EVALUATION OF GROUND SUPPORT AT A TRONA MINE USING INSTRUMENTED CABLE AND REBAR BOLTS

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ABSTRACT

Instrumented cable bolts developed at the Spokane Research Laboratory of the National Institute for Occupational Safety and Health were used in conjunction with existing ground control systems to monitor rock mass loads at Tg Soda Ash's trona mine, Granger, WY. Axial and shear loads were determined to levels of strain gauge accuracy of ±5 N or ±5 microstrain. These gauges were embedded in a remanufactured king wire that replaced the conventional king wire. Cable bolt performance, quality of grout, and installation techniques were also assessed. By using instrumented cables, a mine operator can determine axial load along the cable at predefined gauge locations. These data provide necessary input for an operator to design a safer working environment for miners.

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BACKGROUND

Until recently, external measurement devices such as the "tensmeg" or resistance-wire cable strain gauges [Hyett et al. 1997; Windsor 1987] were used to determine load on cable bolts. Previously, researchers thought that an internal gauge would be too expensive to use with cables as an instrument within mines. Another issue has been that external gauges on cables may fail because of water seepage through the grout before the cable begins to take on load [Goris et al. 1993]. In 1996, the "stretch measurement to assess reinforcement tension" (S.M.A.R.T) cable was developed and patented by researchers at Queen's University in Canada [Hyett et al. 1997]. This system replaces the king wire of a cable bolt with multipoint extensometers enclosed in a tube to measure cable elongation, thereby enabling deformation and load to be determined [Bawden et al. 1998]. The usefulness of a ground control instrument having gauges mounted in the center of the cable or on the king wire was shown by Signer [1990] in research on the use of resin-grouted rebar bolts in coal mines.

In 1998, researchers at the Spokane Research Laboratory (SRL) of the National Institute for Occupational Safety and Health (NIOSH) developed an *instrumented king wire cable bolt* (patent pending). This instrument is manufactured by molding the king wire from epoxy around a flat piece of steel containing strain gauges. Instrumented cable bolts will aid in evaluating geologic conditions, grout quality, effective anchorage length, and cable load.

CONCEPT

The instrumented king wire cable bolt has 12.5-mm-long strain gauges embedded in the king wire at positions defined by the mine operator. Presently, 10 gauges can be installed along a resin-grouted bolt up to 5 m long or a cement-grouted bolt up to 7 m long. These constraints are largely due to current manufacturing processes and not to limits on the system. The gauges can either be set in pairs to detect shear load in the same plane, or the flat stock can be set at 90° angles to detect loads in three directions. The cables are capable of sustaining an ultimate load of 250 kN and can produce reliable readings to 180 kN, as shown by the calibration curve in figure 1.

To create an instrumented king wire cable bolt, strain gauges are first installed on both sides of a 2.4- by 0.5-mm metal strip at various user-specified positions on the bolt (figure 2). The individual strain gauges are connected to an instrument plug by 30-AWG wire. This apparatus is then placed in a steel mold and injected the total specified length of the bolt with a two-part epoxy. This new king wire measures 8.3 mm in diameter.

The original cable is uncoiled strand by strand, the original center wire is replaced by the new epoxy-filled king wire, and the outer six strands are rewound around it, resulting in an instrumented cable bolt. The gauge wires protruding from the center are then inserted into a 12-pin connector. This connector is recessed into a 4.4-cm hex head attached to the cable by means of a barrel-and-wedge assembly (figure 2). The cables are fitted with special heads so they can be inserted by either a jackleg drill or a roof bolter. An instrumentation plug is used to monitor the gauges. A data acquisition system is required to read the loads.

The system has been tested on a Vishay strain indicator box, a Campbell Scientific system, and an Omni Data system.

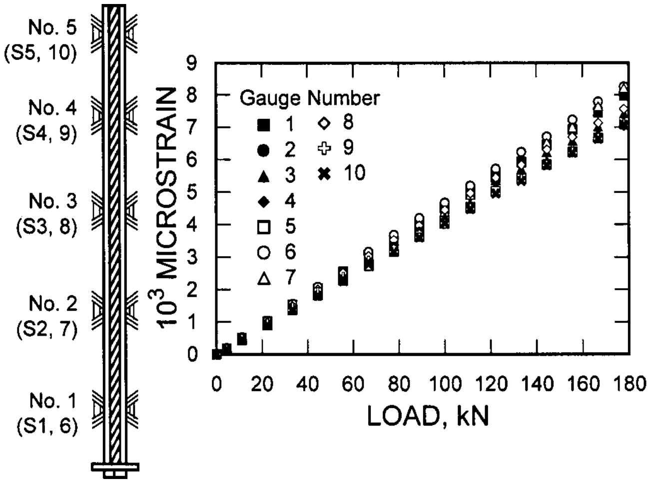


Figure 1.—Calibrated curve for instrumented king wire cable bolt.

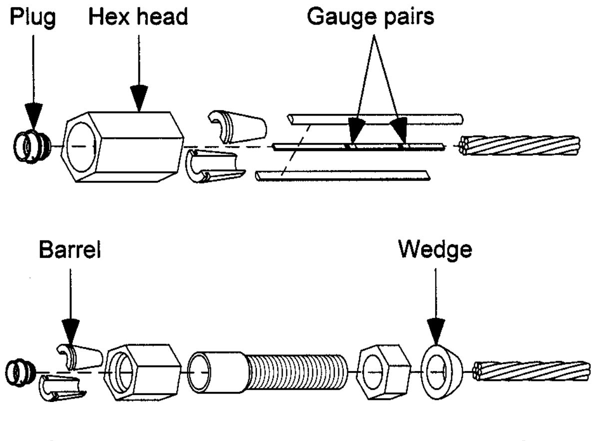


Figure 2.—Instrumented cable bolt assembly with and without pretension head.

MATERIAL DESCRIPTION

Standard cable specifications were the American Society of Testing Materials (ASTM) standard A416, 0.6-in, grade 270 K, low-relaxation, seven-strand cable having a minimum breaking load of 258 kN with 3.5% elongation. Upon removing the original king wire and replacing it with the manufactured one, ultimate load was reduced to 215 kN. Strain readings were reliable to 180 kN with 3.5% strain on the cable at failure. Calibration tests at SRL provided correlation of microstrain to load to enter into the data collection system (figure 1). This technique was used successfully throughout the elastic load-strain range on instrumented rebar bolts by Signer et al. [1997].

CABLE DESIGN

Laboratory tests were conducted on instrumented king wire cable bolts embedded with resin grout in concrete blocks to obtain calibration curves for converting microstrain to load in kilonewtons. Pull tests were also conducted to determine the load-carrying characteristics of the bolts. The strain gauges were mounted 0.15, 0.35, 0.61, 0.91 and 1.22 m from the head of the bolt (figure 3). The cables were loaded to 180 kN using hydraulic pull test equipment. A strain-to-load curve is shown in figure 3 and is typical of what Goris et al. [1994] observed in pull tests with conventional cable bolts.

These tests aid in explaining how load on cable bolts is transferred from the cable to the grout and then into the rock mass. A "shelling" effect is shown whereby the grout-cable interface breaks down and the gauge becomes debonded as load is increased and is taken fully by the cable. Figure 3 shows results of the pull tests as a load profile along the cable length. The curve shows that a 128-kN (~12.8-tonne) pull load on the collar of the cable resulted in measured strain loads of 123 kN along gauges 1 and 6 at a distance of 0.15 m from the collar. Researchers interpreted this measurement, a difference of 5 kN, as the amount of load the cable was not sensing 0.15 m from the collar. At 1.22 m from the collar, the cable did not sense any load, indicating that 1.22 m was the critical bond length. Other researchers (e.g., Goris et al. [1994]) have reported critical bond length to be approximately 1 m for standard cable. This load capability enables an operator to measure failure in real time as debonding of the grout-cable interface is initiated. In addition, the difference between cable load and applied load indicates grout quality, which can be a better field test of the quality of cable bolt installations than field pull tests.

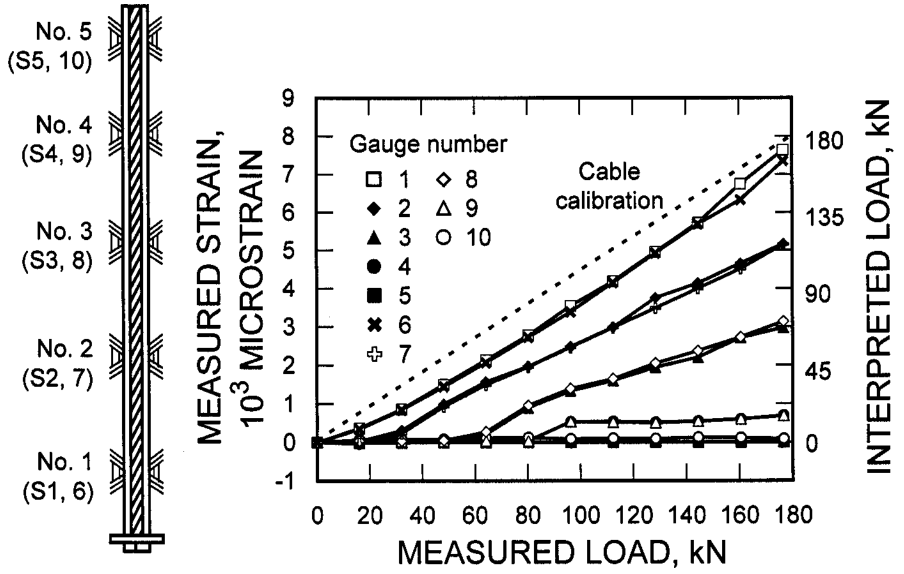


Figure 3.—Calculated load and strain on grouted cable bolt with instrumented king wire.

REBAR DESIGN

The resin-grouted rebar roof bolts used in these tests were standard, grade 60, No. 6 rebar that had been milled with a 6.35-mm-wide by 3.18-mm-deep slot along each side (figure 4). Axial load tests showed that the average yield load of the bolts was 96 kN and the average ultimate load was 158 kN. Before milling the slot, yield load had been 107 kN and ultimate load had been 176 kN. Thus, slotting caused a 10% reduction in strength [Signer 1990].

Strain gauges were installed into the slots as shown in figure 4. The strain gauges were then calibrated in a uniaxial test machine to correlate voltage change to load change. A typical load-strain curve from a tested bolt is shown in figure 5. When the data from the instrumented rebar bolts were reduced, the correlation coefficients from the axial calibrations were used to convert voltage changes to load changes. This process was accurate to ±22 N. When the load levels exceeded the yield point of the steel, voltage readings were converted to strain readings to estimate the degree of plasticity (figure 5).

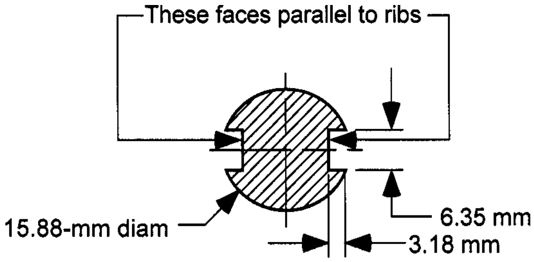


Figure 4.—Cross section of resin-grouted rebar bolt machined for installation of gauges.

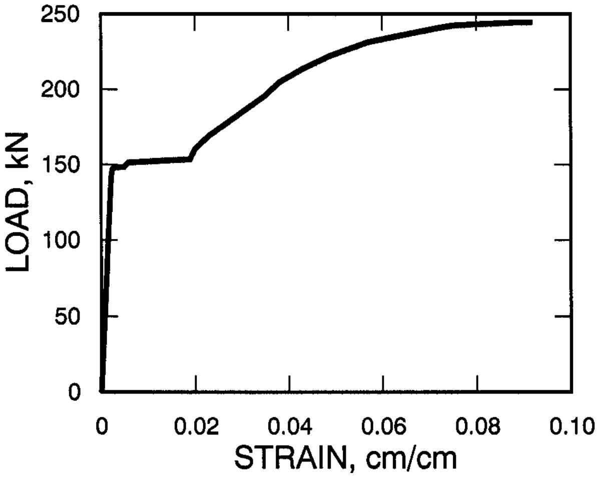


Figure 5.—Typical load strain profile for instrumented rebar bolt.

CASE STUDY: TG SODA ASH, FMC GRAINGER

MINE GEOLOGY

The mine is located in the Green River Basin of southwestern Wyoming. Trona deposits in the basin were formed during the Eocene period within the Wilkins Peak Member of the Green River Formation. The repeated evaporation and recharge of Lake Gosiute, a playa lake occupying the basin during Eocene time, created evaporite layers of trona intermixed with marlstone and alternating layers of oil shale [Leigh 1998].

The areal extent of the basin is marked by the Uinta Mountains in the south, the Rock Springs uplift in the east, the Wind River and Gros Ventre ranges in the north, and the Wyoming Range in the west. There are 42 known trona beds, of which 25 range from 240 to 670 m thick. These beds are numbered 1 through 25, according to the order in which they were deposited (bed 25 being closest to the surface). Beds 1 through 18 consist mainly of fine-grained trona; beds 19 through 25 are composed of a coarse crystalline trona. Mining at Tg Soda Ash takes place in bed 20 approximately 425 m below the surface. The area in which the field study was conducted is overlain by an additional 60 m of overburden.

MINING METHOD

Trona is mined with a drum-and-borer-type continuous mining machine. These machines, traditionally used for coal mining, are custom built to cut the harder trona ore. Tg Soda Ash uses only drum-type continuous miners. Cutting heads are typically 5.3 m wide, but the panel in which the field study was conducted was mined with a 5.6-m-wide cutting head.

The Tg Soda Ash mine uses a modified room-and-pillar mining method. In the field study area, the panel was developed as a four-entry system. An additional two entries were later driven parallel to the existing workings, with an eight-room retreat mined in a chevron configuration 78 m wide by 103 m deep with cross cuts on 12.2-m centers. The retreat consisted of pulling chevrons, a method in which pillars are cut on 12.2-m centers 60° from the direction of advance. This method maximizes the rate of extraction by minimizing ground control problems.

The field study site was chosen for its rapidly changing ground conditions and its proximity to mining activity in this panel. It is believed that the wider cutting head, extra overburden, and weaker geologic material of the roof and floor in the panel contributed to rapidly deteriorating ground conditions in the outside entries of the system, making the area ideal for a field study. During the course of the study, the face was approximately 215 m from the test area and retreated to within 45 m of the test area.

INSTRUMENTED BOLT INSTALLATION

For simplification in the rest of this paper, the term "cable bolt" means a bolt in which the conventional king wire has been replaced with the new remanufactured king wire.

Cable bolts and rebar bolts were installed in the roof of the mine to measure roof loads in the intersection of 350S and 12371E (figures 6 and 7). This location was chosen because of drill access ahead of the mining cycle and because loads would be induced in the bolts as ore was extracted toward the intersection. Mine personnel were interested in determining the potential for instability in the back and the extent of any unstable blocks.

Ground support was installed after development and during rehabilitation. Strain gauges were positioned along rebar and cable bolts at depths that would ensure that loads on the resin-grouted support would be measured. In addition, a set of gauges was mounted at an ungrouted section to measure dead-weight loads in the rock mass. Figure 8 shows the location of the strain gauges with respect to the collar. The longest cable bolts were installed at the center of the intersection because these bolts would receive the greatest loads, while shorter cable bolts were installed north of the intersection closer to the pillar front. Resin-grouted rebar bolts were placed in the south part of the intersection to measure loads where the density of rebar bolts was highest. Sagmeter stations were set at three locations in the intersection (figure 7), and holes were drilled to depths of 2.4, 3.2 and 3.8 m. These sagmeter depths were chosen to correspond with the bolt gauge profiles (figure 8), allowing correlations to be made between deformation recorded by the strain gauges to deformation recorded by the sagmeter stations. This is important because slip expected to occur between the cable-grout-rock interface can be compared to actual rock deformation.

RESULTS OF MEASUREMENTS ON INSTRUMENTED BOLTS

Loads on the cable bolts were measured from April 29 through July 11, 1999. Mining activities influencing the intersection progressed from northeast of the site to the south (figure 6). On June 9, development mining began within one pillar width (8 m) of the intersection. Figure 9 shows all load profiles measured by the 4.27-m-long bolts (bolts 1, 2, 4, and 5) and the 3.66-m-long bolts (bolts 6, 8, 9, and 11). Approximately the last 1.5 m of the bolt was bonded with resin grout. Figure 10 shows load profiles for the 2.44-m-long, fully grouted rebar bolts (bolts 201-204).

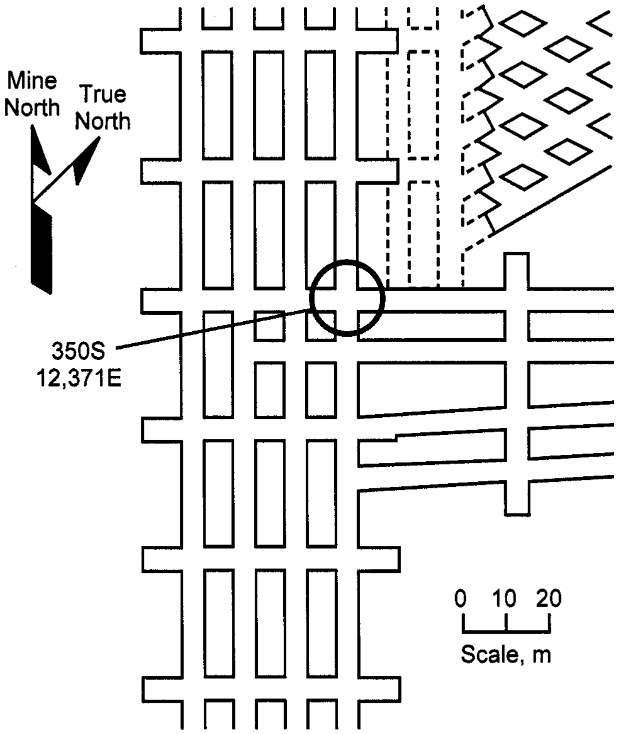


Figure 6.—Instrument locations in mine.

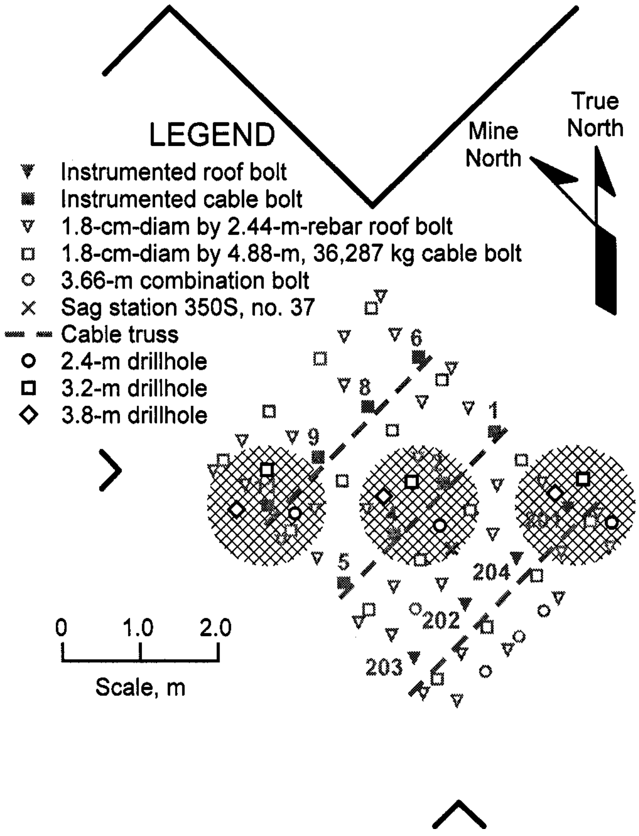
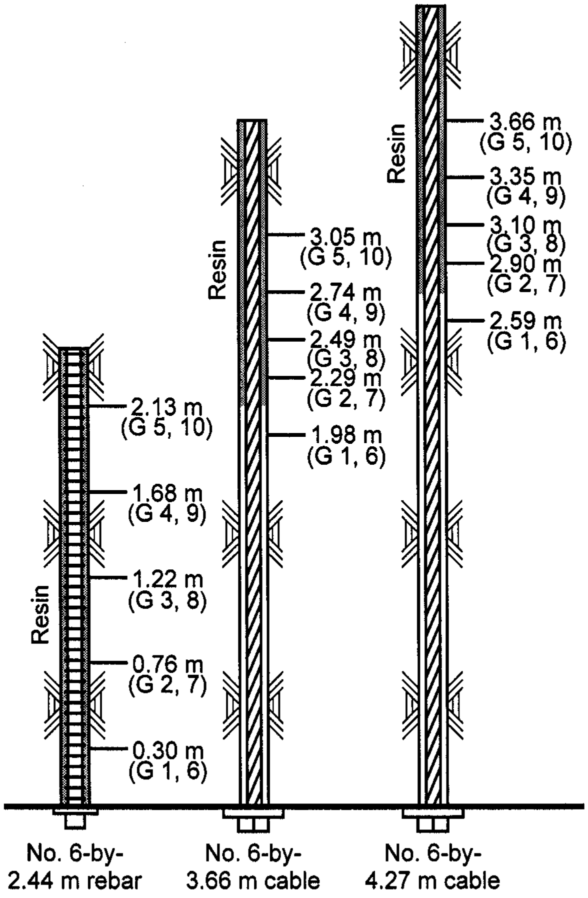


Figure 7.—Bolt and sagmeter locations.



Notes:

1. Assume 1.5-m resin anchor for cable bolts.
2. All gauges are in pairs at given locations.
3. Instrumented cable strength is 213.5 kN, yield at 177.9 kN.
4. Load is 11 kN times microstrain for cables.
5. Current inventory is: four no. 6-by-2.44-m rebar, four no. 6-by-3.66-m cable, four no. 6-by-4.27-m cable.

Figure 8.—Positions of strain gauges on bolts (note two at each position).

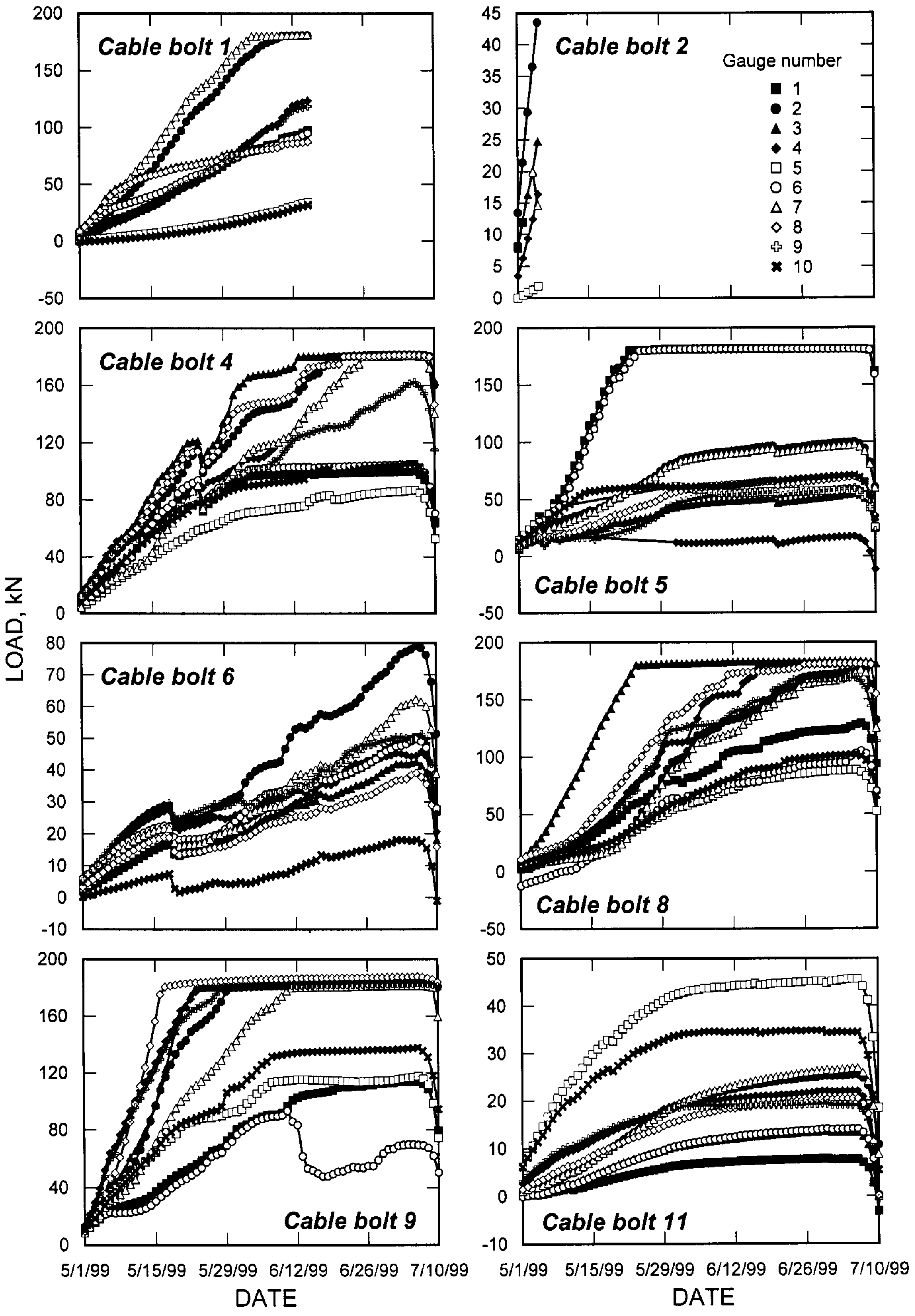


Figure 9.—Load profile versus time on 4.27-m-long bolts (1, 2, 4, and 5) and 3.66-m-long bolts (6, 8, 9, and 11).

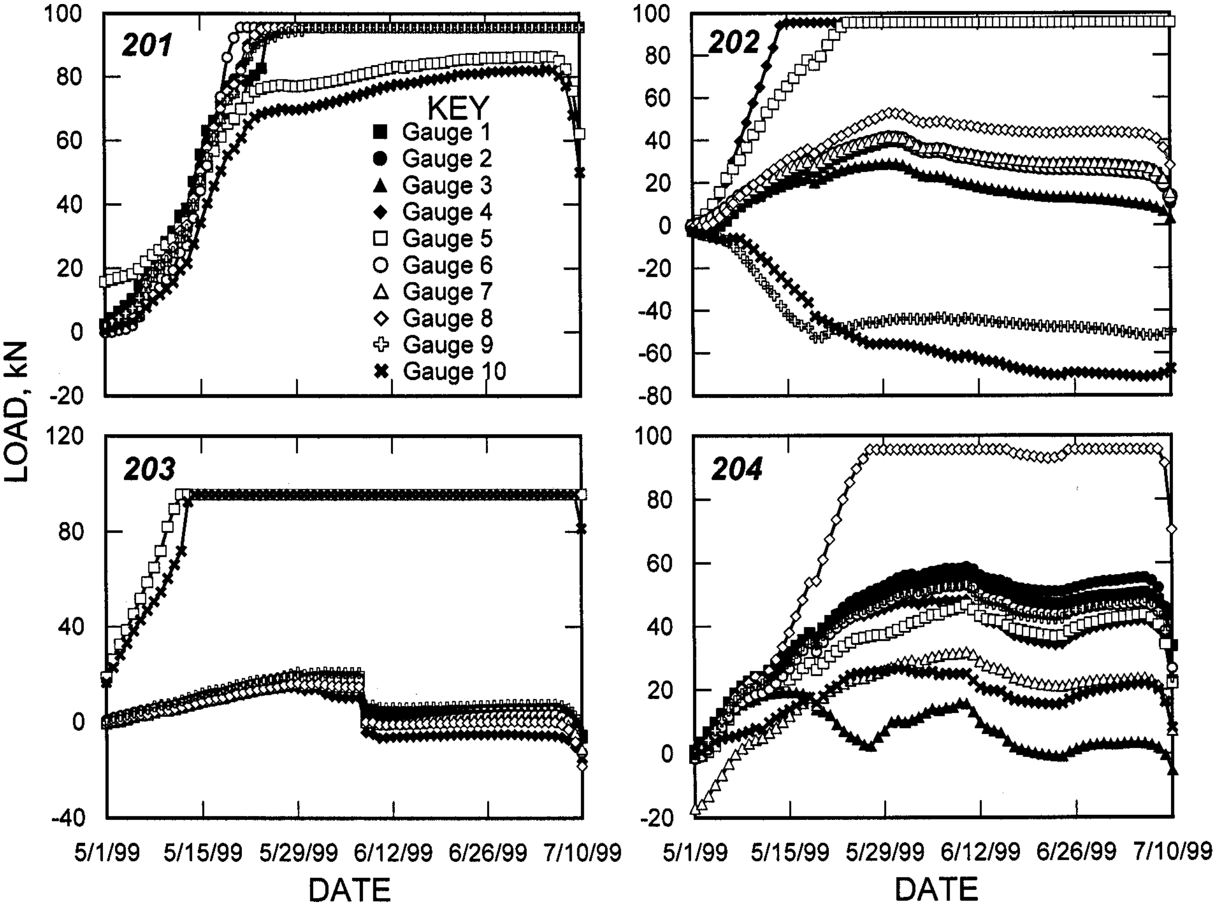


Figure 10.—Load profile versus time on a 2.4-m-long, fully grouted rebar bolt.

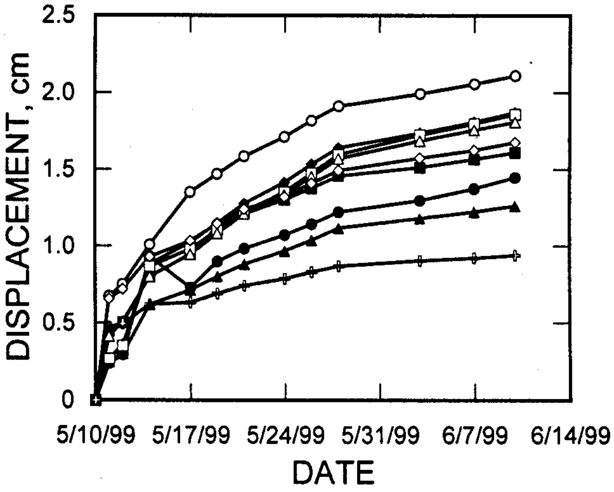
Following is the authors' interpretation of loads on 12 bolts. By recording actual point loads in the bolts, it will be possible to understand more readily the likelihood that instabilities may be forming or that there may be problems with the quality of the installation.

- Gauges 2 and 7 on cable bolt 1 indicated loads up to the yield limit of the steel. These loads were higher than the axial dead-weight loads on the ungrouted section of the bolt and loads on the grouted gauges, indicating that some delamination was occurring close to the gauge. The higher readings were most likely a result of the fact that concentrated load is measured over the gauge length by a strain gauge, whereas an ungrouted gauge measures all delamination cracks over the length of the ungrouted section, which was 2.8 m. The result is an average load much lower than the load on a bonded cable over a given distance.
- Bolt 2 was inspected by mine personnel, who determined that it had broken. This could have happened because the bolt was defective or because of unexplained shearing of the bolt.
- Bolt 4 shows a load-shelling profile similar to that generated in the laboratory (see figure 3). The greatest load was recorded 3.1 m above the back by gauges 3 and 8. The ungrouted length (2.8 m) shows a low load primarily because load was distributed over a large distance, as discussed previously. It must be noted that loads were lower on the gauges on either side of the bolt at 3.1 m. This implies that a crack was close by.
- Bolt 5 shows the classic load shelling profile. The highest load was recorded in the ungrouted section within 2.8 m into the back. The next highest load was at the bonded gauge 2.9 m into the back. Readings again indicate that delamination was largely controlled by cracks within 3 m into the back.
- Loads on bolt 6 were uniform, with an average of 40 kN, excepting for gauges 2 and 10, which were located 2.3 m above the back. This implies that delamination may have been occurring at this location. Note that this bolt was close to the pillar boundary and therefore the depth of the fractured zone would be less.

- Gauge sets 2 and 7 (2.3 m deep), 3 and 8 (2.5 m deep), and 4 and 9 (2.7 m deep) on bolts 8 and 9 showed a load profile approaching, and in most cases reaching, the yield strength of the bolt. This reading indicates that delamination was occurring throughout the horizon or that rock mass loading was higher. These two bolts were placed in the north-center section of the site, which experienced high loads such as those on bolt 4, which had also been placed in the center of the intersection. The deepest gauges (5 and 10) at 3.1 m into the back recorded low values, indicating that the bond at depths between 2.7 and 3.1 m was sufficient to absorb most of the load.
- Bolt 11 was located at a pillar boundary and therefore was receiving more support from the mine rock, resulting in less delamination and lower loads. Representative load curves for the 3.1-m-deep gauge show the greatest amount of load. The second set of gauges, at 2.3 m deep, took the next highest load, and the first set of gauges, at 2.59 m deep, took the lowest loads. Delamination was occurring, albeit at low loads, approximately 3 m above the back.
- Typical axial load curves are shown for bolt 201. These types of curves usually result when conducting laboratory pull tests on instrumented bolts. The curves also show a quick loading rate, which should be expected because the bolt was closest to active mining on the east side of the intersection.
- Strain gauges on bolt 202 were reading both positive and negative strain, which indicate bending of the bolt. Gauges 4 and 9 and gauges 5 and 10 indicated that bolt bending on one side was in the yield zone of that bolt. Loads on gauge 5 showed the same loading horizon as the cable bolts at 2 to 5 m. The remainder of the gauges showed that the nonbending sections of the bolt were under low loads compared to the sections of the bolt showing bending.
- The tip on bolt 203 was undergoing high axial loads in the yield zone. This could be interpreted as an indication that the bolt was just reaching the load horizon at 2 to 3 m into the back. The rest of the gauges were being loaded at relatively low load rates.
- The load curve on bolt 204 was typical except for readings from two gauges. The bolt was supporting ground at all instrumented horizons, with somewhat higher loads at the center of the bolt. These load profiles also indicate that the resin grout was developing a good bond along the entire length of the hole. It is possible that a crack in the back caused grout delamination that affected gauge set 3 and 7. Total lower load readings along the bolt could have resulted from a greater bolt density in the surrounding area.

RESULTS OF MEASUREMENTS AT SAGMETER STATIONS

Three sagmeter stations were installed at three different depths (2.4, 3.2, and 3.8 m) at the intersection of 350S and 12,371E (figure 7). Figure 11 shows that sagmeters at the three stations generated similar curves with displacements ranging from 0.5 to 2.0 cm. In general, the most centrally located station had the greatest displacement at all three depths. Generally, the north-northwest and south-southeast sagmeter stations, which were near the boundary pillars, showed the least amount of deformation. Delamination was observed throughout all horizons with the largest amount of movement between 2.4 and 3.8 m of the back. This roof movement corresponded with data collected from the strain gauges, showing that delamination was generally 2.4 m above the back. Sagmeter readings from the 3.2-m-deep hole at the center of the intersection would be comparable to readings from a 4.3-m-long cable bolt with 1.5 m of resin embedment. This would mean 2.8 m of unbonded cable length.



	Location (relative to center of intersection)	Compare to __	Depth
■	SSE	2.4-m bolt	3.8 m
●	SSE	2.4-m bolt	3.2 m
▲	SSE	2.4-m bolt	2.4 m
◆	Center	4.3-m bolt	3.8 m
□	Center	4.3-m bolt	3.2 m
○	Center	4.3-m bolt	2.4 m
△	NNW	3.7-m bolt	3.8 m
◇	NNW	3.7-m bolt	3.2 m
✛	NNW	3.7-m bolt	2.4 m

Figure 11.—Displacement of back over time.

The above case history is being further evaluated with respect to deformation, mining sequence, and behavior of the back. The depth of failure was most likely 3 m. Employing a support pattern of bolts placed on 1.2- by 1.2-m spacings and a specific gravity of 2.6 for the marlstone-trona-shale back would yield a dead load of approximately 110 kN, which is within the range of loads as measured by the bolts. Although several of the measured loads exceeded the calculated dead load significantly, which could have been the result of mining-induced loading, readings from these cable bolts enable researchers to understand overall support-rock interaction.

CONCLUSIONS

In all installations where the gauges were read, cable bolts provided information about loads in the immediate rock mass. Grout quality could be determined by relating bonding capacity of these cable bolts to the load profile of the ungrouted bolts. The instrumented cable bolt was found to be reliable in indicating load changes and has been correlated to deformation of the adjacent rock mass.

The dangers of assuming that deformation is linear across a bonded cable were also suggested as the load profile showed the relationship of the degree of grout bonding to load along the cable. The simple relationship of strain-to-load calculated with cable modulus is only valid for the ungrouted sections of cable. However, the grouted sections of the cable should be calculated using calibrated data to determine the strain relationship. The above interpretation is only possible if point strains and loads on a cable are known.

This instrumented bolting system is used to aid in determining proper bolt spacings, bolt lengths, and load-carrying characteristics of the bolts, thus allowing a mine manager to design a safer roof support system for miners.

ACKNOWLEDGMENTS

We thank Tg Soda Ash and mine engineers John McDonnell, Christopher Pritchard, and Scott Lehman; without their cooperation, this research would not have been conducted. We also thank Stephen P. Signer, mining engineer at SRL, for his expertise in the application of Campbell Scientific systems; and Richard Curtin, Dennis J. Cox, Richard L. Rains and Joanne L. Johnston, engineering technicians at SRL, for their dedication in constructing the instrumented bolt systems.

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