

Geo-Measurements with Metallic TDR Cable Technology for Infrastructure Surveillance

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ABSTRACT

This paper reviews the new field of geo-measurement with metallic cable time domain reflectometry (TDR) for surveillance of transportation facilities. TDR is radar in a coaxial cable, and is especially advantageous for remote monitoring because of its inherently digital nature. Advances can be separated into those that leverage use of long cables as transducers- “along” technology and those that employ probes at the end of cables- “point” technology. “Along” applications have the unique advantage of monitoring all along long cables – sometimes as long as 1000 ft – for disturbances whose location cannot be predicted in advance. This application has been found particularly advantageous for remote monitoring of highways for mining induced subsidence, development of sinkholes, and landslides. It has also been found useful for monitoring of bridges for scour induced foundation movement and earthquake induced cracking of piers in inaccessible areas. Point applications leverage the “up-hole” or out of the ground location of the electronics to measure at the end of many cables from one instrument. This application has been found uniquely advantageous for measuring water content of subbase materials beneath pavements, porewater pressure in landslides and dams. Simultaneous measurement of water content and density is also under development.

A special focus is placed on the use of “along” technology for measurement of deformation. Two case histories are given that compare response of slope inclinometer and TDR cable for monitoring slope instability in rock and soil. Also included are guidelines for cable installation.

INTRODUCTION

In the 1970s TDR technology began to be applied with geomaterials. Subsequent development has led to its use in a wide variety of fluid measurements: soil moisture, subgrade water content and density, piezometric water pressure, leaking liquids, and contaminating fluids. TDR technology can also be employed in a wide variety of deformation measurement in rock or soil: bridge abutments, landslides, scour, coal mine subsidence, and sink hole formation. Now TDR technology is employed by soil & environmental scientists, geotechnical and agricultural engineers, as well as electrical engineers. Initial empirical methods of application in geomaterials have matured with scientific calibration and improved pulser samplers, cables, and sensors (1).

Essentially TDR is radar along a coaxial cable that can enable surveillance of large volumes with a single instrument. Distances to reflectors along the cable are calculated by time of flight, and characteristics of reflectors anywhere along a cable can be discerned from details of their respective reflected signals. The ability to interpret TDR reflections anywhere along the cable allows activity to be monitored over large volumes or areas and thus TDR monitoring may replace many single-point measurement instruments. This inherent surveillance advantage is propelling new applications of TDR in geomaterials for monitoring chemical spills, oil leaks beneath storage tanks, movement of rock in mines, and potential slope failures in soft soils.

To date, TDR's dominant application in geomaterials has been the measurement of moisture (or water content) of unsaturated soils. This application occurs at a probe at the end of the cable or two-wire transmission line. Thus, unlike "along the cable" applications, the probe locations must be chosen at the time of placement. Moisture (water content) measurements are made in soil for irrigation research and control, soil covers for landfills, base courses beneath highway pavements, bulk storage piles of minerals, and other granular materials where water content is important.

Detection of fluids is an emerging TDR application. Liquid interfaces produce significant reflections in hollow and porous cables, which can be easily detected. This observation has led to the use of TDR for leak and pollution detection along a selectively porous cable, which allows monitoring of large volumes with a single cable. In addition, fluid level detection techniques have led to use of TDR to measure water levels for hydrological purposes, as well as for measurement of water pressures beneath dams.

BASIC PHYSICS OF PULSE TESTING

There are a number of commercially available cable testers and the Tektronix 1500 series is a typical example. An ultra-fast rise time (200 psec) voltage step is launched into a test coaxial cable every 200 μ sec as shown in Figure 1a (2). When the pulses encounter a change in characteristic impedance (i.e., a cable fault), reflected pulses are returned to the cable tester.

Figure 1b is a block diagram of the TDR system. The TDR pulser generates a fast rise time step function. The step propagates through the sampling-receiver (tester) and through the coaxial cable of interest. The receiver uses an electronic sampling technique to produce a lower-frequency facsimile of the high frequency input. Many transmitted and reflected pulses are generated by the TDR in the time necessary to produce a scan. This scan is displayed as a reflection coefficient (i.e., ratio of reflected to transmitted voltage). This reflection coefficient has come to be measured in milli rhos (mrho), where one mrho is 1/1000 th the initial transmitted voltage. In older instruments, it was displayed on a cathode ray tube and photographed, or plotted on a x-y plotter, and the data could also be recorded on analog or digital magnetic tape for future signal processing. Today, this scan is recorded digitally.

The reflected signature may be analyzed along a long length of cable to monitor behavior in a large volume OR over a short length to monitor behavior at a point in a probe geometry. The "along" a length approach employs a cable as a transducer for monitoring deformation and detecting leaks at locations that cannot be predefined. The "at a probe" approach employs probe rods as transducers for measuring moisture content and contaminants at predefined locations. The time delay between a transmitted pulse and the reflection from a change in the cable's capacitance (geometry or material between inner or outer conductors) uniquely determines the fault location. Additional information can be obtained

by analyzing the sign, length, and amplitude of the reflection coefficient signatures which define the type and severity of every change either “along” or at a “probe”.

ROCK AND SOIL DEFORMATION

TDR technology provides a compliment to slope indicator technology. TDR cable surveillance by its digital nature is automatically accomplished remotely and in addition is able to detect very thin or localized shear zones. On the other hand slope inclinometers have been employed successfully, are inexpensive to install, and are sensitive to small, non-localized shearing strains. Use of a combination of TDR and inclinometer or tiltmeter technology would allow both remote operation as well as sensing both gradual tilt and localized deformation. TDR technology is employed to monitor rock mass deformation in dozens and perhaps 100's of mines worldwide. It is less well known for its use in soil and landslides

Installation Details for Deformation Measurement Along Grouted Cables

As shown in Figure 2, the TDR cable must be grouted in its own hole and the grout must fracture early so that the cable can be deformed as movement occurs within the surrounding soil (3). There continues to be a strong tendency strap easily purchased braided coaxial cables to the outside of slope inclinometer casing in larger holes to save money and drilling costs. Unfortunately the braided cables when coupled to inclinometer casing have not performed well. This underperformance is probably the result of low sensitivity of the braided cable and smearing of the localized shear zone by the casing.

Appropriate grout strengths may vary considerably. However, grouts for both soil and rock can be tremmied into place with the drilling rig's own grout pumps: even the thicket and strongest grout. It is not necessary to employ additional grouting equipment. Early installations employed very strong grouts that were developed for rock installations. More recent installations have employed cement-bentonite grouts with unconfined compressive strengths that are only 2 to 3 % of those used for earlier installations in uniform materials. For installation in rock, this consideration is not important because the relatively high strength and stiffness of rock. In order to maximize cable/grout composite sensitivity in soil, it is logical that the shear capacity of the grout should be less than the bearing capacity of the soil just outside the localized shear plane as will be discussed below.

CommScope coaxial, 22 mm diameter cable, with a solid aluminum outer conductor (P3-75-875-CA) has performed satisfactorily at sites where the deformation occurs in fractured rock. . Based on laboratory tests, the grout has a stiffness of 88 MPa and a shear strength of 1.6 MPa. The landfill case described below indicates that the sensitivity of this 22 mm cable installed in small diameter (100 mm and smaller) holes with weak grout responds satisfactorily even when installed in soft to medium strength clay.

Cable Response to Transverse Shear and Extension

Laboratory tests by Su (4) show that cables respond differently to extension and shear. Su grouted cables into pipes, which was later cut, and either pulled (extended) or sheared until first the uncut grout and then the cable failed. Reflection signatures in Figure 3 produced at increasingly larger extension (3a) and shear (3b) displacements show that extension failure produces a broader, smaller amplitude reflection. Shearing produces a narrower, larger amplitude reflection. These reflections can be located anywhere along the cable and still be quantitatively interpreted. The insets show the differences in the geometry at the failed ends of the cable. Extension does not produce as severe a change in the distance between the inner and outer conductor of the coaxial cable. This observation is consistent with the smaller reflected signal associated with extension failure

Road Distress in Rock and Retrofit of Inclinometer Casing

Distress in a limestone causeway supporting a major highway presented an opportunity to compare TDR and inclinometer response. Movements had been occurring since December of 1997, and an instrumentation program was formulated to determine the cause of movement. Among the instruments

installed to monitor subsurface movement were inclinometers and coaxial cables. Comparison between TDR and inclinometer measurements in Figure 4 shows consistent response at a depth of 76.5 m. Movement at this depth occurred within a zone of greater fracture density in the limestone. The reflections at depths of 113 m and 119 m were caused by movement along dolomite-shale contacts. The TDR reflections at a depth of 76.5 m between 6/24/98 and 8/7/98 indicate that the reflection grew by 58 mrhos (58/1000 th in transmitted voltage).

The growth in inclinometer incremental displacement at this depth, over the same time period, was 12.4 mm so the sensitivity was 58 mrho/12.4 mm or approximately 5 mrho/mm. The comparison is made with slope inclinometer *incremental displacement*, which is the local inclination of the probe or the local shear strain as measured over the 60 cm wheel base of the probe. This local inclinometer “tilt” is employed for TDR comparison because the TDR measures localized shearing. When the reading was taken on 8/19/98, it was found that the cable had been sheared off at this depth.

Kinking of the inclinometer casing provided an opportunity to demonstrate the use of TDR technology to extend the useful life of this casing. On 3/2/99 it was not possible to lower a probe down past a depth of 75.6 m in the adjacent inclinometer hole, and on 6/25/99 this inclinometer casing was retrofitted with a grouted coaxial cable to continue monitoring. Ultimately, five of the eight original inclinometer casings were retrofitted with grouted coaxial cables, TDR waveforms acquired after retrofitting show that it has been possible to continue monitoring movement at this depth below the kinked inclinometer casing.

Landfill Slope Deformation on Soft Soil

Deformation of an industrial landfill presented an opportunity to compare inclinometer and TDR response in soft soil. The landfill rests on 1 m of silt and sand, underlain by 9 to 12 m of soft clay, which in turn is underlain by stiffer clay. In accordance with the current standard of practice, inclinometers and piezometers were installed to define the extent of the deformation and monitor effective stress changes. As a field trial of TDR technology to detect and quantify shear within soft clays, coaxial cables were installed in boreholes adjacent to two of the inclinometers.

Response of a CommScope coaxial, 22 mm diameter cable, with a solid aluminum outer conductor (P3-75-875-CA) grouted with a compliant cement bentonite grout is shown in Figure 5. The lower bulge in the inclinometer incremental displacements indicates that subsurface deformation occurred within a shear zone at a depth of approximately 30 m within the soft clay. As shown by the 5 mrho reflection at a depth of 22 m, deformation of the coaxial cable first occurred on 7/10/98 at this depth which is the contact between the fill material and underlying layer of silt and sand. On 8/19/99, a spike of 8 mrho appeared at a depth of 28 m and a second spike of 23 mrho at a depth of 31 m. At both depths, the inclinometer incremental displacement was 2.6 mm. These responses yield a sensitivity of 8 mrho/2.6 mm = 2.7 mrho/mm and 23 mrho/3 mm = 7.7 mrho/mm.

The two lower TDR spikes bracket the depth of the shear zone hypothesized by the slope inclinometers at this and several other locations. These responses verify the hypothesis that the TDR cable will kink and thus produce reflected signals at locations of large relative shearing. The relative strength analysis in the section above demonstrates that the design of the grout is an important consideration for use of TDR cables in soft soil.

Compliant Grouts for Soft Soils and Cable-Grout Interaction

As shown in the example above, it is important that the grout be stiff enough to kink the cable as the soil mass deforms, but not so strong as to fail the soil beyond the shear zone as it moves past the cable. There should be little plastic deformation of this soil adjacent to the localized shear zone or band so that the shear band in the grout is as sharply defined as possible. The more abrupt the boundary between the upstream and downstream passive resistance zones in the soil, the narrower the fracture zone within the grout, the sharper the kink within the cable, and thus the larger will be the reflected TDR voltage signal per unit shear deformation.

An estimate of the proper grout strength to meet the above goals can be estimated by balancing shear forces within the grout with that allowable in the sliding mass adjacent to the shear zone requires that the sliding mass bearing resistance be estimated. Bearing capacity factors for deep foundations as well as those for anchors deeply buried in soft clays provide guidance in the matter. The bearing capacity or resistance of the sliding mass adjacent to the shear zone can be calculated as a function of its shear strength, S_{us} . Based on two-dimensional plastic analysis, the bearing capacity of cohesive soil (clay) is 9 times the undrained shear strength. Three-dimensional studies of the extraction of isolated circular and square anchors in clay (5) revealed that bearing capacity may be as high as 14 times the undrained shear strength. If it is assumed that this resistance is distributed equally along the cable/grout composite for an axial distance of one hole diameter, D , then it will act over an area of D^2 . Thus, the maximum soil bearing resistance or capacity is

$$(9 - 14) S_{us} D^2 \quad (1)$$

The shear force within of the grout can be estimated as the borehole area times the shear strength of the grout, S_{ug} ,

$$S_{ug} \pi D^2/4 \quad (2)$$

Equating (1) and (2) then allows an estimate of the maximum strength of the grout that can be employed relative to that of the soil to preserve the narrowest or "true" width of an intersecting shear zone

$$(9 - 14) S_{us} D^2 = S_{ug} \pi D^2/4,$$

thus

$$S_{ug} / S_{us} = (4/\pi) (9-14) = 11 \text{ to } 18 \quad (3)$$

This estimate can be checked for reasonableness by comparing the properties of the soil and grout for the landfill case history below. In this case soil shear strength was 0.0125 to 0.025 MPa and the grout shear strength was 0.25 Mpa for the responding cable. Thus the ratio of grout to soil shear strength was 10 to 20, which is similar to that estimated from the force-balance considerations above.

SOIL MOISTURE

TDR sensitivity to changes in the dielectric constant of material between two conductors has been adapted to the measurement of moisture content. The success of this measurement technique with unsaturated soils has led to its widespread adoption in agricultural study, irrigation control, and the study of unsaturated particulate material in general. The dielectric constant, $K = \epsilon/\epsilon_0$, of air is 1, ranges from 3 to 5 for most soil mineral grains, and is approximately 81 for water (at 20EC). Thus, a small change in moisture content of unsaturated soils will have a significant effect on the bulk dielectric constant of the air-soil-water medium. The apparent dielectric constant is obtained by measuring the time for a voltage pulse to travel along the probe and return

Measurement of Dielectric with Parallel Rods

The TDR technique of measuring electrical properties of materials was introduced by Fellner-Feldegg (6) using alcohols in coaxial cylinders. Topp et al. (7) extended this application to earth materials by using TDR to determine the volumetric water content of soils in coaxial sample holders. The coaxial cylinders were not suitable for field measurements, so Topp and Davis (8) used a transmission line consisting of parallel rods based on the work of Davis and Chudobiak (9). The TDR trace, as displayed on the oscilloscope screen, develops as follows: the cable tester applies a fast rise-time voltage step to the 50-ohm coaxial cable and triggers a sampler. The step pulse travels down the coaxial cable, through an impedance-matching transformer (or balun), and into a shielded two-wire television cable (a balanced line). The signal traveling in the ground ultimately reaches the end of the rods, sending a reflection back toward the cable tester (10). By repeating this process many times, a stable waveform is developed as shown in Figure 6. This waveform reveals the time (t) between arrival of reflections from the soil surface and from the end of the rods, and the magnitudes of these reflections (V).

Field Experience and Verification of Soil Moisture Measurement

The viability of TDR to measure water content of soils must be assessed by comparison with other techniques commonly employed. This chapter presents such comparative studies with lysimeters, Bowen ratio, neutron probes, and nuclear density gages. For the most part, these comparisons have been made with partially saturated soils. One such comparison, Shown in Figure 7, with a nuclear moisture gauge was conducted by Queensland Transport for granular subbase (11)

Soil Density and Moisture

Drenvich (12) and his coworkers have developed a two "coaxial cable" method of determining both insitu density as well as water content. Driving four vertical metal "spikes" into the soil defines the dielectric volume of for the insitu sample. The second dielectric volume is produced by driving a metal rod into the center of a metal compaction mold filled with the same soil. The same probe head measures the "apparent dielectric constant" for both the "insitu" and "mold" samples. If the soil in the compaction mold is the same soil and has the same water content as the insitu soil, then the density can also be determined.

PORE PRESSURE, LEAKS AND DIFFERENT LIQUIDS

Surveillance of Landslide Water Pressures with TDR Cables

Water pressure measurements of importance to landslide surveillance can also be made with TDR. Water interfaces along a hollow or air-dielectric coaxial cables produce very large voltage reflections because of the large difference in dielectric constants for air (1) and water (81). Thus commercially available air-dielectric cables can be inserted into stand pipe piezometers to measure water level within the riser pipe. The reflection at the air-water interface is illustrated in Figure 8. With no water the signal remains constant (point b to point d) until the end of cable is reached and a positive reflection (point d) occurs due to the open circuit. However, if the air-dielectric cable is partially immersed in water, a negative (downward) reflection (point c) occurs at the air-water interface because of a change in impedance at the interface. The signal remains constant until the end of cable is reached (point f), where a positive reflection occurs

The impedance mismatch at an air-water interface is so large that it can be measured using a half-sinewave TDR pulse. Compared with the step pulse used to acquire the waveforms for deformation monitoring, a half-sinewave pulse has the distinct advantage of reduced attenuation with distance by virtue of the lower frequency content of the pulse. Also, the pulse amplitude launched by commercially available half-sinewave TDR units is one or two orders of magnitude greater than the pulse amplitude launched by step-pulse TDR units. Thus, air-water interfaces can be detected along cables that are thousands of meters in length. This advantage has been demonstrated by retrofitting an existing piezometer at a U. S. Army Corps of Engineers dam with an air-dielectric cable (1).

Detection of Leaking Liquids

PermAlert has developed the system shown in which TDR is used to monitor leaks along specially designed cables or sensor strings. The initial TDR reflections are specific to the condition of the installed sensor cable and are stored in memory as a reference map. An alarm unit continuously updates the TDR reflections and compares them with values of the benchmark TDR waveform stored in memory. When a leak occurs, the liquid wets the sensor cable, which alters the cable's impedance at the leak location. .

Different sensor cables are capable of detecting and locating both water-based and hydrocarbon liquids, while others will detect only hydrocarbons, ignoring water. In most applications, the sensor cable can be dried and reused after a leak is repaired and clean-up has been completed. State-of-the-art "gold cables" have no exposed metal and are designed for corrosive chemical applications. Sensitivity is the length of sensor cable that must be wetted with a specific liquid before an alarm condition occurs, and is a function of sensor string length. .

Detection of Contaminants

Arrival of contaminants can be detected by TDR probes by measuring the magnitude of the reflection produced by a change in the conductivity of the fluid as shown in Figure 9. Normally, water content is measured through differences in the transmission time of the reflection. Thus this approach employs the second measurable parameter obtained from a probe reflection. In order to compare the TDR determination of changes in the conductivity of the fluids values Dalton et al. (13) brought ten soil columns to equal water contents, using waters of ten different conductivity values. Twenty-five days after infiltrating each column with waters of known electrical conductivities, they made TDR measurements and typical waveforms are shown in Figure 8. As shown, reflection amplitudes (V) are inversely proportional to the conductivity, σ .

SOIL-STRUCTURE DEFORMATION

Scour

Cable systems employed to monitor soil and rock deformation can be employed to monitor footing or abutment movement resulting from scour as illustrated in Figure 10. As illustrated the cable is extended from the tester, down along the pier, and into a hole drilled through the footing and foundation material. The cable is incased in grout from the bottom of the hole to the top of the footing. A protective pipe encloses the cable from the top of the footing to the bridge deck to protect the cable from flood born debris.

If scour occurs in such a location and depth to produce lateral movement of the footing, localized shearing will occur at the foundation soil-footing interface as shown. Cable deformation would occur after the grout fractured, and this deformation would produce a detectable TDR reflection. Shearing deformation of metallic cable as small as several millimeters would produce a reflection that could be employed to trigger an alarm system. Such a system has been combined with a TDR based water depth cable and several tilt meters to monitor the performance of a CALTRANS scour critical bridge.

Earthquake Response of Bridge Piers

TDR cables offer a means of quickly detecting cracking damage of reinforced concrete structures caused by earthquake shaking. The cables could be left in place for decades and then probed after earthquakes. Among the more critical structures are bridge piers that support elevated sections of roadway

To study the usefulness of TDR cable response as an index of cracking of concrete produced by earthquake deformation but hidden from view, prototype reinforced concrete bridge columns were fitted with vertical and transverse TDR cables at the base near reinforcement splices and subjected to cyclic lateral loading (15). As shown by the inset in Figure 11, columns were 3.66 m (12 ft) high and 0.6 m (2 ft) in diameter, with vertical steel reinforcing bars were spliced through the bottom 1 m (3 ft) of each column. Two cables were vertically aligned to primarily monitor tensile deformations at the column-base interface, and two cables were installed transversely through the column diameters perpendicular to the vertical cables to monitor shearing between the spliced reinforcement. The dashed lines in the inset mark cable segments encased in concrete; solid lines represent the exposed lengths of cable. Each vertical cable passed through the base beam and exited on one side. Both ends of each transverse cable were exposed to allow interrogation from either end with a TDR pulser.

Response of the cables is compared with the load deformation behavior of the one of the test columns in Figure 11. Column response to cyclic loading is shown by the comparison of maximum horizontal load sustained by the column vs. the maximum lateral displacement at the top of the column. Cable response is shown by the reflection coefficients along the transverse (horizontal) cables produced by faulting cracks at the associated column displacements. Detectable TDR reflections did not occur until after peak loading had occurred. The largest reflections occurred at the lowest cable, that nearest the splice connecting the beam and column reinforcement.

WEB SUPPORT

TDR research and application is supported extensively on the Internet. The Infrastructure Technology Institute at Northwestern University maintains a TDR clearinghouse that contains full text copies of articles, addresses of vendors, and links to related technology and a listserve. It can be reached at

<http://www.itn.northwestern.edu/tdr/index.html>

Selected contents of the Proceedings of the 1994 First International Symposium on TDR Applications in (16), and the entire Proceedings of the 2001 Second International Symposium on TDR Applications (17) are available at this site

In addition there are several list servers that facilitate dialog among TDR specialists. ITI supports a general list server for all aspects of TDR use at

TDR-L@listserv.acns.northwestern.edu

There is another list serve that addresses the needs of researchers involved principally in monitoring soil water content at

owner-sowacs@aqua.ccwr.ac.za

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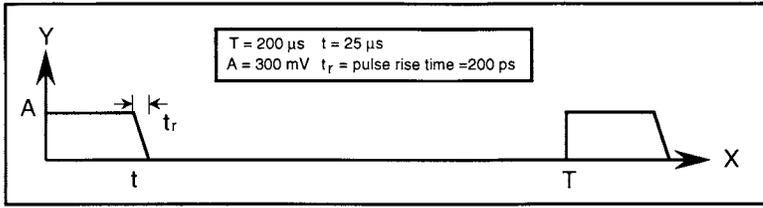
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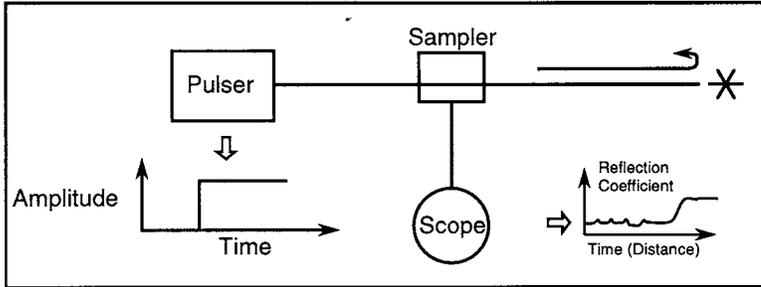
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a)



b)

FIGURE 1 Basic components of TDR cable tester; (a) nominal pulse waveform; (b) operating principle and system components (1).

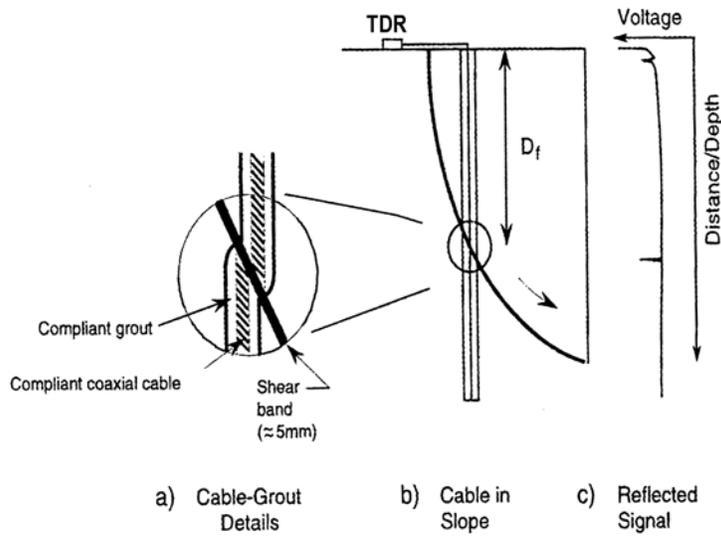


FIGURE 2 Landslide shear zone kinks cable grouted into sliding and stable masses, which produces a reflection signal at the depth of the shear zone.

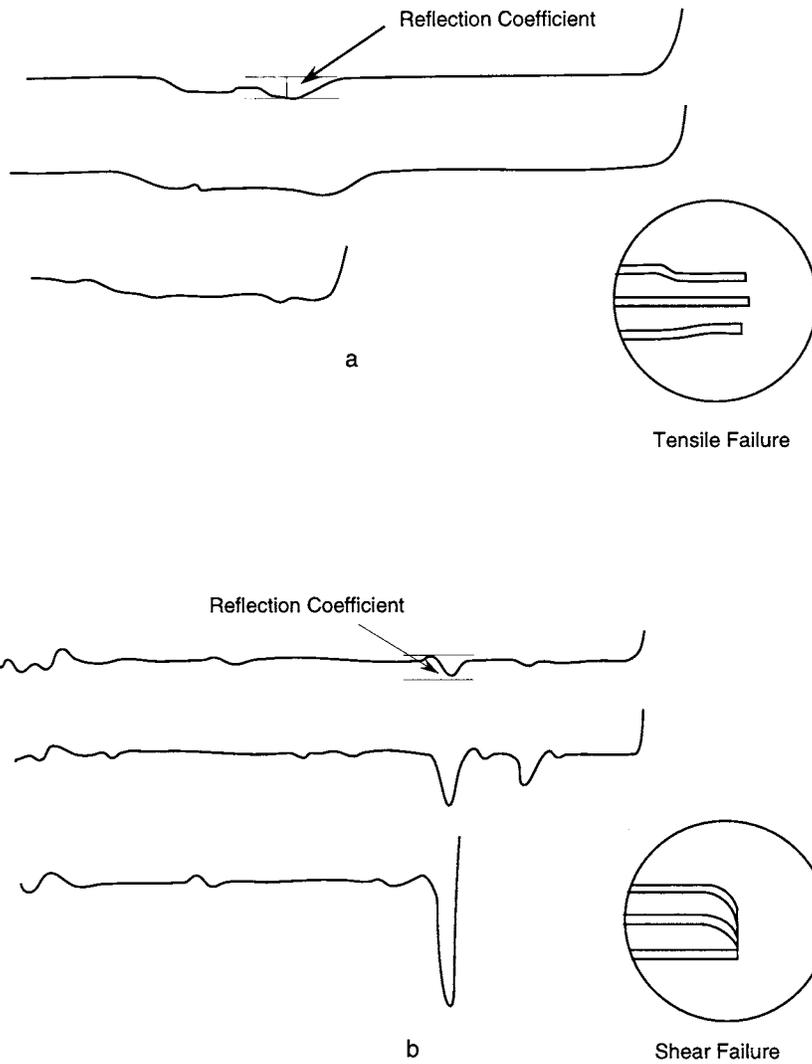


FIGURE 3 Comparison of reflection signatures produced by increasing deformation of cables that are extended (pulled) and sheared. Inset shows differences in the cable shape at failure for the two conditions.

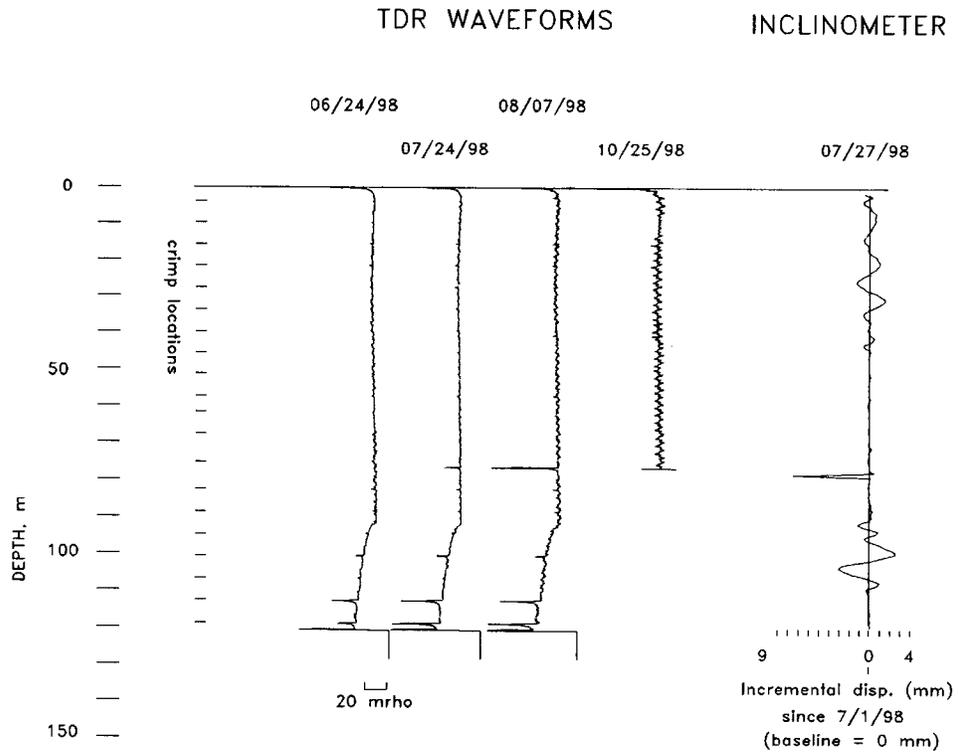


FIGURE 4 Comparison of TDR waveforms and inclinometer incremental displacement in deforming rock mass where joint displacement is shown by a single TDR reflection.

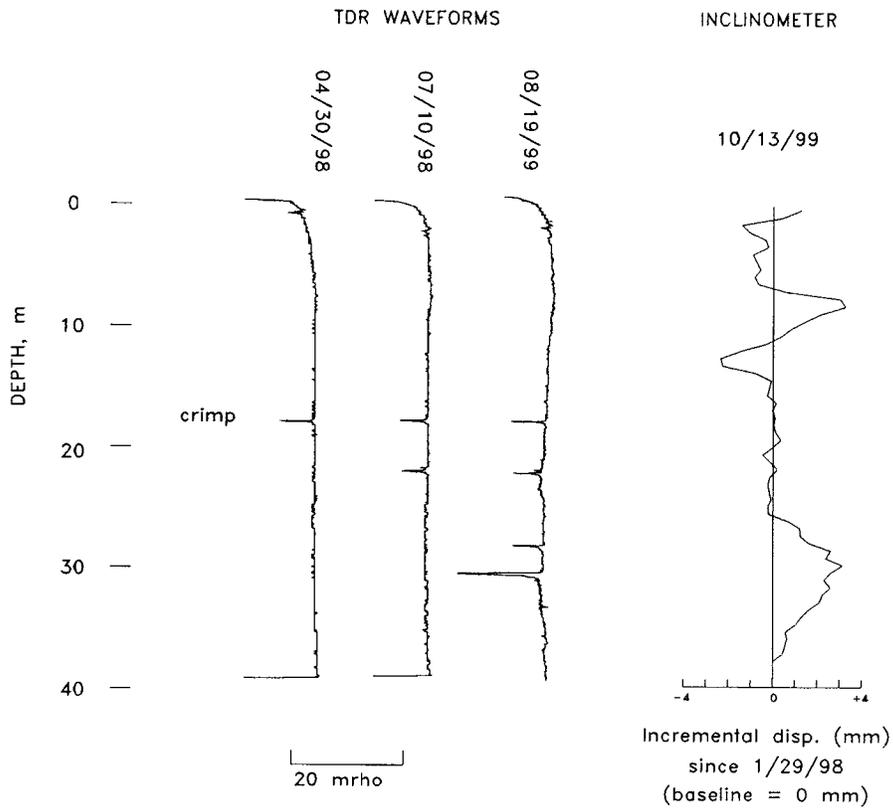


FIGURE 5 Comparison of TDR waveforms and inclinometer incremental displacement in deforming soft soil mass where the shear zone is outlined by two TDR reflections.

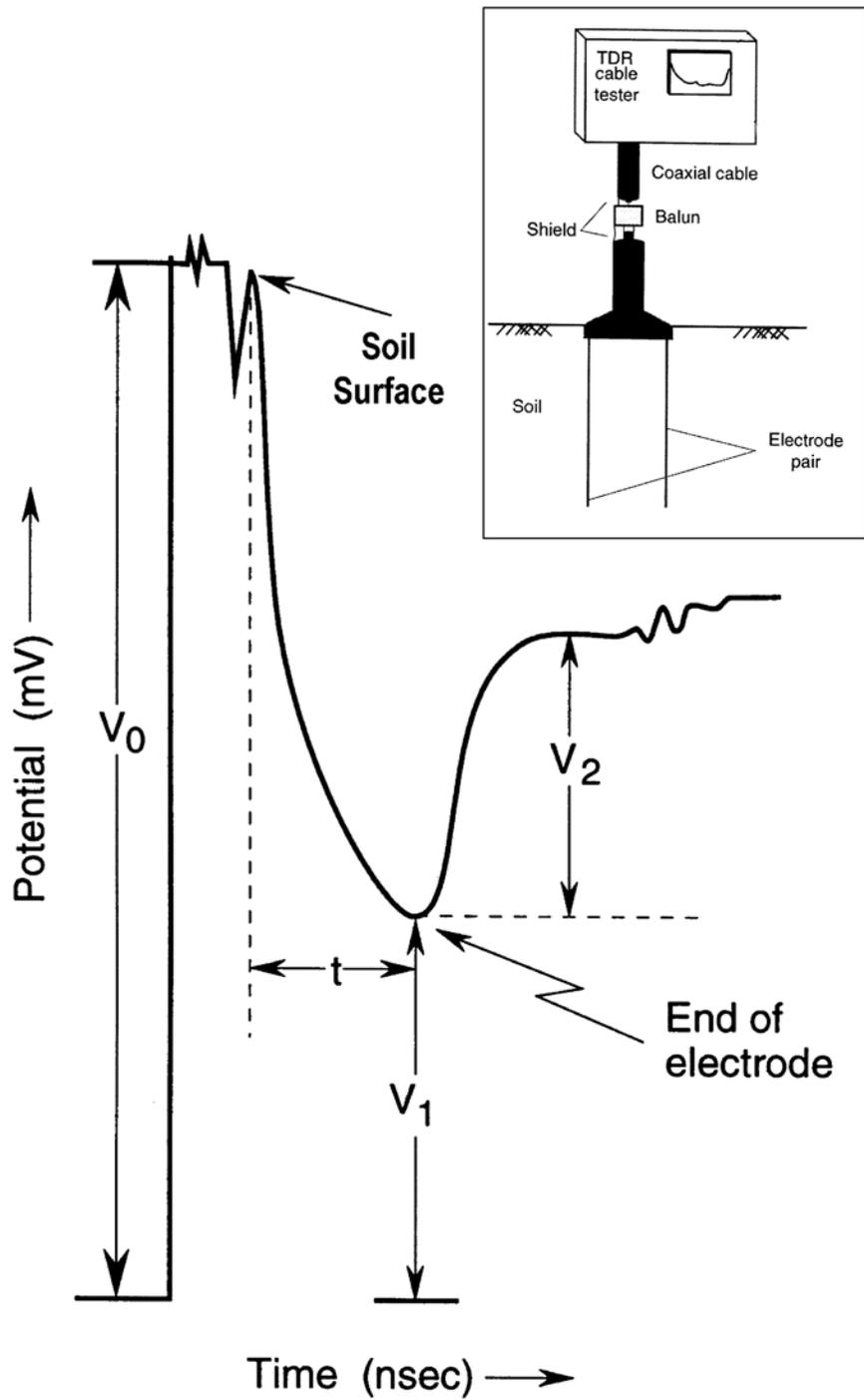


FIGURE 6 Two rod TDR soil moisture probe (insert) and resulting waveform: output voltage, V_0 ; voltage transmitted along probe, V_1 ; time for pulse to travel along probe and return, t ; and reflected voltage, V_2 (13).

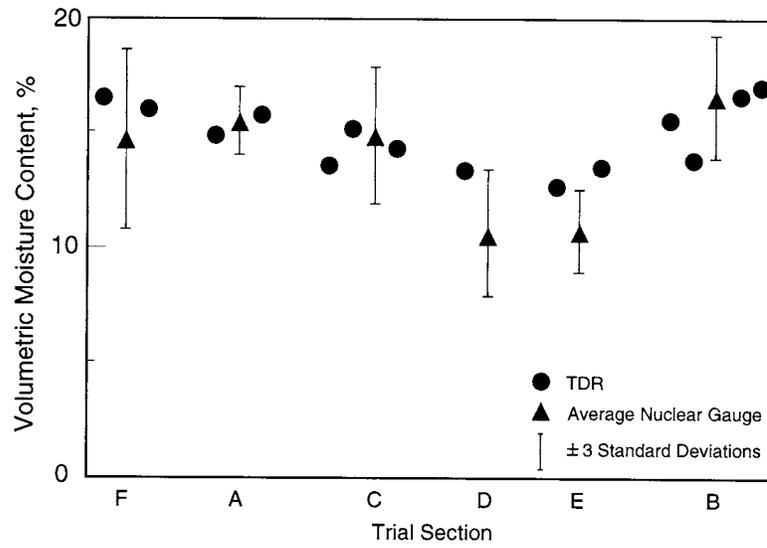


FIGURE 7 Comparison of moisture content as measured by TDR probe and nuclear moisture gauge (10).

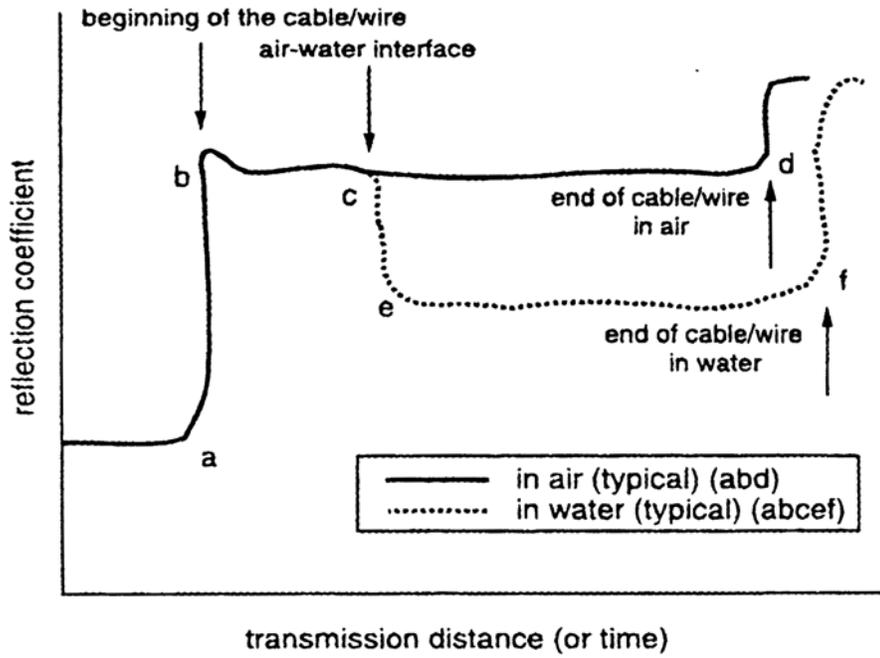


FIGURE 8 Signature of TDR reflection off air-water interface, which shows the very large reflection compared to that produced by cable deformation.

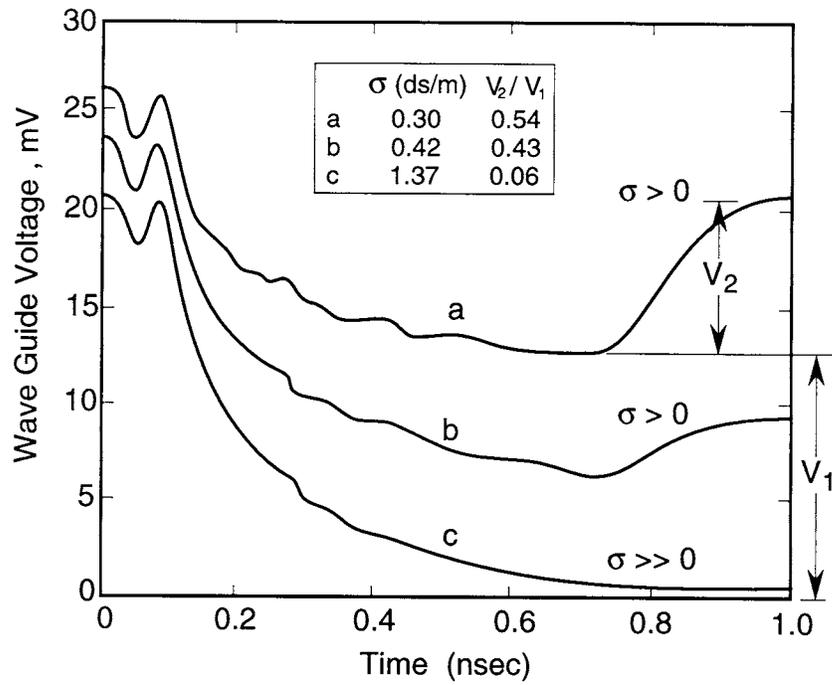


FIGURE 9 TDR signal attenuation in conductively contaminated media showing effect of increasing conductivity (13, 14).

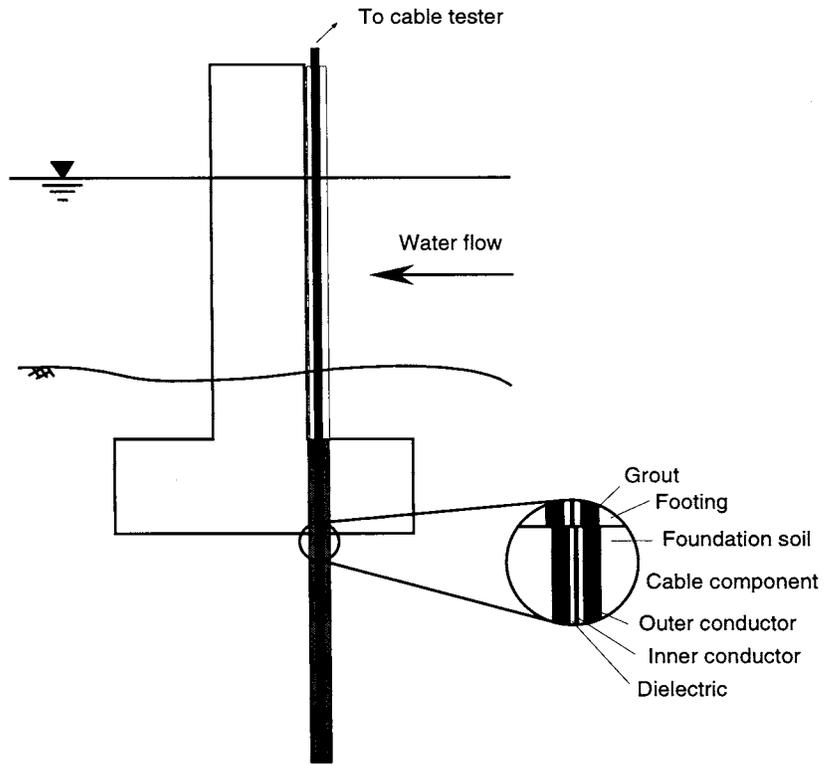


FIGURE 10 Placement of TDR cable through bridge footing to monitor scour induced lateral displacement.

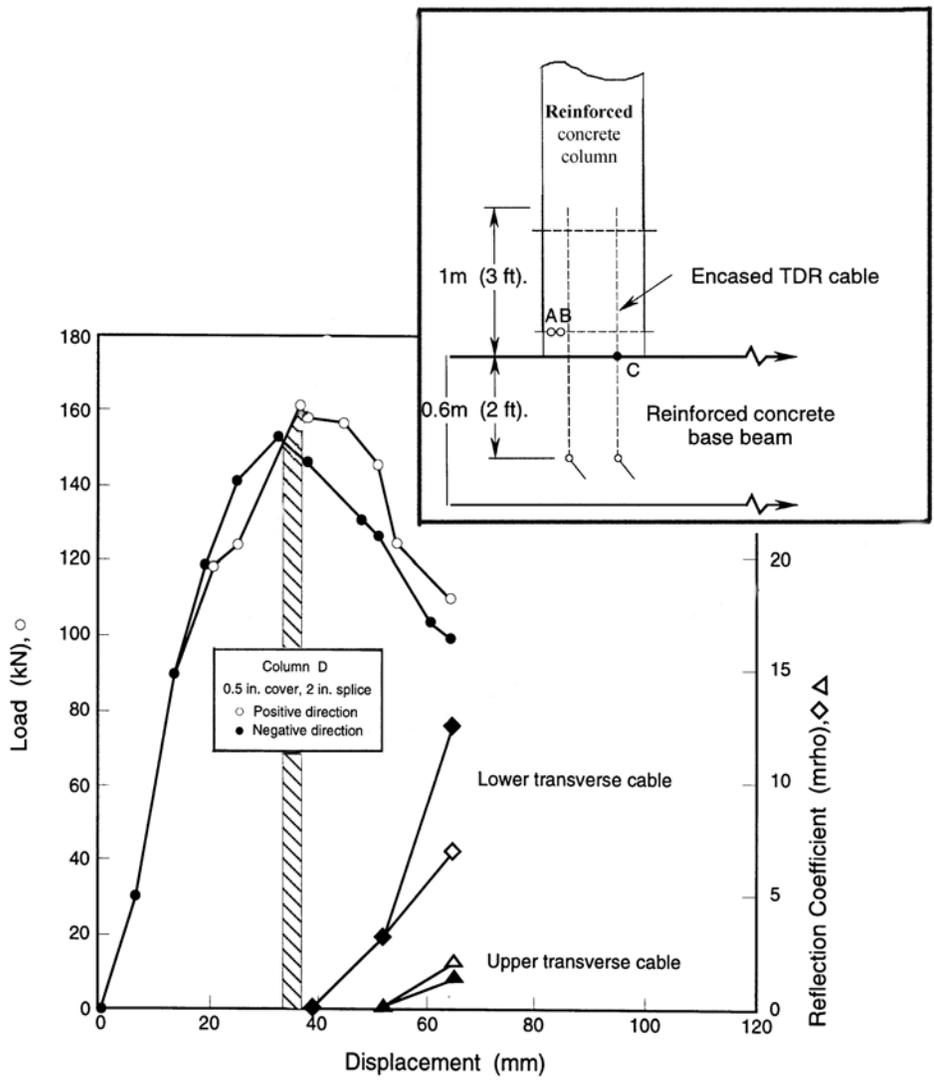


FIGURE 11 Coaxial TDR cables installed in a prototype reinforced concrete pier (insert) and comparison of column load-displacement response with crack induced TDR reflections near the column-footing splices.