operator. The DTD is connected through a short cable to the control and display panel.

When mounted on the drilling machine, this system provides an operator with near real-time display of the changes in specific energy of drilling and drill bit position. A system microcomputer interprets and analyzes these data in near real time, making it possible to identify hazardous roof conditions, such as voids, inclusions, and/or changes in strata. Such information can also be downloaded to a CRT and transferred to the surface, where it can be accessed directly by a PC.

Calibration and testing of the smart roof drill were conducted at Spokane Research Center laboratories. Sandstone test blocks, constructed of alternate hard and soft layers, were cast with voids at specific levels. Cores were taken at the time the blocks were poured to check system calibration. The blocks were used to determine the accuracy of the calculations and the precision with which the specific energy of drilling and bit position could be measured. Following extensive calibrations, initial tests of the drill monitoring and display system showed a definite relationship between the specific energy of drilling and the compressive strength of the medium drilled.

Field trials were conducted in an underground coal mine in Utah. Two test areas were selected, one in which the predominant roof rock was sandstone and one in which it was mudstone. Sampling designs were developed for locating the core holes and specific-energy of drilling holes for the two test areas. A pattern of four core holes, each approximately 3 feet long, were drilled in five locations. Five specific-energy test holes were drilled around each core hole using a template that spaced each test hole 14 inches from the core hole.

One hundred specific-energy test holes were drilled in the sandstone area, and specimens from 20 core holes were collected. Field trials in the mudstone area were completed by collecting an additional 20 core specimens and drilling another 100 specific-energy test holes (Beven and Hill, 1987; Frissell et al., 1992; Frissell, 1991; Howie and Frissell, 1990; Howie and Frissell, 1990b; Frissell et al., 1990; Howie, 1990a, 1990b).

The unconfined compressive strength obtained from laboratory testing of the cores and the specific energy of drilling were compared; the purpose was to provide the upper and lower limits to measurement errors for estimates of specific energy of drilling in slightly different rock types. Detailed geologic logs of the core holes were important because different geologic zones in the cores can be used to reference corresponding data from the drill holes.

**MINE-WIDE MONITORING FOR GROUND CONTROL**

A concurrent research effort involved a mine-wide monitoring system that measured geological engineering data continuously from a remote location to assess the stability of a mine opening. It became apparent that information from the smart drill and the mine-wide monitoring system could be incorporated into a simple geo-sensing system. Such a system could
provide data about the rock mass while actually measuring changes in the geologic environment.

A mine-wide monitoring system consists of a surface PU connected to sensors underground. The system can output visual and/or audio alarms. Important features are that the system be expandable and allow for near real-time action via keyboard control.

To keep up with mining rates, manual data collection can be replaced by a mine-wide monitoring system. This is especially important if data points are numerous and scattered, and if accuracy, speed, and continuous information are essential to a safe mining operation. Various types of sensors may be used with this system to collect ground control data. For example, a roof-layer sensor measures roof bedding separation; if rock movement continues to occur with time, the roof may become unstable and collapse. Other instruments include extensometers, which measure total entry closure and rate of closure, and flat pressure cells, which measure distribution of support load. Using a mine-wide monitoring system to collect and sort data provides additional capabilities for assessing the stability of the geological environment. Figure 2 is an artist's rendition of how a mine-wide monitoring system might be used to collect geotechnical data.

The Bureau of Mines is conducting research on two separate projects on the application of mine-wide monitoring systems to assess mine stability. Objectives of one project are to (1) develop the methodology for a mine-wide monitoring system to monitor the effects of rapid mining on pillar and face loading continuously and automatically, (2) calculate stress redistribution in and around a longwall panel, and (3) characterize roof caving behind longwall supports. This system is now operational in a Colorado longwall mine. The data are collected every 6 seconds, transmitted to a remote location 150 miles away via telephone lines, and analyzed and displayed in near real time. The results of this work have been presented in several publications (Nanna et al., 1991; Conceo et al., 1990; Harron et al., 1993; Hervey and Kneeling, 1993; Maleki and Tiff, 1993).

Figure 2. Installation of instruments to gather geotechnical data with a mine-wide monitoring system.

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The second project involved the use of a mine-wide monitoring system to monitor ground conditions, in a room-and-pillar coal mine in Utah. This application was expanded to include monitoring gate road stability in longwalls. The Utah mine had initially installed a mine-wide monitoring system to detect early signs of fire and to operate fans. Later the system was expanded to monitor and control belt drives, transformers, pump pumps, liquid levels, fluid pressure, air flow, power voltage, and electrical current, as well as bearing temperatures and vibrations at permanent pump stations and ventilation fans. Information on remote pump stations, belt scales, and coal and rock dust bin levels was also monitored and controlled.

However, this system was not being used for ground control purposes (Hyto, 1985). Although nine personnel had been monitoring several gate roads using manual techniques, manual measurements and/or readings of mechanical instruments required too much labor over long periods to be very effective. The reduction of hand-collected data into a useful format was not practical. By using a mine-wide monitoring system, additional valuable information could be gathered and analyzed on a near real-time basis.

In a cooperative effort between the Bureau and the mine operator, an instrumentation plan was developed to investigate characteristics for the equipment needed to collect appropriate ground control data. Requirements were that off-the-shelf instruments be compatible with the existing mine-wide monitoring system and that they could collect data on ground movement in near real time. Instruments had to be mine-worthy, safety approved, and retrievable.

In implementing the project, initial monitoring focused on obtaining roof layer movement and entry convergence readings. The purpose was to identify load redistributions on gate roads and to evaluate ground support methods. Research also involved ways to improve gate road design and support performance.

The resulting mine-wide monitoring system uses a microprocessor that allows for a high degree of measurement accuracy. Linear-motion transducers measure differential roof layer movement, and ultrasonic distance-measuring sensors monitor entry convergence. An electronic barrier provides an intrinsically safe connection between the installed instruments and the main trunk line.

Different analog-to-digital conversion cards are used in this system. One card converts the analog signal from four roof layer movement instruments to a digital signal that is transmitted to the control center at the surface. Separate cards are required for each sonic closure instrument (Chiaretti et al., 1990; Worley and Hyto, 1991).

**THE ROLE OF INTELLIGENT SYSTEMS**

The research described above provides a fertile ground for geo-sensing research using mine-wide monitoring systems and the smart roof drill, particularly if the two systems can be linked together. Figure 3 illustrates one concept of how the two systems might be interfaced. Researchers are now investigating ways to develop such a system. What has become apparent is that it is possible to collect large amounts of data related to ground control and ground stability in a short period of time. One challenge is to determine which data are critical to ground stability and which are not. The data must then be separated and analyzed so that ground control decisions can be made rapidly and accurately.

![Smart roof drill interfaced with mine-wide monitoring system.](image)

To meet these challenges, Bureau researchers began investigating the potential of various AI techniques to discern what changes in drilling parameters monitored by the smart roof drill and what measurements from the mine-wide monitoring system were important relative to changes in rock structure and roof stability. Certain requirements were developed to ensure that costs, time, and accuracy were kept within reasonable limits, including the use of off-the-shelf AI software packages.

The objective is to develop an intelligent system for roof control (ISRC) that will improve the capability of engineers to assess the geologic environment and select roof supports for ground control in coal mines. The ISRC incorporates an expert system that queries the user for information, makes inferences from what is known, and uses "rules of thumb" when...
analytical solutions are not appropriate. The expert system interfaces with the smart roof drill and mine-wide monitoring system to identify geological features, selects significant roof features relative to support parameters, and suggests improvements in the support design. The result is a system that can update support design information rapidly and accurately as mining progresses. A schematic of the architecture of the ISRC is shown in Figure 4.

![Diagram of ISRC Architecture]

**Figure 4. Basic architecture for an intelligent system for roof control.**

As can be seen, the ISRC integrates two neural networks and an expert system. Neural network I maps the mine roof using drilling parameters (thrust, torque, rotational rate, etc.) generated as a bolt hole is being drilled with the smart roof drill. Mapping will allow further classification of roof rock on a scale of relative strength. Voids in the roof are also located and mapped.

Neural network II will use the output of neural network I to build an overall view of the mine entry. Each bolt installation will serve as a data point in mapping the mine roof.

Several bolt holes need to be drilled and bolts installed before a general map of the roof may be generated. However, once this is accomplished and new drill and bolt installation data are transmitted by neural network I, neural network II can classify the state of the roof. At this time, neural network I has been trained using data from the mine's sandstone test area.

A user would interface primarily with the expert system. This system would take outputs from the two neural networks and input from the user (entry width, type of bolts presently being used, etc.) to recommend a specific supplemental support scheme. This scheme could encompass anything from setting posts to changing entry width.

A more detailed description of the ISRC architecture selection process is described in a paper by King (1991). Specifics on the operational mechanics of the architecture, particularly the expert system, are described by Figner (1992). What emerges from this research is that it is not only possible to collect massive amounts of geotechnical data through the use of various geo-sensing techniques and devices, but also to reduce these data to a meaningful, useful form through the application of various AI programs. Figure 5 shows how various knowledge and databases could be used to provide input to an overall geotechnical decision-making system.

**SUMMARY**

The ability to sense changes in the geologic environment, interpret these changes, and make rapid, accurate decisions on support systems in underground coal mining is becoming a reality. Recent technological developments to probe into the rock with a smart roof drill as part of the normal roof bolting process and to decipher drilling machine parameters to detect changes in rock strength and geological conditions show promise. The use of mine-wide monitoring systems to gather information on ground control and support loading conditions and evaluate changes in these conditions can now be considered proven technology. Through the use of AI, mine personnel can now make decisions, for example, about how to control methane and coal dust generation. Research directed toward creating the knowledge and databases for ground control decisions, particularly support selection, is progressing well.

Given these developments, it is clear that research in geo-sensing, as envisioned by the National Research Council, is moving ahead. The problems, however, of being able to "look" into a rock mass and forecast its behavior or determine what changes must be made to ensure the safety of underground workers are not easily solved. Being able to change support systems to match changing rock mass conditions in one step. As work progresses, both the extent of the support knowledge base and the number of knowledge bases will be expanded to cover other aspects of ground control, including mine layout and pillar design alternatives. However, the mandate of the National Research Council is clear. Research in geo-sensing will continue to be a high priority in the Bureau of Mines.

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Figure 5. Composite drawing of gеotechneгіс decision-mаkіng system.

REFERENCES


