

# INSTRUMENTS FOR MONITORING STABILITY OF UNDERGROUND OPENINGS

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## ABSTRACT

For several years, researchers from the Spokane Research Laboratory of the National Institute for Occupational Safety and Health (NIOSH) have been using geotechnical instruments in underground mines to study ground control problems and develop means of reducing accidents and fatalities caused by ground falls. This paper describes many of the different types of instruments, sensors, and data acquisition equipment that have been used for these studies; briefly explains the advantages and disadvantages of various sensor technologies; provides practical recommendations regarding the use of specific instruments and data acquisition systems; and outlines a general approach to the design and implementation of a successful instrumentation plan.

A wide variety of instruments are commercially available for measuring deformation, strain, stress, and/or load. If used correctly, these instruments can provide important quantitative information regarding the mining-induced behavior of the host rock, the performance of ground support systems, and the safety and stability of underground workings. Data collected from these instruments can warn mine staff of impending ground control failures or hazardous working conditions, as well as provide valuable information for the design of ground support systems and the configuration and sequencing of mining excavations. We hope that the practical information presented in this paper will encourage a more widespread use of geotechnical instruments in underground mines and lead to reliable measurements that aid the engineering decisions affecting the safety of miners.

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## INTRODUCTION

Researchers at the Spokane Research Laboratory (SRL) of the National Institute for Occupational Safety and Health (NIOSH) have been placing instruments in mines for several years to study means of reducing accidents and fatalities caused by ground falls. This paper describes ways of using these instruments. The goal of this paper is to share information and tips that encourage mining operators to use instruments to aid in decisions affecting the safety of miners.

In today's world of mining, layout and roof support are designed so that pillar and entry safety factors are only a little above the critical point of failure. Under varying conditions, the amount and type of roof support may greatly affect stability. It is therefore desirable to optimize roof support, i.e., the density and/or type should be sufficient to minimize the risk of ground fall, yet minimize costs. Technical personnel must determine this point using good engineering judgment.

Numerical models can be valuable tools in providing answers to "what if" questions, but they may provide poor information if erroneous assumptions or poor input values are used. For example, a homogeneous continuum model may not be sufficient if joints play a significant role in roof falls. Verification and tuning of models is a step that is quickly forgotten in the rush for an answer.

Instruments have been used increasingly in mines to measure deformation, stress, strain, and load. Such measurements serve two purposes. First, they provide quantitative information that can be useful in determining the mechanics of stability and in aiding engineering decisions. Second, they can be useful in verifying and tuning numerical models.

Bauer [1985] briefly described many types of available ground control instruments. Hanna [1985] comprehensively described instruments and measurement theory as applied to foundation engineering and construction. Dunnycliff [1988] updated information on instruments and how to plan monitoring programs. While new instruments have been designed and improvements made in older ones, it is not the purpose of this paper to give a comprehensive update. Rather, the purpose of this paper is to outline an approach to instrumentation that we have used for several years, describe the basic types of sensor technology, describe our experience with various instruments, list manufacturers of these instruments known to the authors, and provide pointers on continuous monitoring with a data acquisition system.

## INSTRUMENTATION PLANNING

Design and implementation of a successful instrumentation plan requires careful consideration of the following factors:

- A fundamental understanding of the overall rock mechanics, geology, and general site conditions;
- Identification of the critical mechanisms or geotechnical parameters that need to be measured;
- Clearly defined objectives for each of the measurements to be taken;
- Estimates of the magnitude or anticipated range for each of these measurements;
- Selection of instruments, transducers, and data acquisition equipment appropriate for the desired measurements and site conditions;
- Availability of experienced personnel to install, troubleshoot, and monitor the instruments; and
- Established procedures for data collection, analysis, and reporting.

In general, instruments should not be installed until appropriate provisions have been made for collecting, analyzing, and reporting the instrument data.

Programmable data acquisition systems with multiplexers provide the user with the opportunity to scan and record

measurements frequently from a large number of instruments. To ensure that the maximum benefit is derived from instrumentation programs, especially those capable of collecting enormous amounts of data, careful planning is necessary. Entire chapters in geotechnical instrumentation books are devoted to the subject of planning instrumentation programs and interpreting recorded data [Dunnycliff 1988; Hanna 1985]. Similarly, the number of papers presented at instrumentation conferences that address planning issues is sometimes large enough to comprise a technical session [Leung et al. 1999].

A successful instrumentation program starts by defining the purpose of installing the instruments and ends with implementing the decisions derived from interpretations of the data. Dunnycliff [1988, 1999] offers a 21-step checklist in which each step in a successful instrumentation program is described. Because comprehensive information about instrumentation planning is available in geotechnical literature, the following discussion focuses specifically on experience gained from installing instruments and data acquisition systems in underground hard-rock and coal mines, maintaining these systems, reducing the collected data, and interpreting the data for immediate and future use.

Because one of the goals of an instrumentation program is to monitor ground stability and take corrective action for any

imminent problem, instruments that sense displacement and stress changes are commonly used. Instruments should be checked to ensure that they have not been damaged during shipping and handling. In general, displacement transducers should be recalibrated after they have been received, especially if the sensor is a potentiometer or a Wheatstone bridge circuit and if cable is added between the sensor and monitoring device. This action is helpful because the new calibrations will account for resistance caused by the cable. For vibrating-wire transducers, factory calibrations are generally sufficient because calibration constants are not changed by adding cable.

However, operation of the transducers should be verified before they are used underground. It is useful to have calibration sheets for displacement transducers at installation sites to assist in positioning transducers in the desired initial positions.

It is important to place the instruments at locations where the expected parameter changes can be measured accurately. For tabular ore bodies, estimates of change in values, such as stress or strain in pillars, abutments, and backfill, can often be calculated using the tributary load method. More complicated mine geometries may require numerical models to identify areas in the mine that will undergo high stress changes. For extremely critical areas near shafts or shops, it may be necessary to calculate changes in stress and displacement at

specific points using a numerical model before installing instruments. This information can then be used to select the appropriate instrument range. If a two-dimensional numerical model will be used with instrument data collected during mining to evaluate mine stability, it is important to place an adequate number of instruments along the modeled cross section to provide calibration points for the model.

Installing two instruments that measure different parameters at the same location increases the probability that collected data will be useful. For example, pillar stability could be assessed with a stress-change measuring device such as a biaxial stressmeter and a displacement measuring instrument such as a horizontal borehole extensometer [Seymour et al. 1998]. Stress changes in the pillar can be verified by a borehole extensometer, which measures pillar dilation. Similarly, stress changes in backfill could be measured by embedment strain gauges and cross-checked with earth pressure cells [Tesarik et al. 1995]. Borehole extensometers in the mine roof may help analyze loading mechanisms [Tesarik et al. 1999]. Clustering instruments in this manner was useful in numerous instrumentation programs and served to verify measurements and aid in data interpretation. Clustering also provided backup data when one of the instruments or its cable was destroyed or malfunctioned.

## SENSORS AND MONITORING

The authors have primarily used the following sensor technologies for instruments installed in underground mines: strain gauges configured in Wheatstone bridge circuits, potentiometers, and vibrating-wire transducers. These sensors can be read either manually with a portable electronic readout box or at programmed intervals using a computerized data acquisition system set up in a central location near the instruments. Manual data collection methods are typically used in situations where only a limited number of instruments are monitored; individual instruments are installed in remote, isolated locations; it is impractical to route the instrument cables to a central location; personnel experienced with the use of dataloggers are not available; or the additional expense of a data acquisition system is prohibitive. Although manual readings can provide reliable information about the stability of underground openings [Tesarik et al. 1991, 1999], these readings are usually taken too infrequently to allow a meaningful analysis of measurement quality and are subject to human error. If possible, instruments should be monitored with a data acquisition system, and manual readings should be taken periodically with an electronic readout box to verify the datalogger measurements. Frequent readings not only permit better judgment about the quality of the

measurements, but also help associate trends in the instrument data with discrete mining events. The use of dataloggers and their ancillary components is described below in the "Data Acquisition System Basics" section, along with several recommendations for improving the likelihood of quality measurements.

### SENSOR TECHNOLOGIES

#### Wheatstone Bridge

A Wheatstone bridge is a circuit (figure 1) that provides a signal output directly related to strain. If  $R_1$ ,  $R_2$ ,  $R_3$ , and  $R_4$  are the respective resistances of arms 1 through 4 in figure 1, and  $R_1R_3 = R_2R_4$ , then the differential output voltage,  $\Delta E$ , may be represented by

$$\Delta E = V_x \frac{R_1R_2}{(R_1 + R_2)^2} \left( \frac{\Delta R_1}{R_1} - \frac{\Delta R_2}{R_2} + \frac{\Delta R_3}{R_3} - \frac{\Delta R_4}{R_4} \right) \quad (1)$$

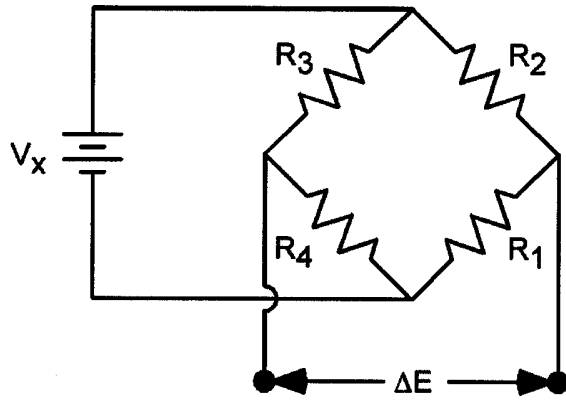


Figure 1.—Wheatstone bridge wiring diagram.

if second-order terms are neglected [Dally and Riley 1991]. In equation 1,  $V_x$  is the applied excitation voltage and  $\Delta R_1$ ,  $\Delta R_2$ ,  $\Delta R_3$ , and  $\Delta R_4$  are the changes in resistance of strain gauges 1, 2, 3, and 4, respectively. If all arms of the bridge are active (or all are subject to strain-induced resistance change), then the circuit is called a full Wheatstone bridge. A half-bridge is described when  $R_3$  and  $R_4$  are fixed and  $R_1$  and  $R_2$  vary with strain. A quarter-bridge is described when only  $R_1$  varies with strain and the other arms of the bridge are fixed.

Load cells and pressure transducers are examples of typical full-bridge sensors. An instrumented bolt or cable has strain gauges positioned at various distances along its length on opposite sides of the bolt. Each strain gauge is read by completing the bridge with fixed precision resistors (quarter-bridge circuit), which are usually located near the data acquisition unit. It is possible to use one set of completion resistors ( $R_2$ ,  $R_3$ , and  $R_4$ ) by using switches on the strain gauge leads. The switches to a particular strain gauge ( $R_1$ ) are closed while the switches to the other strain gauges are left open. The next gauge may be read after opening the closed switches to the current strain gauge and closing the switches to the next strain gauge. The completion resistors should be kept as close to the temperature of the active gauge(s) as possible to avoid thermovoltic errors.

In the case of a quarter-bridge circuit, long wire leads may affect the circuit by reducing sensitivity (see figure 2A, where  $R_1 = R_g + 2R_L$ ). This sensitivity loss is typically compensated for by a reduction in the gauge factor used to convert voltage signal to strain. The loss resulting from signal attenuation may be cut approximately in half by using the three-wire quarter-bridge circuit, as shown in figure 2B.

Advantages of Wheatstone bridge technology are that response is immediate and very sensitive and the instrument can be used for measuring static or dynamic strain. Two disadvantages are that the datum-state reading shifts over time (zero drift) and that the instrument may respond secondarily to temperature. Much of the drift may be attributed to glue creep.

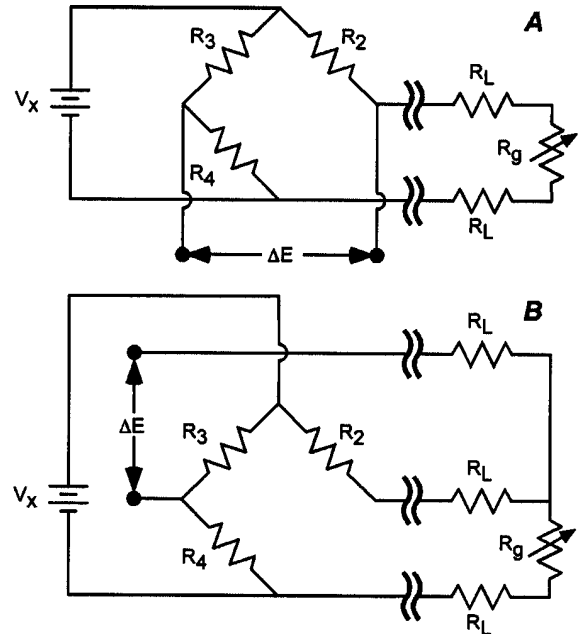


Figure 2.—Quarter-bridge wiring diagram. A, Two-wire leads; B, three-wire leads.

Another disadvantage of the Wheatstone bridge is the low level of the signal,  $\Delta E$ . In a mine environment, there are several possible sources of external current or noise that may overshadow or drown the signal, including high-voltage power cables, leaky-feeder-type communication systems, machine noise, and multiple grounds. In most cases, such effects from external sources are not present. Instrument cables should be hung away from other power cables. Power cables should be crossed only when necessary. A shield should always be placed around the power cable, and the instrument cables should be routed so that they cross the power cable at a right angle.

Multiple grounds have periodically been a problem, particularly with instrumented bolts, where a connection to an earth ground may run through the bolt. If another earth ground has already been established (for example, near the datalogger), a ground loop is formed, which may drive bridge signals up or down, often completely out of its expected range. For this reason, the authors now choose to not connect the datalogger's power supply ground to an earth ground.

### Potentiometer

Figure 3 shows a typical potentiometer circuit used to sense displacement. A resistive element is excited with a constant, known voltage  $V_x$ . A wiper contacts the resistive element along its length. One-dimensional movement of the wiper with respect to the resistive element is sensed by measuring the voltage of the wiper with respect to the ground. The measured wiper voltage ranges from 0 to the excitation voltage, depending on its contact location on the resistive element.

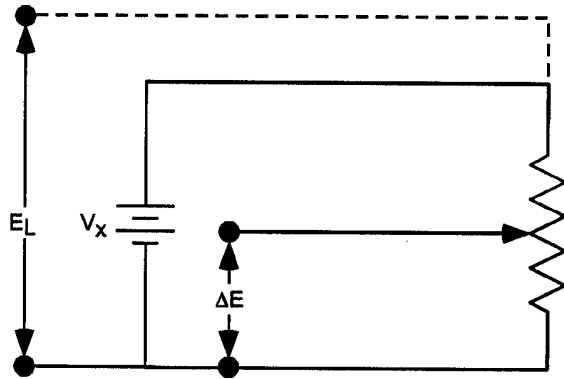


Figure 3.—Potentiometer circuit.

Potentiometers may be manufactured to cover a variety of displacement ranges. Sensitivity depends on the excitation voltage and the voltage monitoring device.

The authors have not encountered noise problems with potentiometers because the level of signal used has typically been 2 to 2.5 orders of magnitude above that of the Wheatstone bridge circuit. However, the user should be aware of the potential to burn up the wiper-resistive element contact if a large electrical current is discharged through the wiper following measurement. One precautionary measure is to connect a resistor to the wiper to restrict the amount of current that can pass through it. The authors have used a 1-k $\Omega$  resistor on the wiper with a 20-k $\Omega$  resistive element.

In the case of long lead wires, the user can choose to use the circuit as is. However, the circuit must be calibrated with the long lead wires before installation. The authors have determined applied excitation voltage using a fourth wire (dashed line in figure 3) to measure the voltage drop across one lead length. The voltage applied at the resistive element is the excitation voltage applied at the datalogger less the drop across two lead lengths. The voltage drop across one lead length is determined with the electric potential between the dashed wire and analog ground. By assuming equal voltage drop in both lead wires, the applied excitation at the resistive element is determined using the following equation:

$$\text{Applied excitation at the resistive element} \approx V_x - 2(V_x - E_L), \quad (2)$$

where  $V_x$  = excitation voltage applied at the datalogger;  
and

$E_L$  = the measurement in volts between the dashed lead and analog ground.

The potentiometer reading may be normalized with this applied excitation voltage. The raw reading, applied voltage, and normalized reading should be stored in the measurement data file.

## Vibrating-Wire Transducer

Vibrating-wire transducers are used in many instruments, including load cells, deformation gauges, surface and embedment strain gauges, earth pressure cells, pressure sensors for piezometers, and liquid level settlement gauges [Dunncliff 1988; McRae and Simmonds 1991; Choquet et al. 1999]. A steel wire is tensioned between two clamps so that it can vibrate at resonant frequency. As the clamps are physically moved relative to each other by applied force to the sensor (displacement transducers use a linear spring to convert displacement to a proportional force on the vibrating wire), the resonant frequency changes. A coil is positioned near the wire. When current is run through the coil, the resulting magnetic field in effect plucks the wire, causing it to vibrate at a resonant frequency reflective of the external force. The vibrations, in turn, cause voltage fluctuations in the coil that correspond to the vibrations. A handheld readout box or automated data acquisition system measures the time it takes to complete a given number of vibration cycles and computes the frequency. Sometimes an interface unit is used to boost the excitation voltage. Signal conditioning and conversion to digits of frequency squared or engineering units are performed by a datalogger.

In the case of a continuous readout, two coils are used. One coil electronically plucks the wire and senses the vibration-caused voltage fluctuations. This frequency is calculated. The second coil vibrates the wire at the same frequency. As frequency changes, so does the plucking frequency of the second coil.

There are several distinct advantages to using vibrating-wire transducers. First, the readings are not sensitive to long lead wire lengths because frequency, rather than voltage level, is being measured. Low-capacitance cable may be required for lead lengths greater than 200 m (650 ft). This means that a cable can be cut in the field to the length needed without offsetting the output signal. Moreover, Choquet et al. [1999] report that manufacturers have perfected the manufacturing process to the degree that there is very little drift in the reading at no load or zero displacement over time and only small changes occur in calibration slopes (within  $\pm 0.5\%$ ) after nearly 4 years. McRae and Simmonds [1991] report that all of their tests, some lasting for over 10 years, show that if wire stress is kept below 30% of yield, long-term drift will be minimal. For pressure transducers where minimum stress is only 13% of yield, long-term drift is insignificant. McRae [2000] reports that his tests show virtually no drift after 15 years. This performance makes vibrating-wire technology very desirable for long-term monitoring.

One problem that has surfaced from time to time is that the datalogger will fail to obtain a meaningful reading when it is monitoring a vibrating-wire transducer that incorporates a vibrating-wire interface to the datalogger. One explanation

may be that the selected frequency sweep range did not include the frequency to be read. More often, however, it is a contact problem where wires are clamped at terminals. These contacts must be tight and of good quality. In the authors' experience, when a poor connection was discovered during sensor checks or calibrations, improving the contact generally solved the problem. A vibrating-wire readout box provides a good backup, as it provides more signal filtering. The authors have never encountered a problem when using a vibrating-wire readout box instead of a datalogger. Experience has helped minimize problems encountered when the sensors are monitored with a data acquisition system.

### DATA ACQUISITION SYSTEM BASICS

The authors have used dataloggers from Campbell Scientific, Inc., for several years. Models 21XQM (now discontinued by the manufacturer) and CR10QM are approved by the Mine Safety and Health Administration for use in methane-air atmospheres. Although operation of one of these dataloggers is relatively simple, learning to use the system may require a little effort. There is a learning curve for the dataloggers and related components, but unattended instrument monitoring and recording are usually well worth the effort required to learn to use the system. In this section, basics of using these dataloggers and associated components are discussed to help the user considering sensor monitoring with an unattended data acquisition system.

The dataloggers collect two basic measurements: single-ended voltage and differential voltage. The difference between these types of measurements will be aided by reference to figure 4, which shows a CR10QM wiring panel with labeled terminals.

A single-ended measurement is a measurement of voltage with respect to ground. For example, a single-ended measurement would be measured between two wire leads. One lead must go into one of the analog ground (AG) terminals. The other lead must connect to one of the input channels (1H

(high), 1L (low), 2H, 2L, etc.). The input channel must be specified with a measurement command in the datalogger program. For example, a potentiometer is read with a single-ended connection to the datalogger. A vibrating-wire sensor with an in-line interface is connected to the CR10QM in the same way; however, instead of a single-ended measurement, the datalogger measures time for a certain number of vibration cycles and converts that measurement to frequency squared or engineering units.

A differential measurement is a measurement of voltage in one lead with respect to that in another lead. The two leads are connected to differential channel input terminals (1H and 1L, or 2H and 2L, or 3H and 3L, etc.). The voltage of the high (H) terminal is measured with respect to the low (L) terminal. For example, Wheatstone bridge circuits are measured by connecting the signal leads to a set of differential channel input terminals on the datalogger.

A CR10QM datalogger has 6 differential inputs or 12 single-ended inputs. The 21XQM has 8 and 16 inputs, respectively. The number of sensors monitored may be extended by using multiplexers. A multiplexer is an electronic switching unit with mechanical relays. It has 4 common terminals and 16 channels of 4 terminals each. A multiplexer is activated by sending and maintaining a voltage that is greater than 3.5 V from a datalogger control port (setting the port high) to the multiplexer's "reset" terminal. When a pulse is sent from a control port of the datalogger to the multiplexer's "clock" terminal, switches close between the multiplexers' four common terminals and the four respective terminals of channel set 1. The next pulse opens these switches and closes the switches between the common terminals and the four terminals of channel set 2. The multiplexer is deactivated by removing the current through the control port (setting the port low).

Wires are run from datalogger terminals (inputs, excitation, and ground) to the four common terminals on the multiplexer. Sensor leads are connected to the appropriate channel set terminals.

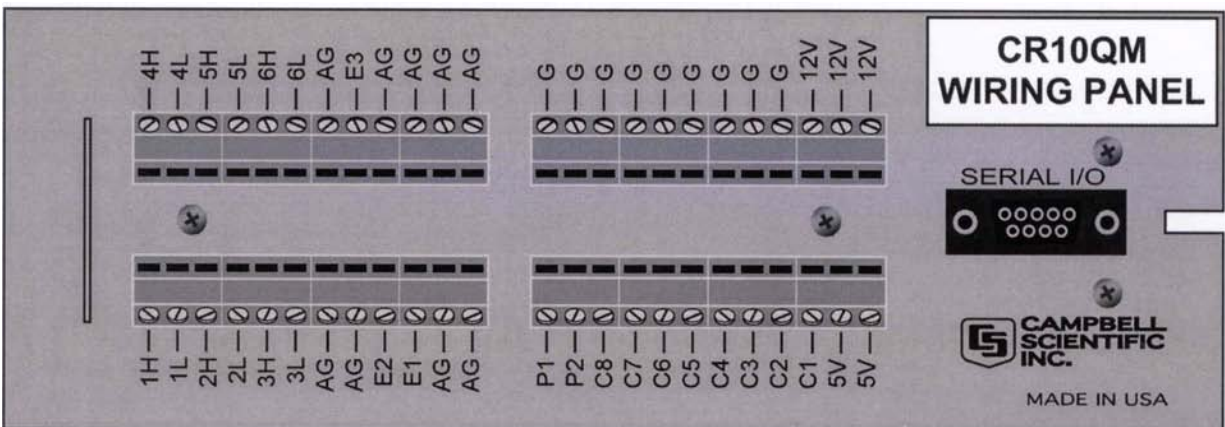


Figure 4.—Campbell Scientific CR10QM wiring panel.

The multiplexer increases the number of possible sensors that may be monitored through a datalogger input terminal or set of terminals. For example, the number of vibrating-wire transducers that may be monitored through a multiplexer is 32 (2 per channel set). Potentiometers require an excitation lead, and Wheatstone bridges require excitation and ground leads. Therefore, it is possible to monitor 16 potentiometers or 16 Wheatstone bridges through 1 multiplexer. Sensor types are generally not mixed on the same multiplexer.

The addition of multiplexers to a datalogger adds some complexity to reading sensors. When a clock pulse is sent to a multiplexer, a set of mechanical relays is closed. To ensure that contact has been made, the user must insert a programmed delay before the sensor is read. Typically, a delay of 0.02 to 0.03 sec is sufficient. Also, a delay of 0.05 sec is good practice following multiplexer deactivation.

PC208W software and interfaces are used for communications, viewing data, and programming. For example, one subprogram provides a real-time connection to the datalogger from a personal computer through an optical interface. Another subprogram is used to communicate with a storage module through an RS-232 cable and interface. Another application is used to view data, and another to process information from those data.

A good programming structural sequence is to—

1. Read the sensors, usually in groups (in a loop) by multiplexer (readings are stored in input locations);
2. Read sensors internal to the datalogger (such as cold-junction temperature, battery voltage, program signature, etc.);
3. Set the output flag;
4. Read time and date;
5. Set resolution (usually high) and write readings from input locations to final storage; and
6. Send the data to an output device, such as a storage module.

Before writing a datalogger program, all circuits should be diagrammed from the datalogger to the sensor so that it is clear what programming instructions and parameters are to be used. With this information, programming is relatively simple. For the user's first program, it may be a good idea to contract with

Campbell Scientific for programming assistance. Once the user understands that program, additional programming is easy.

Once the system is installed, one potential operating problem involves electrical grounds. Until recently, it was the authors' practice to connect all cable shields to shield terminals and connect the terminals to one earth ground near the datalogger. In addition, the authors would connect the datalogger power supply ground to the same earth ground. While this practice seems logical for protecting transducers and the datalogger when a cable is compromised, it can also affect readings if the system is connected to a Wheatstone bridge. Ground potentials can vary significantly between sensor locations. In fact, one of the authors has measured a difference in ground potential of approximately 1 V between points in a coal mine roof just a few feet apart. When the instrument itself becomes part of a ground, as can happen with instrumented bolts and cables, any difference in ground potential between the instrument and the ground near the datalogger induces a ground loop and affects measurements. In such cases, it is not a good practice to connect shields at the multiplexers or datalogger. Recently, the authors began leaving the datalogger ground floating (not connected to an earth ground).

The authors always collect and store raw analog measurements. Sometimes the raw data are also processed and stored, but raw data are always saved. This procedure provides a backup in case of an inadvertent mistake in processing.

Lastly, the authors strongly recommend spending some time in the laboratory performing checks on the instruments and datalogger before installing the instruments in the field. This check avoids many problems that may be more difficult to solve underground or after installation. Monitoring sensors over a period of time in the laboratory can identify many problems. Similarly, instruments should also be checked at the installation site before they are installed. Experience has shown that use of connectors should be avoided if possible. The authors prefer to hard-wire instrument cables to datalogger and multiplexer terminals. This avoids problems such as cold solder junctions and the abuse that connectors always suffer underground as cables are run. In the event that use of connectors is unavoidable, cold solder junctions may be found by identifying erratic sensor readings when the connector is heated with hot air.

## INSTRUMENTS

Experience is important to increase the quality and probability of success in installing instruments. In the sections that follow, specific instruments and instrument types that the authors have used are described. Comments and tips are offered.

### DISPLACEMENT INSTRUMENTS

The authors have used both potentiometer (linear and rotary) and vibrating-wire sensors in instruments that measure displacement. Some instruments were purchased from various

manufacturers, while the hardware of some other instruments was manufactured in-house. The type of instrument used should depend on how much displacement is expected, number of required in-borehole anchors, instrument accuracy, stability over time, and operational constraints. For small expected displacements over a long period of time, grouted anchors or hydraulic anchors may be more desirable than spring anchors. For larger expected displacements, a spring with attached piano wire running to string potentiometers mounted at the borehole collar may be sufficient.

One of the authors used rotary potentiometers with a geared spindle that was supposed to mesh with a threaded rod. However, the gears sometimes skipped because the gear teeth and thread profile did not match well. The skipping problem was also very dependent on the force between these members. Force adjustments did not solve the problem.

Simple instruments that require manual measurements have been tried by the authors with varying degrees of success, because several possible sources of error may be introduced. Therefore, the authors generally avoid instruments that require manual measurements except where necessary (such as closure measurements).

Instruments are available from several manufacturers. The authors have used vibrating-wire sensors, and linear and rotary potentiometers. Variations on these instruments are available from Geokon, Inc., Lebanon, NH; Roctest, Inc., Plattsburgh, NY; RST Instruments, Vancouver, British Columbia, Canada; and Slope Indicator Co., Bothell, WA. SRL researchers have used string (rotary) potentiometers made by Celesco Transducer Products, Inc., Canoga Park, CA, with hardware manufactured in-house to monitor sag at different depths in a coal mine roof [Signer et al. 1993].

## INSTRUMENTED BOLTS

An instrumented bolt [Serbousek and Signer 1987; Johnston and Cox 1993] (figure 5) is an instrument that has been used increasingly in recent years by SRL researchers [Signer 1990, 1994; Larson et al. 1995; Larson and Maleki 1996]. It consists of strain gauges bonded to milled surfaces on opposite sides of a bolt. In addition to measuring strain, the gauges may be calibrated in the elastic range to calculate load directly as long as load has not progressed past the yield point of the bolt steel. If gauges are monitored over time, a row of these instrumented bolts reveals useful information about roof deformation and roof conditions. The information may aid in determining potential roof hazards and justifying changes in roof support to optimize or increase safety. The instruments are commercially available from Jenmarr Corp., Pittsburgh, PA, and Rock Mechanics Technology, Ltd., Staffordshire, U.K., although the authors have only used bolts instrumented by SRL technicians.

Because of the low level of the signal, the potential of the instrument serving as a ground, and differences in ground potential from point to point in an underground roof, external

noise may be introduced to the gauge signal. The user should follow suggestions found in the "Data Acquisition System Basics" section to minimize the likelihood of this problem.

If long cables link the gauges to a data acquisition system, a three-wire, quarter-bridge circuit should be used.

## INSTRUMENTED CABLE BOLTS

A new development in cable bolt sensor technology is replacement of the bolt's original king wire with an instrumented king wire [Martin et al. 2000] (figure 6). Similar to an instrumented bolt, an instrumented cable bolt is a support device as well as a rock mass strain-measuring device in underground mines. Characteristics of the rock mass in an underground mining environment can be determined by these devices, which provide a means for mining engineers and mine inspectors to predict roof falls.

The gauges are mounted on a narrow strip of steel at intervals determined by expected roof conditions, the instrumented metal strip is placed in a steel mold, and the mold is injected with epoxy. This results in a new king wire. The remaining six cables are then rewound around the new king wire, creating a seven-stranded instrumented cable. Maximum length of the cables is 6 m (20 ft) because of the physical constraints of the wires connecting the gauges. The maximum number of gauges is 10, or 5 on each side.

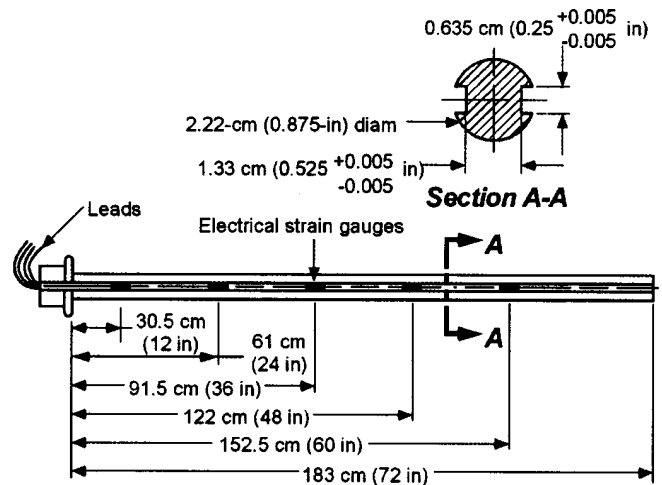


Figure 5.—Instrumented bolt (after Signer and Lewis [1998]).

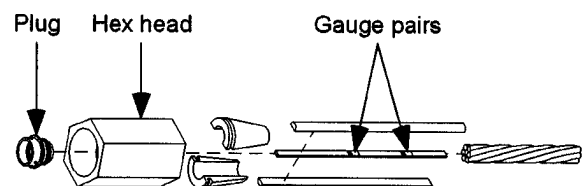


Figure 6.—Instrumented cable bolt (from Martin et al. [2000]).



The gauges can either be set in pairs in the same plane to detect shear or at 90° angles to detect lateral loading. The cables are inserted in a mine roof using cement or resin grout. They are capable of holding an ultimate load of 214 kN (48,000 lb). Data readings are reliable to bolt loads of 178 kN (40,000 lb).

The cables are fitted with a special hex head and inserted into the rock with either a jackleg drill or a conventional roof bolting machine. The cable bolts are spun into the drill hole, mixing the grout for adhesion. The special head also has a connector that allows for data acquisition after installation.

The same cautions and limitations that apply to instrumented bolts apply to instrumented cable bolts.

### HOLLOW INCLUSION CELL

Worotnicki and Walton [1976] developed the hollow inclusion stress cell (HICell) (figure 7) at the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia. These cells are available from Mindata, Seaford, Victoria, Australia, and from Reliable Geo, LLC, Yakima, WA, in the United States. The HICell is actually a group of strain gauges and strain gauge rosettes embedded in a thin epoxy shell. It is bonded to the wall of an EX-size borehole. Installers drill to the approximate installation depth with a 152-mm (6-in) barrel. An EX hole is extended for approximately 61 cm (24 in). Glue is displaced by a piston and forced into the annulus between the shell and the borehole wall. When stress is relieved through overcoring [Hooker and Bickel 1974], the

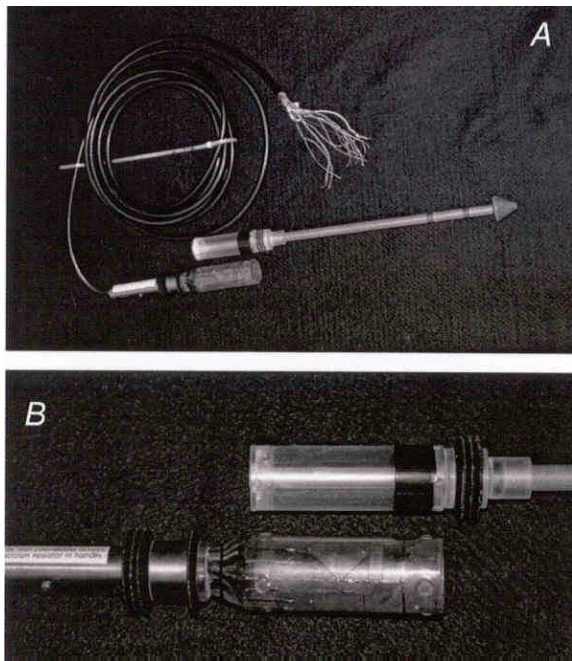


Figure 7.—Hollow inclusion stress cell. A, Strain gauge shell with piston, dowel, and cable; B, closeup of shell and piston.

stress state may be inferred from strain measurements collected from one installation.

Isotropic elastic properties are determined using results of a biaxial test on a recovered rock core and instrument. For isotropic rock, Larson [1992] developed a data reduction code, STRESsOUT. For transversely isotropic rock, five independent elastic constants are needed, and Amadei [1983] has developed a data reduction solution. However, laboratory tests on cores with orientations along the axes of anisotropy are required to determine all elastic constants. These constants can be estimated, but such estimates decrease the quality of stress state determination.

Tesarik and McKibbin [1989] installed and overcored four HICells at the Magmont Mine, a lead mine in Missouri. The stresses they determined from the overcoring measurements were subsequently used as initial stresses in a two-dimensional, finite-element model employed to analyze stress redistribution during pillar recovery.

Johnson et al. [1993] overcored four HICells and a borehole deformation gauge in three boreholes at one site and two boreholes at another site in the Homestake Mine, Lead, SD. Because results from overcoring varied, they discussed causes, such as variability of geology and material properties, anisotropy, and use of statistics with the least-squares approach.

In an underground platinum and palladium mine, Johnson et al. [1999] used HICells to measure in situ stress and subsequent stress change ahead of the face during advance of a footwall drift. Stress components calculated by multiple linear regression fit the strain measurements with little error. The correlation coefficients for each determination were in the range of 0.90 to 1.00.

Usually it is difficult to obtain good results in coal-measure rock because most sedimentary cores fracture easily during drilling. However, if good cores can be obtained, overcoring the HICell will usually result in good-quality measurements.

Conducting a dry run before HICell installation is very important. This is accomplished by using nails instead of lead pins in the shear pinholes. This practice allows an installer to learn to sense the right technique for inserting an instrument in an EX borehole.

A problem was recently encountered while installing a HICell. Three seal rings are positioned close together on the base of the instrument and on the piston. Recently, it was found that the grooves for those seals were positioned closer together than had been done in the past. In a 38.1-mm (1.500-in) hole, these seals did not have room to bend and thus were forced over the top of each other. This made it impossible to push the piston into the EX hole. A solution discovered by the SRL installation team and verified by Mindata [Walton 1999] was to remove the middle seal on both the base of the instrument and the piston. We have completed two successful installations with this modification. Also, Mindata now recommends not cutting V-shaped grooves in the seals, as is encouraged in the installation manual.

## BOREHOLE DEFORMATION GAUGE

The three-component borehole deformation gauge (figure 8) was designed by the former U.S. Bureau of Mines (USBM) [Merrill 1967]. Pistons that contact the borehole wall press against cantilevers mounted inside the body of the instrument (figure 9). Strain gauges bonded near the base of the cantilevers (two on the top surface and two on the lower surface) are connected as a full Wheatstone bridge and calibrated to reflect changes in the diameter of the borehole. Like the HICell, this gauge is installed in an EX hole and overcored [Hooker and Bickel 1974; Bickel 1993]. During overcoring, borehole diameter changes are measured in three different orientations

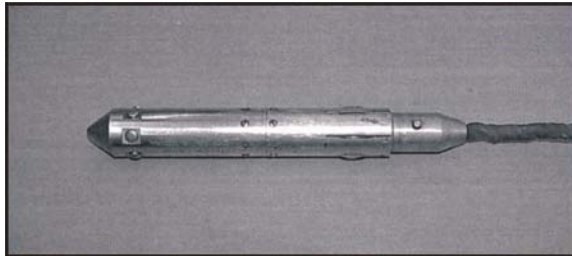


Figure 8.—Borehole deformation gauge.

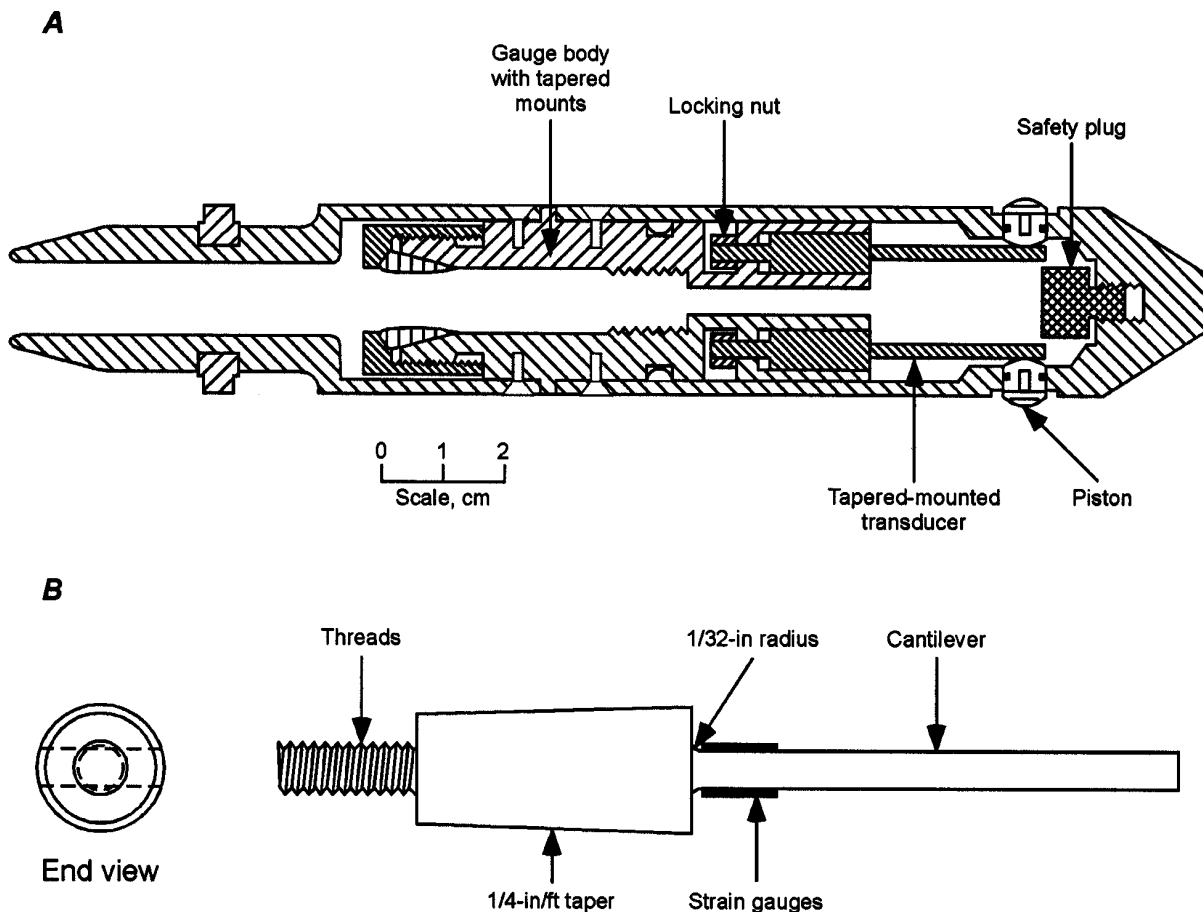


Figure 9.—Schematic of three-component borehole deformation gauge. *A*, Main body showing location of tapered-mounted cantilevers and pistons; *B*, closeup of a cantilever showing location of strain gauges (after Bickel [1993]).

spaced at 60° intervals. Pistons that contact the borehole wall displace a cantilever. Strain gauges bonded near the base of the cantilever form a full Wheatstone bridge circuit. Changes in signal are calibrated to calculate changes in diameter. After overcoring, a biaxial test is performed to measure the Young's modulus of the overcore.

The borehole deformation gauge is easy to use and install. There is no curing time as there is for the HICell. However, much drilling is required to determine all independent components of the stress tensor because the instrument must be overcored three different times, each time in a different non-coplanar borehole. Stress components are fit to the measurements using the least-squares method, as demonstrated by Panek [1966]. This calculation may be performed with the STRESsOUT code [Larson 1992].

NIOSH researchers have recently used this instrument for measuring horizontal stress in a coal mine roof [McKibbin 2000]. In this case, one borehole orientation was used. The results from multiple overcores were consistent. The method and data reduction are described by Bickel [1993], but in his analysis, he assumed that the borehole axial strain was zero because it was not measured. That assumption must be evaluated. Equations used in data reduction are discussed by Obert and Duvall [1967].

Girard et al. [1997] overcored a borehole deformation gauge at the 7400 level of the Homestake Mine. The stress state determined from these measurements compared well with stresses calculated from equations developed by Pariseau [1986], which represented principal stresses as a function of depth. Measurements by Johnson et al. [1993] in conjunction with HICell measurements were mentioned in the previous section.

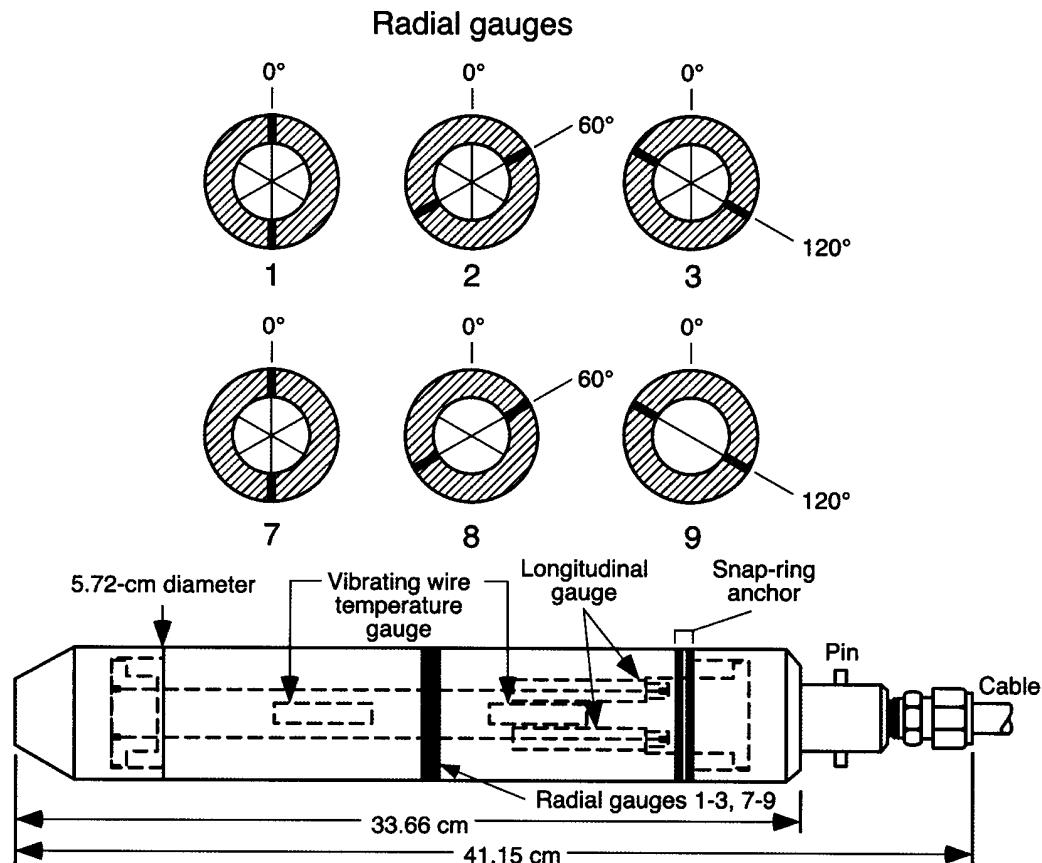
The borehole deformation gauge is available from Geokon.

### BIAXIAL STRESSMETER

The biaxial stressmeter is a rugged and reliable stress monitoring instrument manufactured by Geokon. The stressmeter is typically grouted in a BX-size (60-mm (2.36-in)) drill hole to measure compressive stress changes in a plane perpendicular to the instrument's longitudinal axis. As the walls of the drill hole deform in response to stress increases induced by mining, deformation in the host rock is transferred through a thin, grouted annulus to the stressmeter's body (a thick-walled steel cylinder approximately 34 cm (13 in) long). Radial deformation of the steel cylinder is measured by one or two sets of three vibrating-wire gauges oriented  $60^\circ$  from each other and closely spaced along the center of the instrument's longitudinal axis (figure 10). From these radial deformation measurements,

the magnitude and orientation of changes in major and minor secondary principal stresses can be calculated using equations developed by Savin [1961]. The biaxial stressmeter can also be equipped with two longitudinal vibrating-wire gauges that measure overall change in the length of the instrument. To account for the effects of stress changes outside of the biaxial measurement plane, the longitudinal measurements are used to calculate axial strain and correct the computed secondary principal stress changes for the Poisson component of stress changes acting in the direction of the drill hole. In addition, the stressmeter can also be equipped with two vibrating-wire temperature sensors that measure the temperature at the instrument's location. Because the vibrating-wire gauges have a slight temperature sensitivity, the manufacturer provides temperature calibration factors for each of the radial and longitudinal gauges. Data from the temperature sensors are used in conjunction with these calibration factors to correct the computed radial and longitudinal strains and compensate for the influence of temperature fluctuations near the instrument.

The manufacturer currently supplies various models of the biaxial stressmeter with either three or six radial gauges and with or without the longitudinal gauges and temperature sensors. Because consistent readings from all three of the radial gauge orientations (i.e.,  $0^\circ$ ,  $60^\circ$ , and  $120^\circ$ ) are required to calculate the magnitude and orientation of the secondary



principal stress changes, the authors highly recommend using a duplicate set of radial gauges for data redundancy and added reliability. Although the amount of longitudinal and temperature corrections have generally been small, the authors also prefer to order the biaxial stressmeter with two longitudinal gauges and two temperature sensors so that these corrections can be quantified accurately and the stress changes adjusted if necessary. For situations where maximum accuracy is desired or the temperature changes are expected to be large, the instrument should be ordered with the full complement of radial, longitudinal, and temperature gauges.

Before installing the biaxial stressmeter, the authors typically perform a point-load test with the instrument to confirm internal wiring configurations, verify the operation of the radial gauges, and check the configuration and programming of data acquisition equipment. Usually the electronic readings collected from the biaxial stressmeter are analyzed using spreadsheet software because of the complexity and number of data-reduction equations. As a general rule, the response of the vibrating-wire transducers should be graphed and analyzed prior to converting the electronic readings to engineering units and calculating the magnitude and direction of the stress change. Graphing the electronic readings helps identify anomalous data, diagnose the performance of the datalogger components, and interpret the response of individual gauges that are not functioning as expected. Inconsistent data can be difficult to detect and interpret from stress change calculations alone.

To measure stress changes in a vertical plane, the biaxial stressmeter is typically installed in a drill hole inclined slightly below horizontal to ensure that the grout flows to the bottom of the hole and completely fills the annulus around the instrument. The installation hole is usually drilled with a diamond core drill for about 1.5 m (5 ft) past the target depth for the instrument. After initially filling the hole with about 3 m (10 ft) of grout, the biaxial stressmeter is inserted into the drill hole, pushed through the grout to the target depth, and carefully rotated into position (i.e., radial gauge 1 oriented vertically) using self-aligning setting rods or a leveling device. To lock the instrument securely at this desired position in the drill hole, two opposing snap-ring anchors are activated from the collar of the hole by pulling a cable attached to an anchor-release pin.

The remainder of the hole is then filled with grout to help ensure that the biaxial stressmeter is completely covered with grout. Grouting the entire hole also alleviates problems with stress concentrations or creep in the drill hole near the instrument's location, which can introduce errors in the stress change measurements. The biaxial stressmeter is generally installed using a relatively thick mixture of Five Star Special Grout 400, an expansive cement-based grout manufactured by Five Star Products, Inc., of Fairfield, CT. A thick grout mix helps deter grout migration through fractures or discontinuities near the drill hole and provides sufficient viscosity to displace extraneous water from the hole.

Using these procedures, Seymour et al. [1999] have installed biaxial stressmeters in a variety of underground mines and host rock formations to monitor and evaluate mining-induced stress changes in mine pillars and abutments. By measuring both the magnitude and direction of the secondary principal stress changes, the biaxial stressmeter provides valuable insights into the behavior of the host rock and the redistribution of mining-induced stresses. Data from these instruments have been used to determine the transfer of mining-induced loads to cemented back-fill pillars [Tesarik et al. 1991], evaluate the ground support capability of frozen gravel pillars [Seymour et al. 1996], and monitor stress redistribution ahead of a longwall [Seymour et al. 1998]. The instrument's robust design and vibrating-wire transducers are particularly well suited for monitoring long-term changes in stress. Because the biaxial stressmeter is securely grouted in the host rock, the instrument does not seem to be adversely affected by vibrations caused by blasting or mining equipment.

To measure stress changes in a horizontal plane, the biaxial stressmeter is installed in a vertical drill hole. At a proposed nuclear waste repository in Sweden, several biaxial stressmeters have been installed in boreholes drilled in the bottom of a test drift to measure both thermal and mining-induced stress changes around cylindrical excavations that may eventually house canisters containing radioactive waste material [Röshoff 1999]. In addition, Geokon is currently developing a borehole packer for installing the biaxial stressmeter in overhead drill holes. SRL researchers recently used a prototype version of this borehole packer to install biaxial stressmeters in the roof of a coal mine.

## BOREHOLE PRESSURE CELLS

Borehole pressure cells are used to monitor stress change in one direction (e.g., vertical stress change profiles at several points through a pillar). They consist of rectangular flatjacks embedded in a cylinder of grout (figure 11). The cylinder is placed in a 60-mm (2.375-in) diameter borehole and set to a pressure about 10% more than the estimated absolute stress in the host rock. The viscoelastic-viscoplastic nature of the coal or rock allows a pressure equilibrium to be reached. Thereafter,

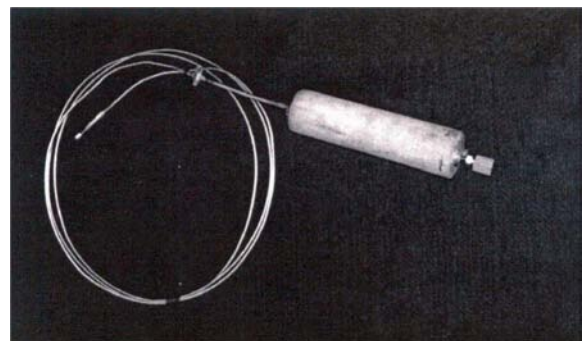


Figure 11.—Borehole pressure cell.



any changes in stress of the host rock are reflected directly in equal changes in fluid pressure in the flatjack.

These gauges may be monitored with hydraulic gauges. Typically, we have used both hydraulic gauges and pressure transducers and monitored them with a datalogger.

Three cells may be installed in the same borehole. After a cell is placed and oriented in the borehole, the cell is seated by pumping hydraulic fluid into the flatjack. The cell is then pressurized to a predetermined level before the valve is turned off. Resetting the pressure is sometimes necessary after 24 hr.

The hydraulic failure rate appears to be about 10% to 20% when the cells are manufactured by experienced hands. Good-quality cells can only be achieved if made by a careful, experienced manufacturer. The authors used cells manufactured only by employees of the Denver Research Center of the former USBM. However, Geokon manufactures a flatjack intended to be grouted into a borehole.

### EARTH PRESSURE CELLS

Hydraulic earth pressure cells (figure 12) are commonly used to measure stress changes in unconsolidated or cemented materials. This instrument consists of two rectangular or circular stainless steel plates welded together around their edges. A thin cavity is left between the two plates and filled with a fluid such as antifreeze or hydraulic oil. Pressure applied to the cell induces an equal pressure on the internal fluid that, in turn, is sensed by a transducer connected to the cavity between the two welded plates with high-pressure stainless steel tubing [Dunnicliff 1988].

Earth pressure cells are generally used to identify loading trends and are not relied upon for precise measurements. Because the stiffness of the instrument and the medium in which it is placed most likely will not be equal, the earth pressure cell may not sense the same stress change as the surrounding medium. Furthermore, the modulus of the in-place material may vary considerably from one location to another as a result of unequal compaction or heterogenous components,

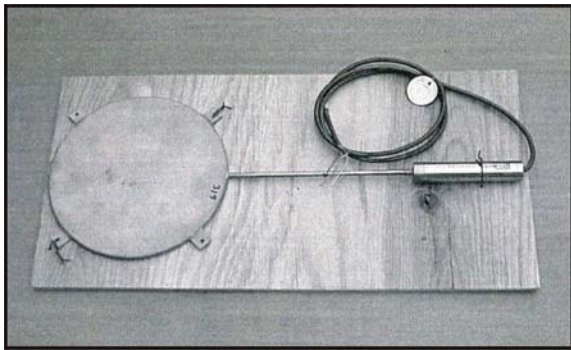


Figure 12.—Earth pressure cell.

such as coarse or fine aggregate. This modulus variability may cause discrepancies or scatter in the stress change measurements. Finally, it is difficult to calibrate the instrument accurately in the laboratory in a medium other than fluid.

The authors generally use earth pressure cells with vibrating-wire transducers to measure stress changes in cemented backfill. To avoid point loading or damaging these instruments when they are installed in cemented rockfill, the earth pressure cells are precast in wood forms using a cemented backfill mix with minus 6.35-mm (0.25-in) aggregate. The forms are constructed large enough to form a protective layer several inches thick on all sides of the instruments. As soon as the cast instruments can be handled without breaking the protective layer, the forms are removed, and the instruments are placed at their desired orientation in the backfill stope. Casting the instruments helps maintain alignment during installation and protects the cells when wet backfill is placed over them. To ensure that the desired orientation of the earth pressure cells is maintained during the bulk filling of an underground opening, an additional protective layer of cemented rockfill approximately 0.6 m (2 ft) thick is placed over the instruments and allowed to cure for at least 24 hr before heavy equipment is driven over the instruments. Earth pressure cells installed using these procedures have supplied important information regarding the mining-induced loads that were transferred to cemented backfill stopes as adjacent ore panels or pillars were mined [Tesarik et al. 1993, 1995]. They have also been used to evaluate the long-term ground support provided by cemented backfill [Tesarik et al. 1999].

In mines that use hydraulic fill, earth pressure cells are anchored to wire mesh using cable ties or bailing wire. If wire mesh or some other means of anchoring the instrument is not available at the desired location in the stope, the instruments can be suspended with wire in a wooden frame without a top or bottom and placed directly in the fill by hand. However, care should be taken to maintain the desired orientation of the instrument. This technique was successfully used at an underground coal mine; the earth pressure cells were installed in in-panel entries as they were backfilled with an air-entrained mixture of fly ash and cement [Seymour et al. 1998].

Earth pressure cells are made by several instrument manufacturers, including Geokon, Rocrest, RST Instruments, and Slope Indicator Co.

### EMBEDMENT STRAIN GAUGES

The authors generally use embedment strain gauges (figure 13) with vibrating-wire transducers to measure relative displacement in cemented backfill. Strain is calculated by dividing the relative displacement between the instrument's two end flanges by the length of the instrument, typically 15 to 25 cm (6 to 10 in). Typically these instruments are installed



**Figure 13.—Embedment strain gauge.**

near the location of an earth pressure cell to provide an estimate of the backfill's in situ modulus (i.e., stress change divided by strain change).

For cemented backfill with a modulus ranging between 690 and 1,380 MPa (100,000 and 200,000 psi), a 25.4-cm (10-in) long embedment strain gauge with a 6.35-mm (0.25-in) maximum displacement range can be used to determine strain changes up to a stress change level of between 17 to 34 MPa (2,500 to 5,000 psi). Problems have been encountered using embedment strain gauges with smaller displacement ranges because the maximum displacement range was exceeded. On the other hand, erratic results were obtained from 1-m (39-in) long instruments with 12.7-mm (0.5-in) displacement ranges that were placed vertically in cemented fly ash. The reason for these variations is not fully understood, but the embedment strain gauges may have buckled as mining-induced loads were transferred to the backfilled entries because of the longer length of the instruments.

Installation procedures for embedment strain gauges are the same as for earth pressure cells, except waxed cardboard cylinders are typically used to precast the instruments instead of wooden forms. Except for the above-mentioned problems, these instruments have generally provided good results and have typically given a more precise indication of backfill loading changes than the earth pressure cells.

Embedment strain gauges are made by Geokon, Roc-test, and Slope Indicator Co.

### **VERTICAL BACKFILL EXTENSOMETERS**

To measure relative displacement over large vertical distances in backfill, vertical extensometers can be constructed as shown in figure 14. For applications where boreholes can be drilled in placed backfill, sections of 15.9-mm (0.625-in) diameter steel rod coupled together serve as the extensometer measurement rod, and steel rebar welded to a small length of rod is used as the downhole anchor. A mixture of cement and water is poured down the hole to set the anchor, followed by

dry sand to prevent pieces of backfill from spalling and wedging between the steel rod and the side of the drillhole. The head assembly, which consists of a vibrating-wire displacement transducer, bearing plate, and a short length of 38-mm (1.5-in) steel pipe welded to the plate, is placed over the steel measurement rod, and the transducer is screwed into the rod. The transducer is set at the desired position using an aluminum extension rod and is held in place with a compression fitting. Finally, the excess portion of the aluminum rod extending above the compression fitting is cut off, and a protective head is bolted onto the bearing plate. These instruments have successfully monitored compressive strains in backfill caused by overburden stress redistribution, as well as tensional strains caused by undercutting backfill [Tesarik et al. 1993].

When drilling in cured backfill is not feasible, extensometers can be assembled as successive backfill lifts are placed. In this situation, the bottom anchor is constructed of a 45.7- by 45.7-cm (18- by 18-in) steel baseplate with a 51-mm (2-in) steel coupler welded to the top of the plate. The first section of a 15.9-mm (0.625-in) diameter steel measurement rod is inserted through a hole in the baseplate and secured with a nut. The first section of 51-mm (2-in) pipe is threaded into the steel coupler to protect the measurement rod as backfill is placed around the instrument. The outside surface of this pipe is greased during construction to help reduce friction between the outer surface of the pipe and the cured backfill. As successive lifts of backfill are placed, sections of rod and pipe are coupled together until the desired instrument height is achieved. The 38-mm (1.5-in) steel pipe on the head assembly is then inserted inside the 51-mm (2-in) protective pipe, leaving several inches of backfill between the bearing plate and the top of the 51-mm (2-in) pipe. This gap allows the instrument to retract as the backfill compresses under load. The transducer is set and secured at the desired position as described above, and the protective cover is bolted onto the head assembly. Following these procedures, backfill extensometers ranging from 4.3 to 16.5 m (14 to 54 ft) long have been successfully installed in cemented fill stopes and used to determine the vertical strain induced within the backfill by mining [Tesarik et al. 1991, 1995].

### **HORIZONTAL BACKFILL EXTENSOMETERS**

The authors have attempted to measure horizontal strain in cemented backfill stopes (horizontal dilation in response to vertical loading), with only marginal results. At one mine site, two 3-m (10-ft) long commercially available borehole joint meters were hung end-to-end from steel cables that spanned the width of a 7.3-m (24-ft) wide stope [Tesarik et al. 1991]. Some of these instruments were damaged during installation when backfill dumped from the bench above surged forward and distorted the flexible instrument into a slight arc. Data recorded by the jointmeters that still functioned after the stope was completely filled were difficult to interpret because, unlike most of the other rock mechanics instruments installed at this site,

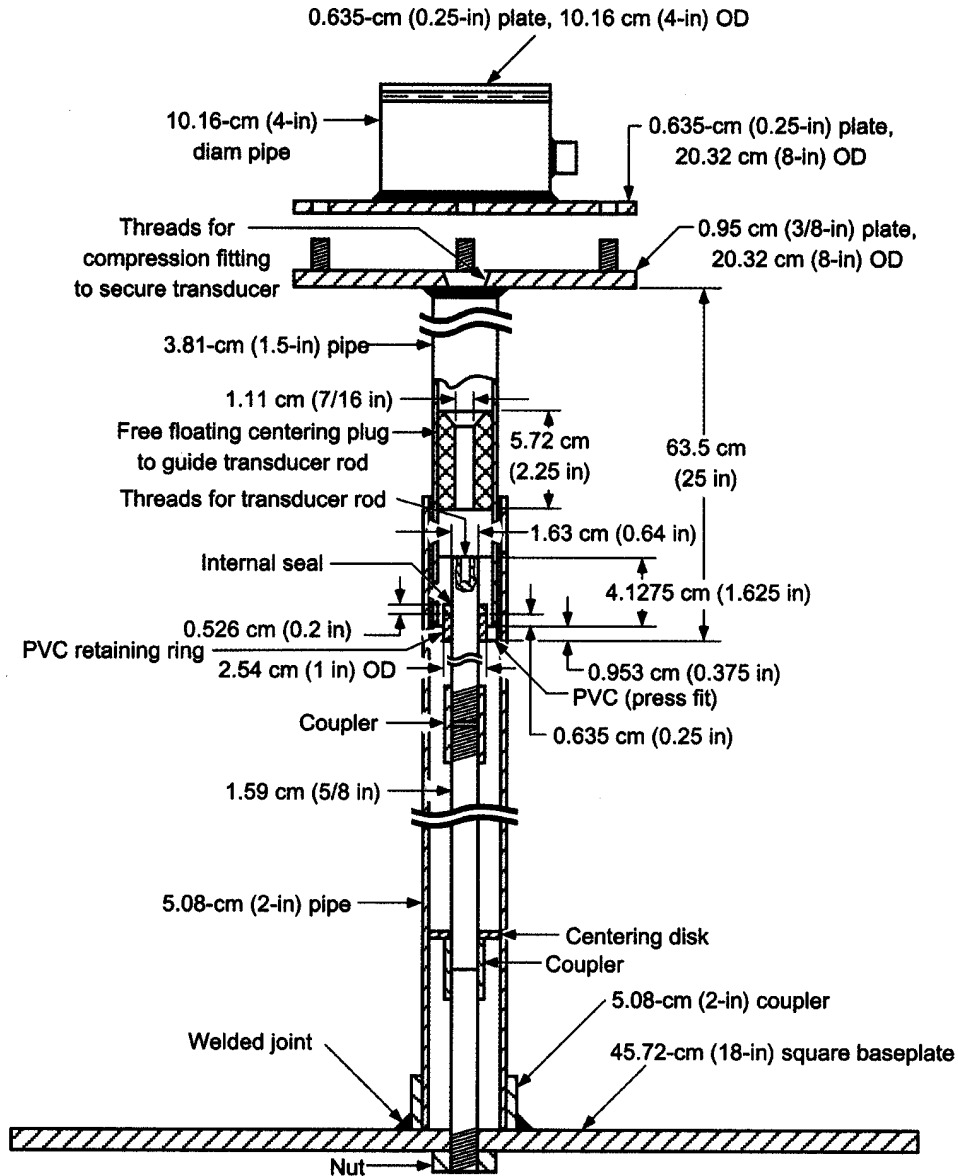


Figure 14.—Vertical backfill extensometer.

changes in instrument readings were not always related to a specific mining event. Compressive strain, which may be attributed to backfill shrinkage, was recorded by some of these instruments after the stopes were first filled.

To help prevent damage from surging or falling backfill, horizontal extensometers were fabricated at SRL with steel, rather than plastic, protective pipe. Steel-bearing plates at each end of the extensometer were also enlarged to increase the contact area between the instrument and the backfill. These

instruments were placed directly on the floor of partially backfilled stopes and covered with wet backfill using a front-end loader. This practice protected the instruments from the weight of mining equipment and the large backfill loads that were subsequently placed over the instruments. These more robust extensometers recorded horizontal compressive trends from 73 to 145 days after installation, followed by relatively small tensional strain changes that were difficult to interpret [Tesarik et al. 1993].

## CONCLUSION

Design and implementation of a successful instrumentation plan requires careful planning and consideration of site-specific factors, such as geology, identification of critical mechanisms and parameters, clearly defined objectives of measurements, estimates of the range of these measurements, types of transducers, ease of installation, how the sensors will be monitored and monitoring interval(s).

An overview of sensor technologies has been presented. Precision and the ability to sense sudden changes is a distinct advantage of Wheatstone bridge technology, but zero drift often makes it unsuitable for long-term monitoring. Vibrating-wire

technology has been proven to provide reliable long-term measurements. Potentiometers have been used successfully to measure displacement.

The authors have summarized the use of several instruments and offered tips to help the user obtain better measurements. Also, the experiences of coworkers are cited. It is hoped that the information conveyed here will enable mine operators to make measurements on their own or improve on past measurement programs and that measurements obtained might be useful in making decisions that improve the safety of miners.

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## REFERENCES

- Amadei B [1983]. Rock anisotropy and the theory of stress measurements. Lecture Notes in Engineering No. 2. Brebbia CA, Orszag SA, eds. Berlin: Springer-Verlag.
- Bauer ER [1985]. Ground control instrumentation: a manual for the mining industry. Pittsburgh, PA: U.S. Department of the Interior, Bureau of Mines, RI 9053.
- Bickel DL [1993]. Rock stress determinations from overcoring: an overview. Denver, CO: U.S. Department of the Interior, Bureau of Mines, Bulletin 694.
- Choquet P, Juneau F, Debreuille PJ, Bessette J [1999]. Reliability, long-term stability and gage performance of vibrating wire sensors with reference to case histories. In: Leung CF, Tan SA, Phoon KK, eds. Field Measurements in Geomechanics: Proceedings of the Fifth International Symposium on Field Measurements in Geomechanics—FMGM99 (Singapore, December 1-3, 1999). Balkema, pp. 49-54.
- Dally JW, Riley WJ [1991]. Experimental stress analysis. 3rd ed. New York: McGraw-Hill.
- Dunncliff J [1988]. Geotechnical instrumentation for monitoring field performance. New York, NY: John Wiley & Sons.
- Dunncliff J [1999]. Systematic approach to planning monitoring programs using geotechnical instrumentation: an update. In: Leung CF, Tan SA, Phoon KK, eds. Field Measurements in Geomechanics: Proceedings of the Fifth International Symposium on Field Measurements in Geomechanics—FMGM99 (Singapore, December 1-3, 1999). Balkema, pp. 19-30.
- Girard JM, McKibbin RW, Seymour JB, Jones FM [1997]. Characterization of in situ stress conditions at depth—Homestake mine, Lead, South Dakota (Abstract). Paper No. 104. Int J Rock Mech Min Sci 34:3-4.
- Hanna TH [1985]. Field instrumentation in geotechnical engineering. Trans Tech Publications, pp. 687-759.
- Hooker VE, Bickel DL [1974]. Overcoring equipment and techniques used in rock stress determination. Denver, CO: U.S. Department of the Interior, Bureau of Mines, IC 8618.
- Johnson JC, Larson MK, Brady TM, Whyatt JK, Langston RB, Kirsten H [1999]. Stress measurement of a jointed rock mass during drift development. In: Hagan TO, ed. SARES 99: 2nd Southern African Rock Engineering Symposium. Implementing Rock Engineering Knowledge (Johannesburg, Republic of South Africa, September 13-15, 1999). Int Soc Rock Mech, pp. 94-101.
- Johnson JC, Pariseau WG, Scott DF, Jenkins FM [1993]. In situ stress measurements near the Ross shaft pillar, Homestake Mine, South Dakota. Spokane, WA: U.S. Department of the Interior, Bureau of Mines, RI 9446.
- Johnston JL, Cox DJ [1993]. Instrumentation procedures for fully grouted rock bolts. Spokane, WA: U.S. Department of the Interior, Bureau of Mines, IC 9341.
- Larson MK [1992]. STRESsOUT—a data reduction program for inferring stress state of rock having isotropic material properties: a user's manual. Spokane, WA: U.S. Department of the Interior, Bureau of Mines, IC 9302.
- Larson MK, Maleki H [1996]. Geotechnical factors influencing a time-dependent deformation mechanism around an entry in a dipping seam. In: Ozdemir L, Hanna K, Harny KY, Peng SS, eds. Proceedings of the 15th International Conference on Ground Control in Mining. Golden, CO: Colorado School of Mines, pp. 699-710.
- Larson MK, Stewart CL, Stevenson MA, King ME, Signer SP [1995]. A case study of a deformation mechanism around a two-entry gate-road system involving probable time-dependent behavior. In: Peng SS, ed. Proceedings of the 14th International Conference on Ground Control in Mining. Morgantown, WV: West Virginia University, pp. 295-304.
- Leung CF, Tan SA, Phoon KK, eds. [1999]. Management of instrumentation in geomechanics. In: Field Measurements in Geomechanics, Proceedings of the 5th International Symposium on Field Measurements in Geomechanics—FMGM99 (Singapore, December 1-3, 1999). Balkema, pp. 109-162.
- Martin LA, Pakulnis R, Curtin RP [2000]. Field tests of cable bolts using instrumented king wires. Presentation at Canadian Institute of Mining, Metallurgy and Petroleum (CIM) 2000 meeting, March 5-10, 2000, Toronto, Ontario, Canada.
- McKibbin RW [2000]. Personal communication, January.
- McRae JB [2000]. Personal communication, May 5.
- McRae JB, Simmonds T [1991]. Long-term stability of vibrating wire instruments: one manufacturer's perspective. In: Sørum G, ed. Proceedings of the 3rd International Symposium on Field Measurements in Geomechanics (Oslo, Norway, September 9-11, 1991). Balkema, pp. 283-293.



- Merrill RH [1967]. Three-Component Borehole Deformation Gage for Determining the Stress in Rock. U.S. Department of the Interior, Bureau of Mines, RI 7015.
- Obert L, Duvall WI [1967]. Rock mechanics and the design of structures in Rock. New York, NY: John Wiley and Sons, pp. 413-417.
- Panek LA [1966]. Calculation of the average ground stress components from measurements of the diametral deformation of a drill hole. U.S. Department of the Interior, Bureau of Mines, RI 6732.
- Pariseau WG [1986]. Research study on pillar design for vertical crater retreat (VCR) mining. Salt Lake City, UT: University of Utah. U.S. Bureau of Mines contract No. J0215043.
- Röshoff K [1999]. Personal communication, December.
- Savin GN [1961]. Stress concentrations around holes. New York, NY: Pergamon Press.
- Serbousek MO, Signer SP [1987]. Linear load transfer of fully grouted roof bolts. Spokane, WA: U.S. Department of the Interior, Bureau of Mines, RI 9135.
- Seymour JB, Tesarik DR, Larson MK, Shoemaker J [1998]. Stability of backfilled cross-panel entries during longwall mining. In: Peng SS, ed. Proceedings of the 17th International Conference on Ground Control in Mining. Morgantown, WV: West Virginia University, pp. 11-20.
- Seymour JB, Tesarik DR, McKibbin RW [1996]. Stability of permafrost gravels in an Alaskan underground placer mine. In: Myrvang AM, Vik J, eds. Proceedings of the Fourth International Symposium on Mining in the Arctic (Longyearbyen, Svalbard, Norway, July 27-30, 1996). Sintef Rock Min Eng, pp. 147-156.
- Seymour JB, Tesarik DR, McKibbin RW, Jones FM [1999]. Monitoring mining-induced stress changes with the biaxial stressmeter. In: Leung CF, Tan SA, Phoon KK, eds. Field Measurements in Geomechanics: Proceedings of the Fifth International Symposium on Field Measurements in Geomechanics—FMGM99 (Singapore, December 1-3, 1999). Balkema, pp. 55-60.
- Signer SP [1990]. Field verification of load transfer mechanics of fully grouted roof bolts. Spokane, WA: U.S. Department of the Interior, Bureau of Mines, RI 9301.
- Signer SP [1994]. Field evaluations of grouted roof bolts. In: New Technology for Longwall Ground Control; Proceedings: U.S. Bureau of Mines Technology Transfer Seminar. Pittsburgh, PA: U.S. Department of the Interior, U.S. Bureau of Mines, SP 01-94, pp. 91-101.
- Signer SP, Lewis JL [1998]. A case study of bolt performance in a two-entry gateroad. In: Peng SS, ed. Proceedings of the 17th International Conference on Ground Control in Mining. Morgantown, WV: West Virginia University, pp. 249-256.
- Signer SP, Mark C, Franklin G, Hendon G [1993]. In: Peng SS, ed. Comparisons of active versus passive bolts in a bedded mine roof. In: Peng SS, ed. Proceedings of the 12th Conference on Ground Control in Mining. Morgantown, WV: West Virginia University, pp. 16-23.
- Tesarik DR, McKibbin RW [1989]. Instrumentation and modeling of the North 140 Section of Magmont Mine, Bixby, MO. Spokane, WA: U.S. Department of the Interior, Bureau of Mines, RI 9215.
- Tesarik DR, Seymour JB, Mudlin ME [1993]. Analysis of backfill and pillar performance in the B-Neath orebody at the Cannon mine. In: Glen HW, ed. Minefill 93, Fifth International Symposium on Mining with Backfill (Johannesburg, Republic of South Africa, September 1993). S Afr Inst Min Metall, Symp Ser S13, pp. 55-64.
- Tesarik DR, Seymour JB, Yanske TR [1999]. Long-term stability of a backfilled room-and-pillar mine. In: Leung CF, Tan SA, Phoon KK, eds. Field Measurements in Geomechanics: Proceedings of the Fifth International Symposium on Field Measurements in Geomechanics—FMGM99 (Singapore, December 1-3, 1999). Balkema, pp. 431-435.
- Tesarik DR, Seymour JB, Yanske TR, McKibbin RW [1995]. Stability analysis of a backfilled room-and-pillar mine. Spokane, WA: U.S. Department of the Interior, Bureau of Mines, RI 9565.
- Tesarik DR, Vickery JD, Seymour JB [1991]. Evaluation of in situ cemented backfill performance. Spokane, WA: U.S. Department of the Interior, Bureau of Mines, RI 9360.
- Walton RJ [1999]. Personal communication, November.
- Worotnicki G, Walton RJ [1976]. Triaxial 'hollow inclusion' gauges for determination of rock stresses in situ. In: Proceedings of the ISRM Symposium on Investigation of Stress in Rock—Advances in Shear Measurement. Int Soc Rock Mech, pp. 1-8.