Determination of Physical Properties of Cable Bolts in Cement Grout Pull Tests Using Instrumented King Wires

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ABSTRACT

Whereas many researchers and mine engineers have conducted tests using different types of grout, grout ratios, and physical modifications of the cable to determine cable bolt load characteristics, few studies have been conducted on cables fitted with internal instruments. Those studies that have been done have concentrated on cable behavior averaged over significant cable lengths. Researchers at the Spokane Research Laboratory (SRL) of the National Institute for Occupational Safety and Health in Spokane, WA, are investigating the physical properties of cable bolts by replacing the conventional king wire with a modified king wire on which strain gauges have been installed . This paper documents test results on these modified cable bolts. Three tests were conducted at SRL on 1.83-m-long cables grouted into two 0.91-m-long pull-tube assemblies. Load along the cable was monitored with 20 strain gauges installed along the length of the cable.

The instrumented cable bolt provided reproducible point measurements of cable load as opposed to load measurements averaged over significant cable lengths. Such point measurements can assist in interpreting the influence of cable confinement, grout quality, rock mass stiffness, and other factors. The instrumented cable bolt is a practical field and research tool because it can predict point loading along the cable and thereby allow interpolation of maximum possible loads on a cable.

INTRODUCTION

Many researchers and mine engineers have conducted a large array of tests using different grout types, grout ratios, and cable physical attributes (Garford bulbs, buttons, birdcage, nut cage, etc.) to determine load characteristics (Goris 1990). A limited number of studies have looked at load distribution along a cable bolt. However, tests using instrumented cable bolts in steel tubes were conducted only with extensometer-type internal instruments (Hyett and Bawden 1997) and externally mounted strain gauges (Choquet and Miller 1987; Goris et al. 1993; Chekired et al. 1997; Windsor and Worotniki 1986).

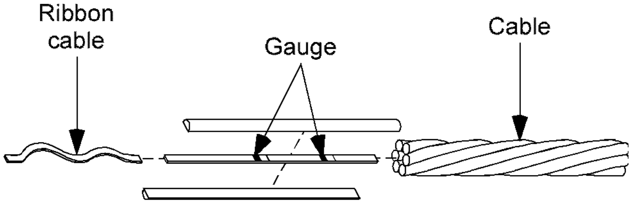


Figure 1.—Instrumented king wire with gauges and connecting cable.

Well-established commercial instruments exist for measuring load in cable bolts. These include the Tensmeg and SMART cable. The Tensmeg is a 60-cm-long, externally mounted strain gauge, and the SMART cable is an extensometer fashioned inside a replacement king strand in a cable bolt. However, the anchor spacings within a SMART cable are usually no less then 1 m.

The Spokane Research Laboratory (SRL) has developed a new instrumented cable bolt (Fig. 1) (patent 6,311,564) in which the original king wire has been replaced with a strip of steel to which strain gauges have been attached (Fig. 2). The cable bolt was 1.8 m long and 15.8 mm in diameter and has an ultimate strength of 258 kN. Twenty strain gauges were positioned at 7.6-cm intervals along two sides of the replacement king wire. The cable was then inserted into two 0.9-m-long sections of schedule 80 steel pipe (so that 10 gauges were in each pipe section) and grouted with Type I/II portland cement at a 0.35 water:cement mixing ratio.

Strain is defined as change an infinitesimally small length. A strain gauge does not actually measure strain, but instead measures the change in length (deformation) along some fixed length. As the length of a strain gauge increases, its ability to measure small local strains accurately over short distances decreases. The main advantage of the new instrument is that cable stretch can be measured over a short distance, thereby providing an accurate estimate of load over a small (approximately 1 cm) length of a cable. That is, as the grout transfers axial load to the cable, the strain gauge on the king wire will give aload reading in microstrain. The instrument has the potential to give more information than can be obtained from existing cable load monitoring approaches. It also provides valuable insight into cable support behavior.

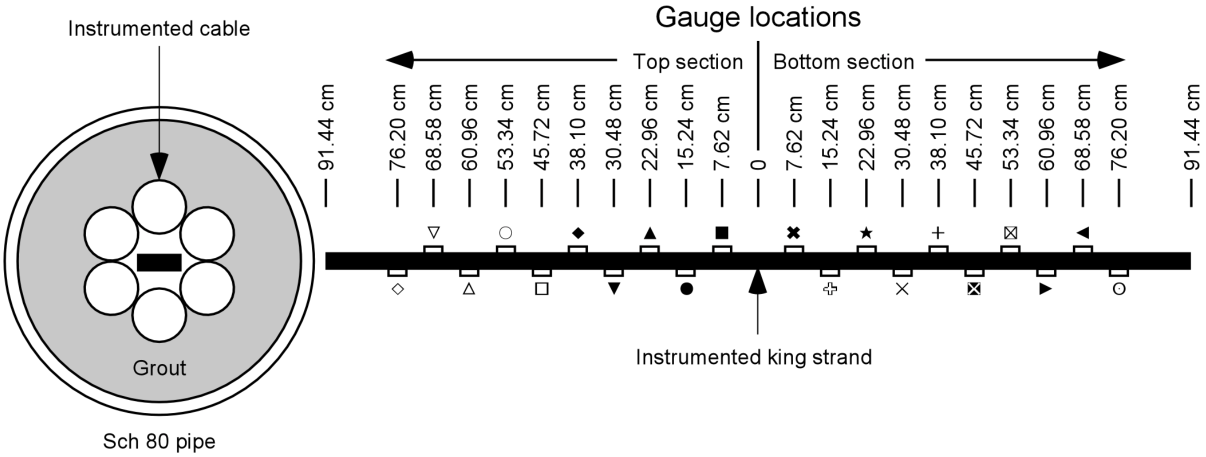


Figure 2.—Instrumented cable grouted in steel pipe.

LABORATORY TESTS

Three tests were intended to duplicate crack dilation in underground mining environments and followed the procedure developed by Goris (1990). The resulting measurements gave a load profile for the instrumented cable. The data sets tracked strain through the elastic and into the plastic range of the instrumented cables.

The pull-test system (Fig. 3) was built to prevent the tubes from twisting during the tests. The test apparatus was the same type as used by Goris (Goris and Conway 1987) during his testing program at the U. S. Bureau of Mines. The pull tests were conducted using a hydraulic machine having a maximum capacity of 1780 kN. As load was applied, the upper head of the machine moved away from the stationary bottom part. This action caused the two pipes to separate in the middle and caused grout shear along the cable-grout interface. Because of surface roughness and a weld bead on the inside of the pipes, slip along the grout-pipe interface did not occur (Goris and Conway 1987).

Continuous readings of load, strain, and displacement in the cable bolt were taken throughout the test at a load rate of 2.2 kN/min. Load readings were collected electronically from a load

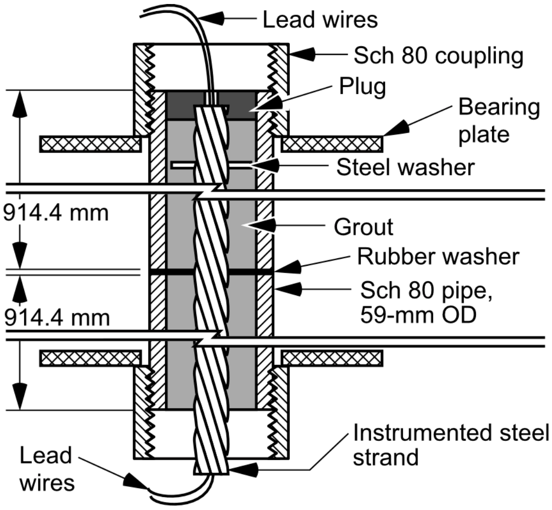


Figure 3.—Pull-test apparatus

cell within the test machine. For duplicability, displacement readings were obtained from a micrometer on the pull tubes and a LVDT on the machine.

At 28 days of grout curing, the first pipe was pulled apart and the resulting load, displacement, and strain at various points along the cable were measured. The second and third tests were conducted after 30 days. An average compressive strength of 57 MPa was achieved at 28 days. The tests were run on all three samples until the cable-grout bond failed. In all three tests, the grout failed before the cable; however, the cables were all undergoing plastic deformation.

Methods of estimating cable load are based on cable stiffness. Therefore,

$$P = K \times \varepsilon \qquad \text{Eq. 1}$$

where P = cable load, K = cable stiffness, and ε = cable strain. Manufacturer's specifications state that the common K value = 28,410 kN. This estimate of P from ε is accurate for the elastic deformation range of a cable and is valid up to about 0.8% strain or 22,700 kN.

CALIBRATION OF UNGROUTED CABLE

Calibration Tests

Five conventional cables were used to create the instrumented cables, since there is a large database of pull-test results on conventional cables grouted in steel pipes with cement grouts. Prior to being placed in the field, the cables were loaded to 178 kN of pull, to obtain a calibration curve for each gauge. The maximum load for elastic cable deformation is 178 (Fig. 4). The drift observed was largely due to the length of the lead wire connected to the individual gauges and was taken into account using an average calibration curve (Fig. 4).

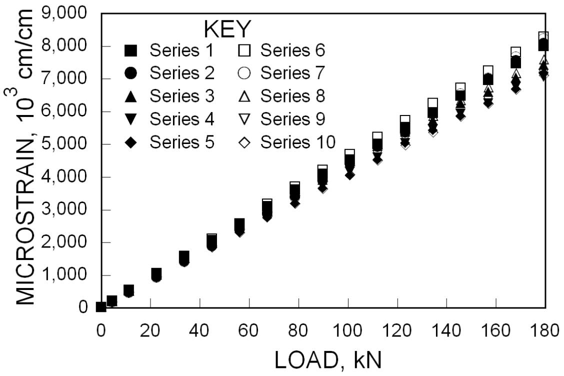


Figure 4.—Calibration curve for instrumented cable bolt.

The slope of load versus microstrain in Figure 4 gives the stiffness of the instrumented cable. The ribbon cable on the SRL instrumented cable does not carry appreciable load.

A simple approach to determining the stiffness of the six-strand instrumented cable is to assume that the king wire carries one-seventh of the cable load, which would result in a stiffness of 24,500 kN for a six-strand cable. Calibration test 3 indicated an instrumented cable stiffness between 21,528 and 25,264 kN at a load of 178 kN. This range in stiffness brackets the expected stiffness for a standard cable with one strand removed (six-sevenths of the standard seven-strand stiffness). If the cable bolt is deforming as a unit, all measured strains should be the same. The range in values of measured stiffness may be due to differential movement between the instrumented king wire and the six external cable strands. A second source of variation in stiffness may be the location of individual strain gauges with respect to the cable strands. Higher strain (lower stiffness) may correspond to gauges positioned directly under a cable strand.

Pull Tests

Three pull tests were conducted on instrumented cables grouted into steel pipes. Figure 5 shows pull-test results plotted as applied load in kilonewtons versus displacement in centimeters. In each test, the maximum applied load was 200 kN, which is the yield point of the instrumented cable.

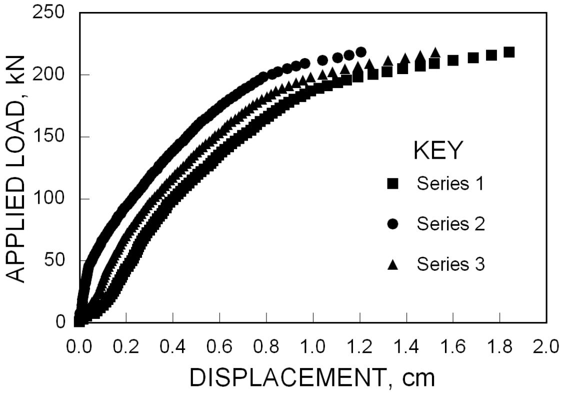


Figure 5.—Displacement pull tests.

TEST INTERPRETATION: LOAD VERSUS STRAIN FOR GROUTED CABLE

The load-to-deformation relationship of a grouted cable system is more complex in the laboratory than with an ungrouted cable. The gauges installed 76.2 cm from the loading point did not show significant loading until an applied load of approximately 156 kN was reached. The gauges started to show significant loading at a constant rate so that the gauges at 38.1 cm showed loading at approximately half of 156 kN. This load transfer rate can be expressed as C, or the ratio of loaded cable length to applied load. Thus,

$$C \approx \frac{76.2 \text{ cm}}{155{,}680 \text{ N}} = 4.89 \times 10^{-4} \text{ cm/N} \qquad \text{Eq. 2}$$

Therefore, the load at which each strain gauge will start to deform can be estimated as follows:

$$P_0 = \frac{L_0}{C} \qquad \text{Eq. 3}$$

where L_0 = distance of strain gauge from applied load, P_0 = applied load required to deform strain gauge initially, and C = length-to-load constant at 4.89×10^{-4} cm/N.

After a strain gauge has started to take load, any additional load will directly increase the strain on the gauge. Strain will be related to the increase in load based on the K of the cable bolt. Remember that K for a standard seven-strand gauge cable is 28,410 kN and should, therefore, be six-sevenths of that for the six-strand cables used in this research. Thus K = 24,019 kN.

Based on the constant load transfer rate and cable stiffness, theoretical strain-versus-load curves were calculated for three of the gauges monitored in pull-test 2. Figure 6 compares measured and calculated strains.

There is reasonably good agreement between the measured and theoretical strains for the gauge at 7.62 cm and excellent agreement for the gauge at 38.1cm. At high strain values, measured microstrain exceeds theoretical microstrain because the cable has exceeded the 0.8% elastic strain limit. The good agreement for the gauges at 7.62 and 38.1 cm suggests that the basic theory for calculating a constant load transfer rate for instrumented cables is valid. Agreement is poor between measurements and theory for the gauge at 68.6 cm, and this is cause for some concern. It appears that the instrumented king strand is being pulled past the outer cable strands, which would result in low strain readings well before the cable could be expected to carry load at this strain rate. Slip of the instrumented king strand at 68.6 cm would explain the lower-than-expected strain values when the gauge would be expected to be loaded (Fig. 6).

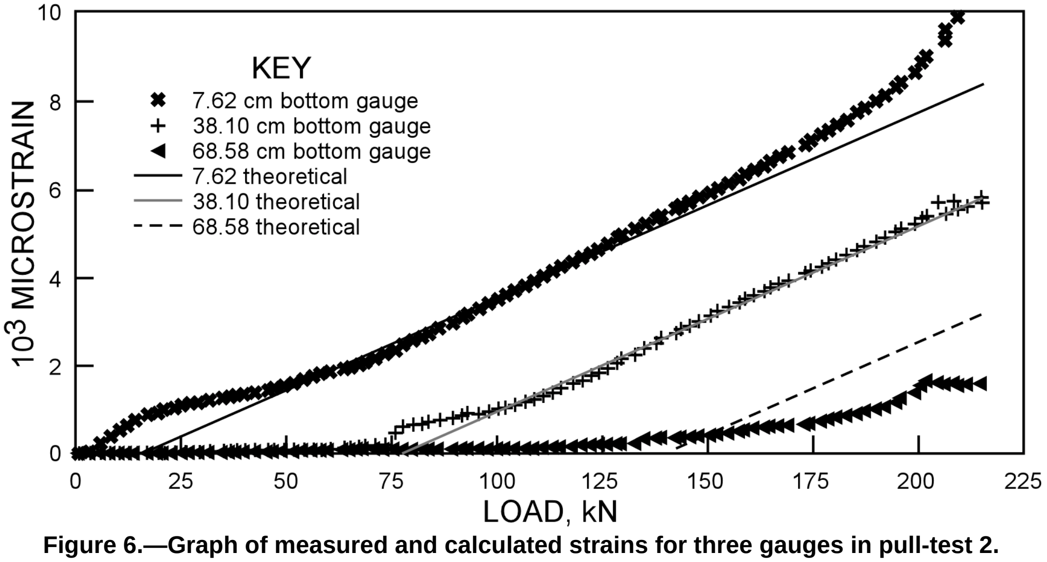


Figure 6.—Graph of measured and calculated strains for three gauges in pull-test 2.

Additional data from tests at the Noranda Technology Centre (NTC) in the early 1990's (Milne et al. 1992) support this interpretation. A pull test was done on a 0.91-m-long grouted cable with strain gauges bonded to the external cable strands at 15.2-cm spacings. The load-versus-microstrain graph had a form similar to that of the SRL tests (Fig. 6), and the load transfer rate was approximately 2.28×10^{-4} cm/N. A maximum load of only 112 kN was applied to the cable because most of the externally bonded strain gauges and wires had failed at this load. The SRL approach of protecting the gauges and wires in a replacement king strand creates a more practical situation.

COMPARISON BETWEEN EXISTING AND PROPOSED CABLE INSTRUMENTS

All approaches for measuring load in cable bolts are based on the principle of measuring deformation over a fixed length and relating it to load on the basis of cable stiffness. As the fixed length measuring distance increases, the accuracy of the estimate of cable load at a point may decrease. Using the load and strain distributions proposed above, the load estimate obtained from various basal measuring lengths can be compared. It is assumed that load along a grouted cable is driven by dilation of a single crack. Properties estimated from SRL tests of six-strand cables are used in the following analysis, where K on six-strand cables = 24,019 kN and C on grouted cables = 4.89×10^{-4} cm/N.

Deformation-based estimates of cable load relate load to deformation by simply dividing deformation by monitoring distance to approximate strain and multiplying the resulting figure by cable stiffness. This gives an average load or strain along the measured length. Distances of 0.91 and 1.83 m, which are the typical distances used for monitoring load on conventional cables, are assumed.

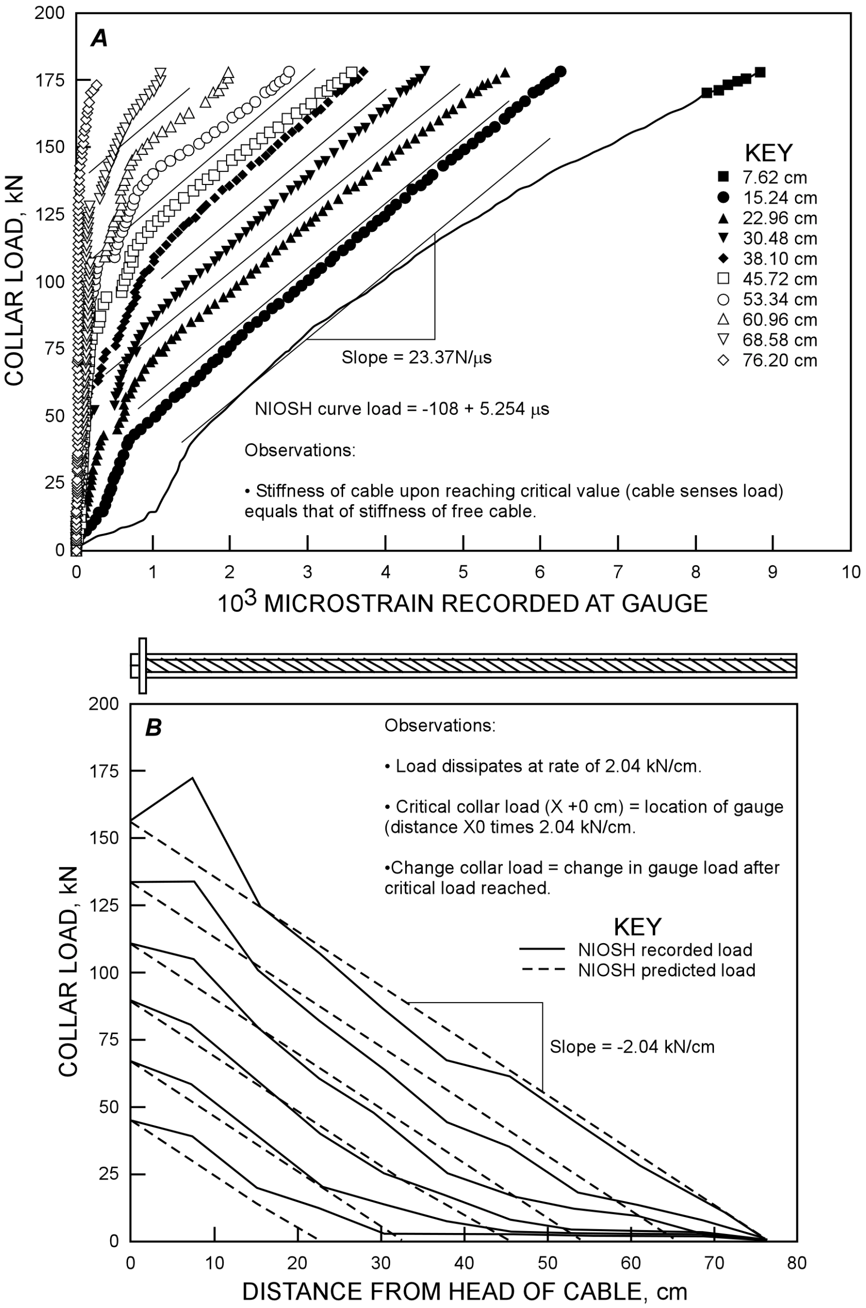
Using K and C, Table 1 shows what different estimates of load would be at different base lengths for strain gauges positioned at various distances from a single dilating crack. A similar qualitative comparison was proposed by Windsor (1992); however, no values were provided. Windsor states that “A discontinuous load profile in a cable is very difficult to measure properly and requires both discrete measurements (i.e., short base length ‘cells’) and integrated measurements (i.e., long base length ‘gauges’).” Table 1 assumes the cable bonds and properties indicated during the tests of the SRL instrumented cable. Conventional cables with different grouting conditions would exhibit different behavior. If multiple cracks were dilating and loading a grouted cable, much less discrepancy among the different loads would be predicted by the various instrument configurations.

TABLE 1.— Theoretical load and deformation measured for different cable instruments

Actual cable load, N	Cable length loaded on each side of crack, cm	Calculated crack dilation, cm	Load based on fixed measuring length, N		Load measured at varied distances of SRL gauge from crack, N			
			91 cm	18 cm	0 cm	30.5 cm	45.7 cm	61 cm
22,240	11.2	0.01	2,668	1,334	22,240	0	0	0
44,480	21.8	0.04	10,675	5,337	44,480	0	0	0
88,960	43.7	0.15	42,700	21,350	88,960	26,680	0	0
133,440	65.5	0.36	86,736	48,038	133,440	71,168	40,477	12,899
177,920	87.1	0.64	131,216	84,957	177,920	115,648	84,512	53,376

Interpretation of Load Profile

Collar load is plotted against recorded microstrain at the individual gauges shown in Figure 7*A*, while the load profile along the length of the cable for different collar loads is shown in Figure 7*B*. Figure 7*B* also shows the strong correlation between predicted (Eq. 2) and actual loads. When the critical load at the collar (x-0) exceeds 5204 N × “distance of gauge from collar [in centimeters],” the gauge will commence sensing load so that every incremental change of collar load will equal a similar increase in load sensed by the gauge. This implies that a gauge located 25.4 cm from the collar will sense load only when the collar load exceeds 25.4*2043 N/cm, or 51,908 N. When the collar load increases from 51,908 to 56,356 N, the gauge at 25.4 cm will sense the incremental load of 4448 N. A further observation is that the slope of collar load versus microstrain as recorded by the individual gauges parallels the slope of a free cable after a “critical load” has been exceeded (Fig. 7*A*).



Observations:

• Stiffness of cable upon reaching critical value (cable senses load) equals that of stiffness of free cable.

Observations:

• Load dissipates at rate of 2.04 kN/cm.

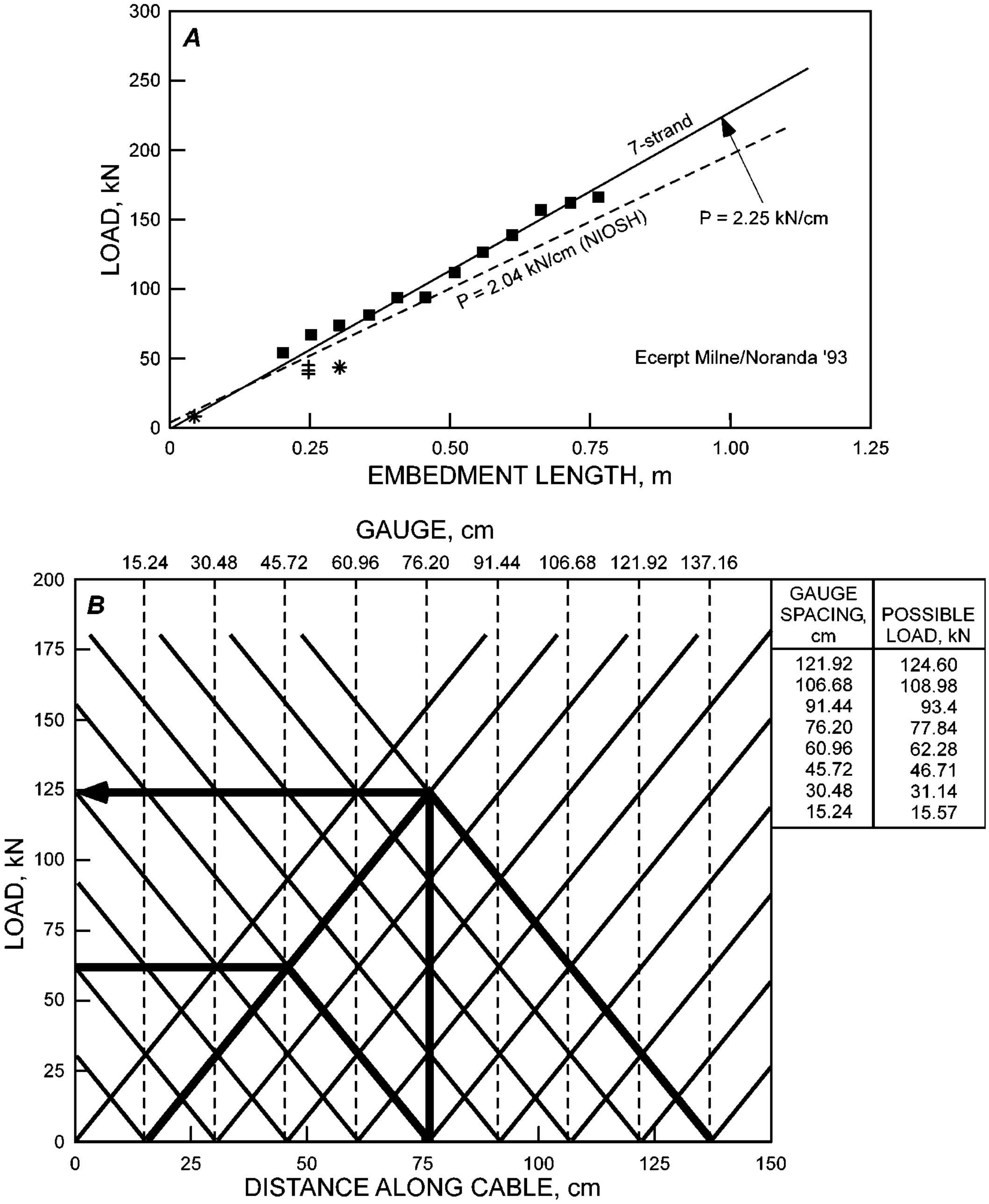
• Critical collar load (X +0 cm) = location of gauge (distance X0 times 2.04 kN/cm.

•Change collar load = change in gauge load after critical load reached.

Figure 7.—*A*, Load profile curve; *B*, load correlation curve.

Load Profile Matrix

Figure 8*A* shows the critical collar load required before the individual gauges sense load at various embedment lengths for the standard seven-strand (Goris et al. 1993) cable and for the SRL instrumented cable. The slopes of the two cables are similar, as would be expected since slope is largely a function of the bond strength of the wire in contact with the grout. (The number of wires in contact with the grout is the same for a standard seven-strand cable and the SRL cable.) This is an important observation as it implies that load on the SRL instrumented cable would behave in a manner similar to load on a standard seven-strand cable.



GAUGE SPACING, cm	POSSIBLE LOAD, kN
121.92	124.60
106.68	108.98
91.44	93.4
76.20	77.84
60.96	62.28
45.72	46.71
30.48	31.14
15.24	15.57

Figure 8.—Load profile matrices. *A*, Load versus embedment length. Squares indicate data points. *B*, Load matrix graph.

In Figure 8*B*, the load matrix is interpreted as having a gauge positioned every 15.2 cm along the cable. A load of 0 N at the gauge infers a possible load increase of 2.04 kN/cm. Therefore, gauges positioned 1.2 m apart, as are the gauges at 15.2 cm and 137.2 cm, indicate a load of 125 kN at "x = 76.2 cm." This is based upon the assumption that there is a single crack. Alternatively, a gauge located at "x = 76.2 cm" and indicating a load of 0 N negates this possibility. However, an interpreted load of 62 kN is possible if a crack was located midway between the gauge at 15.2 cm and the gauge at 76.2 cm. This method should be employed when estimating predicted load on the crack based upon recorded measurements and their proximity to the interpreted location of the crack. This situation has been presented in Table 1 and shows that it is critical to interpret loading based upon measured conditions rather than relying on single or average loads.

CONCLUSION

The SRL instrumented cable bolt is a unique field and research tool that shows significant potential for improving our understanding of the load deformation behavior of grouted cables. Using measured load distribution along the cable will make it possible to predict point loading and the load transfer rate along the cable and the resulting stiffness of a grouted cable. The behavior of an SRL instrumented cable bolt largely parallels that of a standard seven-strand cable; however, this should be further confirmed in the field. A comparison among a SMART cable, a standard seven-strand cable (Tensmeg), and the SRL cable should be considered to confirm that the stiffness of an SRL cable parallels that of a standard seven-strand cable. This would ensure that measured loads are also the loads recorded on an adjacent standard cable. The SRL cable provides a source of reliable point measurements, which will help evaluate the effects of cable confinement, grout quality, and rock mass stiffness, among other factors. As mentioned by Windsor (1992), the behavior of a grouted cable bolt needs to be assessed over both small and large measuring intervals. The SRL cable provides insight into how a cable responds to load by measuring loads over small intervals. This tool has the potential to assist in understanding the overall interaction of cables, rock, and grout.

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