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Evaluation of Ultrasonic Measurement Systems for Bolt Load Determinations

By Stephen C. Tadolini

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**UNITED STATES DEPARTMENT OF THE INTERIOR
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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

dB	decibel	μs	microsecond
ft	foot	$\mu\text{s}/\text{cm}$	microsecond per centimeter
in	inch	s	second
in/s	inch per second	V	volt
lbf	pound (force)	V/cm	volt per centimeter
MHz	megahertz		

EVALUATION OF ULTRASONIC MEASUREMENT SYSTEMS FOR BOLT LOAD DETERMINATIONS

By Stephen C. Tadolini¹

ABSTRACT

The U.S. Bureau of Mines has developed ultrasonic measurement instrumentation capable of measuring strains and elongations on tensioned and untensioned mine roof bolting systems. This report evaluates the pulsed-phase-lock-loop and pulse-echo systems. The pulse-echo systems measure time of flight of a signal through the bolt. The ultrasonic instrument converts the measurement into elongations or stress. The most recent Bureau instrument development converts travel-time measurements directly into elongation, load, stress, and torque by simple data manipulation from the keyboard. Bolt preparation and instrument calibration are described in detail.

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INTRODUCTION

Millions of rock bolts, both tensioned and untensioned, are used each year for structural support. The applications range from underground mining environments to geotechnical applications of tieback walls and canal lock support. An increasing percentage of these bolting systems utilize resin-anchor and resin-mechanical-anchor combination bolts as well as mechanical anchor bolts. The method by which expansion anchor bolting systems carry roof loads is well understood and documented. The

support capability of a given anchorage system installation depends on such factors as rock characterization, bolt characteristics, and bolt tension. Measurement of installation and postinstallation bolt tension provides a great deal of information about the effectiveness of the bolts and the behavior of the supported structure. This study was conducted as part of the U.S. Bureau of Mines program to improve safety in the mines.

BACKGROUND

Current practice in civil and mining environments is to use load cells, strain gages, pressure pads, or vibrating-wire instruments to determine initial and subsequent bolt load. An obvious disadvantage of these types of instruments is that instrumented bolts receive special handling during the installation process. This may make it nonrepresentative of typically installed bolts. Also, the cost per bolt with these types of measurement systems is high.

Current practice in production is to use torque wrench readings on a small statistical sample of the bolts, as required by Federal regulations in the mining industry (9).²

This method has the disadvantage that torque measurements are only about $\pm 30\%$ accurate as related to bolt load. The conversion of torque to load in the installation is also highly dependent on component shape, washers, lubrication, and installation thrust. The method may also disturb the anchorage that has been obtained in the immediate host rock, while the small sample gives only a vague indication of overall structural stability. Resin-grouted or concrete-grouted bolts or supports cannot be tested with a torque wrench because the measurement would only reveal the torsional resistance of the steel.

ULTRASONIC MEASUREMENT EQUIPMENT

To overcome the measurement problems associated with the determination of bolt stability and integrity, ultrasonic measurement systems were investigated and adapted by the Bureau for use with tension and untensioned support in the geotechnical and mining industries. These ultrasonic measurements provide an easy-to-use, high-accuracy, low-cost-per-bolt system that is capable of determining the amount of load being subjected on an installed support system.

The principle involved is simple. The round-trip travel time of a sonic pulse or group of sonic waves propagating through a bolt is measured. This travel time is affected by bolt stress and bolt strain and changes linearly to a fraction of a percent with respect to axial bolt loads. The waves are introduced into the bolt by a piezoelectric transducer attached at the bolt head, which also detects the return waves that have reflected back from the bolt end or other internal reflector, such as a small-diameter hole drilled orthogonal to the bolt axis.

To accommodate strain gages or vibrating wires, modifications are necessary that can create zones of induced stress concentrations; these stress concentrations can produce erroneous test results, particularly at low stress levels. Such modifications are not necessary when using ultrasonic instruments. By measuring the axial deformation of a bolt throughout its length, calculations can be made to determine the amount of load induced at these locations by the applied end-loading conditions. This information can provide a clearer understanding as to the overall loading characteristics of full- and partial-column resin-grouted bolts.

Making the required time measurements, however, is very complex because the changes in round-trip travel time are very small. To appreciate the electrical and mechanical complexity of the instrumentation problem, it is important to recognize that a typical 5/8-in-diam, 4-ft-long mine bolt stretches only 0.00064 in per 100 lbf of axial load. Considering that the signal makes a round trip (8 ft) through the bolt and that a typical signal velocity is 231,000 in/s, causing the instrumentation to change at least

²Italic numbers in parentheses refer to items in the list of references at the end of this report.

one unit for a 100-lbf change, time must be stably resolved to about 5.5×10^{-9} s at a typical probing frequency of 2.25 MHz. Any error source need only cause an equivalent change of the order of $0.02 \mu\text{s}$ to become a major difficulty. Signal attenuation is also severe, reaching about 80 dB for the described bolt. The near-field focal length of typical transducers at frequencies used is only a few inches. Beyond this, the wave front spreads out in a conical fashion. Since bolt signal paths are relatively long, the signal path is quite complex because the waves reflect off the sides of the bolt, become mode converted from P- to S-type waves and back, and constructively and destructively interfere (2).

The research in the ultrasonic field was undertaken by examining two fundamental approaches to the measurement. Pulsed-phase-lock-loop (P^2L^2) systems were studied first. These systems measure time indirectly by shifting their probing frequency to maintain constant output to reflection wave-phase differences as the bolt loads. The frequency change, which is easy to measure, then becomes an indirect measure of time change. Pulse-echo systems were examined, evaluated, and selected for use in this investigation. These systems have the ability to measure travel time directly by incorporating special electronic techniques to provide the required time resolution (5).

PULSED-PHASE-LOCK-LOOP SYSTEMS

The configuration of the P^2L^2 system, shown in figure 1, uses a tone burst of, typically, six cycles to drive the transducer. The transducer also detects the reflected tone burst. The electronic continuation of the driving gated tone burst is then multiplied with the received tone burst, as described mathematically in equation 1:

$$E_o = M_1 \sin(\omega_1 t) \times M_2 \sin(\omega_2 t + \theta), \quad (1)$$

where E_o = multiplier output voltage,

M = amplitude,

θ = phase difference between reflection and continuation of driving tone burst,

ω_1 and ω_2 = angular velocities of driving and reflected signals, respectively,

and t = travel time.

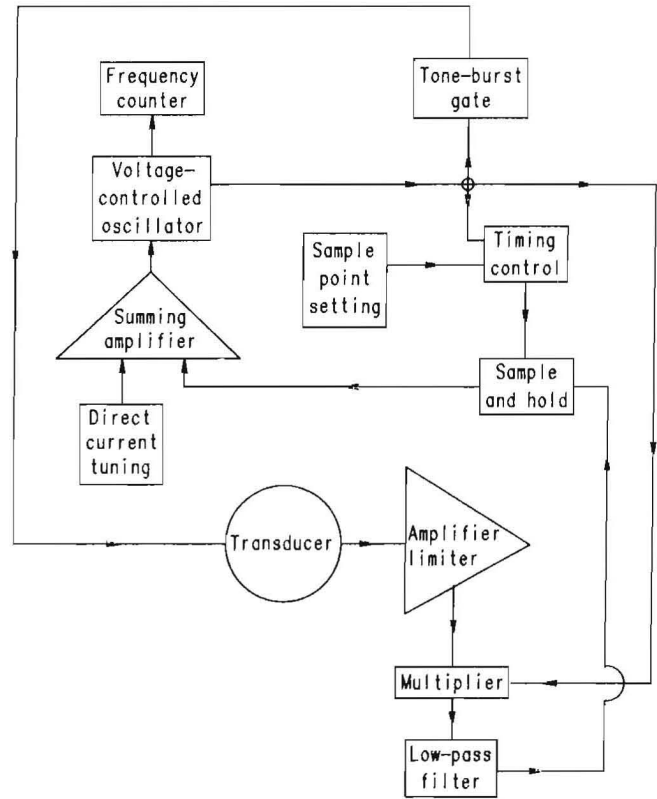


Figure 1.—Configuration of pulsed-phase-lock-loop system.

Using the trigonometric formula, $\sin A \sin B = \cos(A - B) - \cos(A + B)$, reduces to

$$E_o = 1/2 M_1 M_2 [\cos(\omega_1 t - \omega_2 t - \theta) - \cos(\omega_1 t - \omega_2 t + \theta)]. \quad (2)$$

Equation 2 reduces further, since in this case $\omega_1 = \omega_2$, to

$$E_o = 1/2 M_1 M_2 [\cos(-\theta) - \cos(2\omega_1 + \theta)]. \quad (3)$$

The second term in equation 3 is of relatively high frequency compared with the first term. A low-pass filter is used to effectively remove the second term. The filtered voltage is then used to drive a voltage-controlled oscillator (VCO), which then changes the driving frequency in direct proportion to its input voltage, completing the loop.

The loop locks with the two signals in quadrature. The locking tendency of the loop can be discovered by considering perturbations from $\theta = 90^\circ$. Assume the phase difference increases in magnitude from 90° . Then $\cos(-\theta)$, which is in the third quadrant, will reduce from 0 toward -1. The VCO input voltage will then decrease. This reduces the driving frequency, which reduces θ , since the origin of the output tone burst is fixed in time, and the reflection arrival time does not vary with frequency. This continues until θ returns to 90° . Assume the phase difference decreases from 90° . Then $\cos(-\theta)$, which is now in the fourth quadrant, will increase from 0 toward 1. The VCO input voltage will then increase. This raises the driving frequency, which increases θ . Again this continues until $\theta = 90^\circ$. Thus, the loop locks in quadrature. The total travel time of the tone burst can be described in terms of a total phase angle: $\phi = N \times 360^\circ + \theta$, where N is the whole number of cycles between the tone burst initiation and the start of the reflection:

$$\phi_i = 2\pi F_i t_i, \quad (4)$$

where F = the frequency,

and subscript i = initial value.

Consider now that the bolt will be stretched while the loop is locked, so the final ϕ is as follows:

$$\phi_f = 2\pi F_f t_f, \quad (5)$$

where subscript f = final value,

subtracting

$$\phi_f - \phi_i = 2\pi(F_f t_f - F_i t_i). \quad (6)$$

As discussed previously, the action of the P²L² is to keep the phase constant, so

$$F_i t_i = F_f t_f. \quad (7)$$

But $F_f = F_i + \Delta F$ and $t_f = t_i + \Delta t$,

so from

$$F_i t_i = F_i t_i + \Delta F t_i + \Delta t F_i + \Delta F \Delta t. \quad (8)$$

Subtracting $F_i t_i$ and dividing both sides by Δt reduces to

$$0 = \frac{\Delta F t_i}{\Delta t} + F_i + \Delta F. \quad (9)$$

Again, substituting $F_f = F_i + \Delta F$ and simplifying equation 9 reduces further to

$$\frac{\Delta t}{t_i} = - \frac{\Delta F}{F_f}. \quad (10)$$

This is the basic relationship between time and the frequency that is the measured quantity of the P²L² instrument (ϕ). It is necessary to keep track of both the current frequency and the change in frequency to calculate a number linearly related to bolt stretch. The important frequency denominator subscript has been ignored in previously published literature (2). A typical P²L² system signal is shown in figure 2.

Several laboratory experiments and one in-mine experiment were carried out during this study with a P²L² instrument. Using typical roof bolts, the stability of the instrument in mine or minelike conditions ranges to hundreds of hertz, equivalent to a load on the order of several thousand pounds. A careful analysis showed that the principal source of difficulty was that the transducer was oscillating at its mounted resonance rather than at the frequency of the driving tone burst. This meant that anything that would alter the installed transducer resonance would distort the desired reading. Because of this, very small amounts of temperature change, position change, or couplant change caused stability problems. Another problem was that altering the instrument to allow it to be

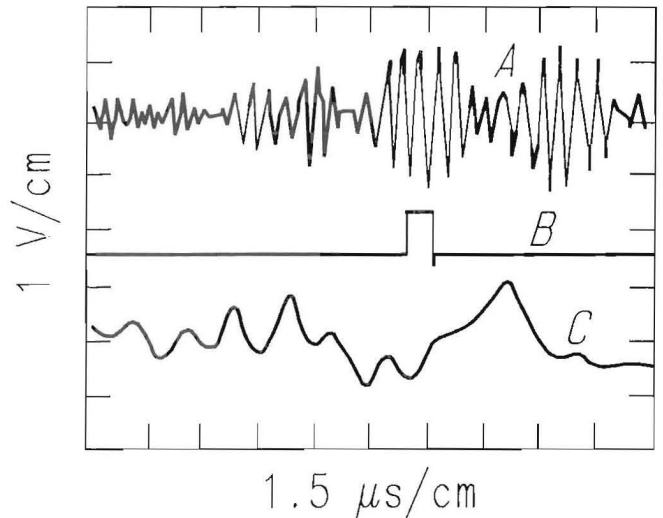


Figure 2.—Typical pulsed-phase-lock-loop system signal. A, Reflection signal; B, sample point pulse; C, filtered multipiler output.

portable and gassy-mine permissible would present significant electronic problems.

These problems are explained in detail in a Bureau Report of Investigations, which provides a complete analysis of P²L² systems (4). For these reasons, further research on the P²L² technology for bolt load measurement applications was given a very low emphasis. A parallel research effort has shown that the mine bolt load measurement can be satisfactorily made using pulse-echo technology.

PULSE-ECHO SYSTEMS

Five commercial strain-measuring pulse-echo systems have been examined for use in determining mine bolt loads. Three other systems measuring reflected energy were also examined. None were found suitable for mine-roof bolt strain or elongation measurements. The most potentially useful unit was selected and modified for the mine-bolt application. A schematic of a pulse-echo system is shown in figure 3. The pulse-echo systems measure the travel time of a sonic pulse directly. A single pulse of approximately 300 V is used to drive the transducer and initiate the timing circuitry. The round-trip travel time of the pulse wave is obtained when the reflected signal is detected by the transducer. From the earlier discussion of time-resolution requirements, it is evident that the trigger point on the reflected wave must be very stable. If a straightforward voltage level trigger is used, it will shift in time as signal amplitude varies. The only points on a sinusoidal wave that remain stable in time as amplitude varies are the zero crossings and the peaks. The circuitry in the trigger box typically combines a voltage level criterion with a zero crossing after the voltage threshold has been exceeded. Automatic gain control (AGC) logic is used to ignore unwanted reflections and noise. The AGC mainly suppresses the signal gain for a selected period and then very suddenly increases gain for a period corresponding to the approximate arrival time of the desired reflection. The pulsing process repeats typically about 400 times per second. The timing circuitry averages several hundred readings to improve accuracy and then updates the display. The correction logic corrects the time value for stress-caused velocity change and also for

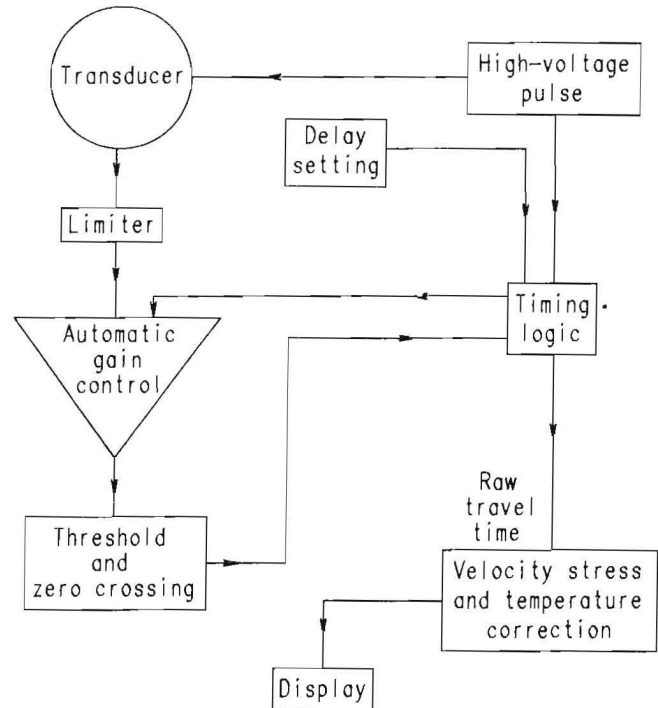


Figure 3.—Schematic of pulse-echo system.

non-stress-inducing, temperature-caused length change. It also can compute equivalent length change from the corrected time values and the initial length. A modified commercial unit has been built to improve gain, gain control, and portability, and to provide the potential for permissibility.

Research has found pulse-echo instruments capable of resolving 0.0001 in of elongation. An important consideration in any type of application is that readings be repeatable as the transducer is removed, then replaced at a later time to take a new reading. The research program, to date, has shown that repetition accuracy of ± 0.0001 in can be achieved. This is accomplished by using magnetic hold-down on the transducer to provide a consistent force on the bolt, ensuring that the head flat is perpendicular to the bolt axis, and by using a low-viscosity, high-conductivity couplant material.

BOLT PREPARATION

MACHINING

The use of the ultrasonic instrumentation requires that at least one modification to the bolt be made prior to bolt installation. Since bolt manufacturers are required by law to stamp bolt specifications on each bolt head, each head needs to be lathe turned or ground smooth in order to accommodate the ultrasonic signal transducer (fig. 4). The strength of the ultrasonic signal is dependent on the amount of energy that can be transmitted across the gap bridging the transducer and the bolt. If there is an air gap, the signal will be almost totally reflected back into the transducer before it reaches the bolt, because of the poor acoustic impedance match between air and the transducer. Figure 5 shows a bolt with the required specification numbers, the numbers removed, and the transducer attached to the head of the bolt.

DRILLING

The application of ultrasonic technology requires that the calibration of a few bolts be applied to a large number

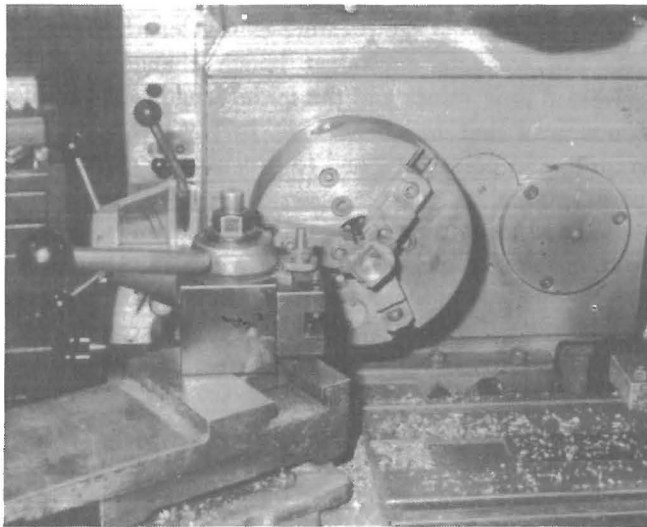


Figure 4.—Lathe machine removing stamped numbers.

of similar bolts. Bolt-to-bolt manufactured length variations of 0.1 in are common. This would, of course, ruin the 0.0001-in resolution achieved by the ultrasonic instrument. To deal with this problem, a uniform distance reflector is established by drilling a 0.040-in-diam hole perpendicular to the bolt axis from 2 to 15 in from the head. In testing 30 bolts to failure, the hole has been found not to have any measurable effect on bolt strength, owing to the very small area affected by stress concentrations around the hole. Because of small errors in hole position and small variations in bolt structure and composition, uniformity is currently limited to about ± 0.0015 in as measured by the instrument. Using individually calibrated bolts, as was done for research purposes in this investigation, allows resolution of ± 50 lbf. If the bolt is bent more than about 5° axially, accuracy deteriorates significantly owing to wave diffraction from the curvature and to the outer fibers of the bolt being stretched past yield. Resolution deteriorates to about ± 1300 lbf where signal levels are still high enough to provide useful measurement.

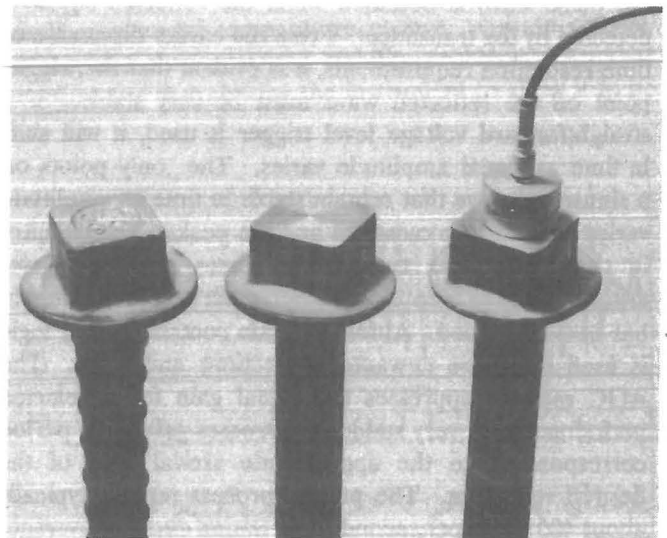


Figure 5.—Unsurfaced bolt head, surfaced bolt head, and unsurfaced bolt head with ultrasonic transducer attached (left to right).

CALIBRATION

To perform accurate measurements, the initial length of the reflector signal and the sonic velocity of the bolt material must be known. The sonic velocity is set by applying the instrument to a bolt stub of known length and then adjusting its velocity setting until the instrument reading equals the known length. Next, the initial head-to-reflector distance in an unloaded bolt is measured using the ultrasonic instrument with the velocity setting previously calibrated. Finally, the velocity change with load is calibrated by setting a stress factor in the

instrument. To set the stress factor, the above bolt is loaded to a measured level. Its exact length change is measured using linearly variable displacement transducers (LVDT's), accurate to 0.00001 in. The stress factor is adjusted until the length change shown by the instrument equals the length change measured by the LVDT's. A typical value of the stress factor for mine bolts is 0.27. The instrument is now ready to measure the true strain of the bolting system as it is loaded. A triggered signal from a maximum signal peak is shown in figure 6.

INSTRUMENTATION

The first instrument that was modified for these types of measurements was the Raymond bolt gage (3).³ This instrument was designed to measure the loads on bolts used in manufacturing and construction. These fasteners tend to be short in length, typically less than 6 in. By making a significant modification to the instrument's receiver circuit board, measurements could be made on

long, slender bolts. This modified instrument has the capability of locating the reflective signal from a single location. The temperature has to be updated manually prior to each measurement. Additionally, the material velocities and the calibration factors must be input into the instrument prior to each set of measurements. The output of this instrument is given in units of elongation or distance. Either reading can be converted to stress, strain, or load with the proper data manipulation. An oscilloscope can be attached to the instrument to view the signal and verify proper trigger location. The Raymond bolt gage is shown in figure 7.

³Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

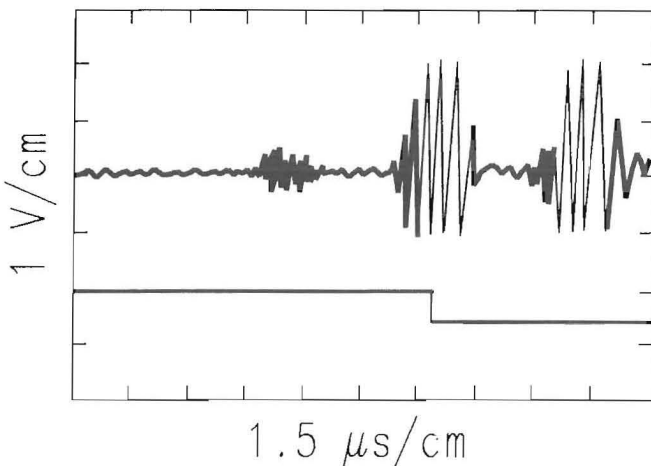


Figure 6.—Triggered signal from maximum signal peak. (Top line is the instrument's signal; bottom line is the trigger.)

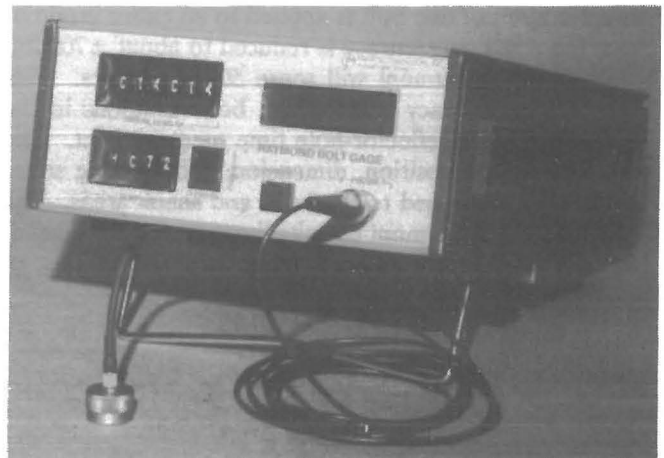


Figure 7.—Raymond bolt gage.

The latest advance in pulse-echo technology is the Bolt Mike model S-1 ultrasonic measurement device. This instrument was fabricated, according to Bureau specifications, by the StressTel Corp. This instrument directly converts reflectivity time into elongation, load, stress, and torque. The Bolt Mike model S-1 measurement device can automatically update the temperature factor 10 times per second and thus requires no manual updating while acquiring measurements. The instrument is capable of monitoring three different sections of a bolt simultaneously, which can be used to eliminate the effects of bending. The Bolt Mike S-1 measurement device (shown in figure 8) has programming cards inserted into the instrument to make the required area calculations, signal velocities, and any stress or load factor that the operator wants to apply to a set of given data. Additionally, any factor can be updated or changed manually from the keyboard. The instrument has an RS-232 port that allows for rapid data transmission to peripheral computers or other instrumentation.



Figure 8.—Bolt Mike S-1 measurement device.

CURRENT STATUS

The pulse-echo technique is capable of resolving ± 50 lbf on an installed bolt. Experience has shown that once the appropriate gain range has been set by observing the signal on an oscilloscope, nonexpert personnel can make accurate readings of bolt loads. In a situation where the calibration of one bolt is applied to an entire group of bolts, the absolute accuracy is reduced to about ± 700 lbf, although the instrument will sense 50-lbf changes. This reduction in accuracy comes from bolt variations in the apparent head-to-reflector-hole time measurement. The variations in composition, dimension, and forming stress are primarily confined to the head and shank areas. The multireflector instrument permits the removal of the head- and shank-area effects and minimizes the effects of bending.

The measurement technique has passed through a transition stage from instrumentation improvement to research data acquisition. The laboratory and field work, designed to measure bolt loads, has produced results only obtainable with ultrasonic measurement systems. The information acquired to date indicates that reliable measurements can be made on expansion anchor and all types of resin-grouted bolting systems (1, 7-8). The field data are often difficult to interpret because of the number of factors and influences that need to be considered in underground openings as well as geotechnical applications. As with any piece of geotechnical instrumentation, the operator's experience has a considerable effect on the success of the measurements.

CONCLUSIONS

The Bureau investigated P^2L^2 systems and pulse-echo systems to develop a system capable of determining the elongations and loads on bolts. The work on P^2L^2 systems was abandoned when it was discovered that accurate

measurement would require the creation of a stable nonresonant transducer that would be capable of transceiving a signal that precisely follows the driving frequency. The Bureau investigated several alternate

solutions and selected the pulse-echo system for bolt load determination. Two units have been developed and are immediately available for use. These units are the Raymond bolt gage and the Bolt Mike model S-1 measurement device. The units are capable of computing the round-trip travel time of an electronic pulse and converting the time into elongation. The Raymond bolt gage is capable of converting the travel time into elongation and stress values. The Bolt Mike model S-1 measurement device converts travel time into elongation, stress, load, and torque.

The use of an ultrasonic technique has many advantages over current research and industry practices: The accuracy

is high; the measurement is quick; one person can make the measurement with minimal physical strain; bolt anchorage is not disturbed; and partial- or full-column grouted bolts can be measured. The measurement reflects the true state of the bolt, independent of the bolting systems components, application of thrust, or installation method. The variability of the torque-tension relationship does not impact ultrasonic measurements. The technique, if developed to full industrial capability, has the potential to provide more meaningful bolt load data for research and mining practice.

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