Monitoring Deformation in Rock and Soil with TDR Sensor Cables

Part 1. Concept and Case History

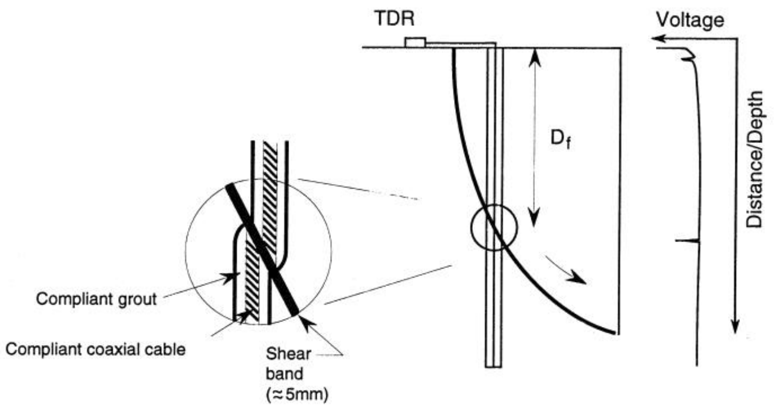
Charles H. Dowding
Matthieu L. Dussud
William F. Kane
Kevin M. O'Connor

Historical Background

Time Domain Reflectometry (TDR) is a remote sensing electrical measurement technique that has been used for many years to determine the spatial location and nature of various cable faults. In the 1950s TDR technology was adapted to locate and identify faults in power and communication cables. As a result, TDR cable testers are considered standard equipment in these industries. In the 1970s TDR technology began to be applied to geomaterials and has been adapted for use by soil scientists, agricultural engineers, geotechnical engineers and environmental scientists. This article concentrates on the geotechnical application of monitoring subsurface deformation in soil. If there is sufficient interest, future articles in GIN could focus on use of TDR for monitoring moisture content and pore water pressure.

TDR Concept and Cable Installation

In concept, TDR is similar to radar along a cable. As shown in Figure 1b, a voltage pulse, produced by a TDR pulser, travels along a two-conductor coaxial metallic cable until it is partially reflected by deformation of the cable. The distance to the deformation can be calculated knowing the propagation velocity of the signal in the cable and the time of travel of the voltage pulse from the disruption to the cable tester. As shown in Figure 1a, a cable is grouted into a borehole, then rock or soil movement shears the grout and deforms the



a) Cable-Grout Details b) Cable in Slope c) Reflected Signal

Figure 1. Shearing mechanism and induced reflection on a grouted TDR sensor cable

cable, which changes the geometry (thus impedance) between the inner and outer conductors. This change in impedance produces the reflected voltage pulse shown in Figure 1c. The travel time of the reflected pulse determines the location of the shearing zone. The amplitude of the voltage reflection is proportional to the amount of cable deformation that is correlated with the rock or soil movement.

Initially, TDR was geotechnically applied to monitor rock mass deformation, which occurs predominantly along joint interfaces (Dowding et al., 1988). The large stiffness of rock and the high degree of strain localization along rock joints allow installation of stiff cable with standard drilling and grouting procedures. As a result, the technique has been adopted worldwide by the mining industry.

At the opposite end of the spectrum of geomaterials, the low stiffness of soft soil and the relatively small strain localization in the early stages of failure in soft soils, complicate the application of TDR technology. For TDR to be effective in soil, a shear band must occur to produce the localized strain necessary to locally deform the cable. Deformation occurring along a shear band in soil must be transferred to the cable through the grout. Thus, the composite soil-grout-cable must faithfully transfer the relative soil displacement to the cable. Ideally the grout should be no more than 5 to 10 times stronger than the surrounding soil (Blackburn, 2002). A grout that is too strong may not fail with the soil and thus smears or widens the shear band, whereas a grout that is too weak will not kink or distort the cable.

A coaxial cable consists of a solid core (inner conductor) and a cylindrical shield (outer conductor), separated by a dielectric such as foam polyethylene. As shown in Figure 2, two main types of coaxial cables are recommended for TDR application. Bare solid aluminum or copper outer conductor cable are the most common types; however, more compliant copper braid outer conductor cables are also being developed for use in soft soils (Cole, 1999). At this time, the stiffer cables are commercially available while the compliant cable is under development and fabricated manually in short lengths.

Grout for TDR cable installation is typically a lean cement mix with the bentonite and water content adjusted to achieve various compressive strengths. Ideally it's viscosity should be low enough to be pumped with a drill rig water pump, but it is common to use a grout pump. The viscosity can be reduced (fluidity increased) by introducing additives such as Intrusion Aid R, which also acts as an expansion agent to reduce shrinkage. Refer to Mikkelsen (2002) for an excellent discussion of grout mixing procedures and strength, as well as field crew errors in using grout mixes with higher water content and bleeding.

For best results, the cable should be installed in its own dedicated borehole and the grout must be strong enough to shear the cable, but weak enough to be failed by the surrounding soil, (Pierce, 1998). For installation in rock, this relative strength and stiffness consideration is not important because of the relatively high strength and stiffness of rock. In order to maximize cable/grout composite sensitivity in soil, it has been hypothesized that the shear capacity of the grout should be less than the bearing capacity of the soil just outside the localized shear plane. This may be as high as 5 to 10 times the shear strength of the soil. Installations in soft natural soils and fills indicate the need to carefully calibrate the stiffness of the grout with the soil. More research is needed in this regard.

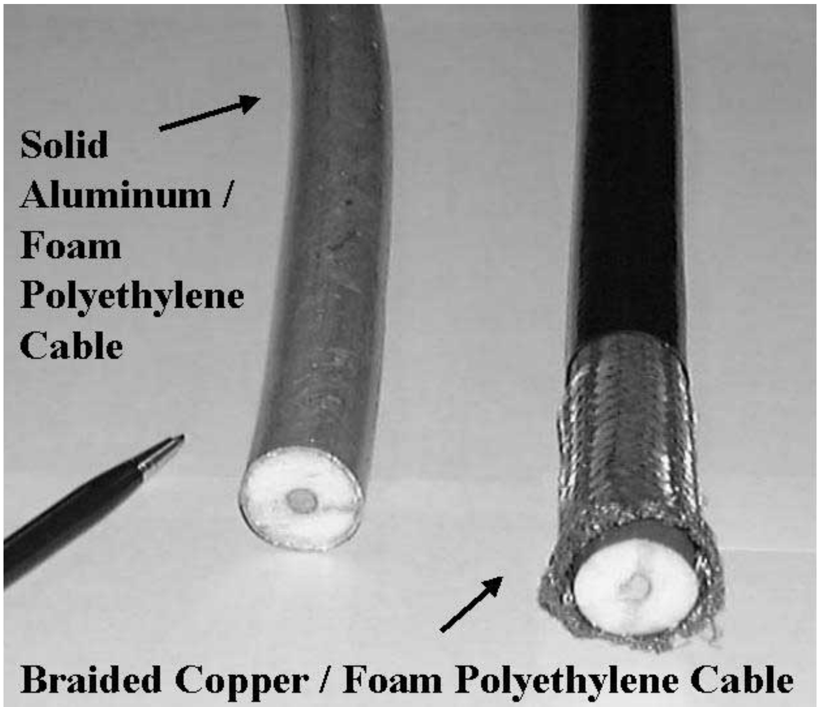


Figure 2. Two most common types of coaxial TDR sensor cables.

Deformation Modes

Crimping and localized shearing of a coaxial cable will produce a distinct TDR reflection spike such as the one in Figure 1c. If the cable is severed by shear, there is a large positive reflection immediately following the negative spike.

If the cable is simply cut off with a saw or severed in tension, there will not be a negative spike preceding the large positive reflection. Consequently, in cases where TDR has been used to monitor strata movement in mines it has been possible to determine if the strata separate in extension or shear at joints or rock mass discontinuities. It has also been possible to quantify the tensile deformation by monitoring changes in distance between crimps made in the cable prior to installation in drill holes (O'Connor and Dowding, 1999).

Correlation Between TDR Reflection Magnitude and Inclinometer Displacements in Soil

TDR technology provides a method of deformation measurement that can be employed as a complement to, and comparison with, inclinometer measurements. The two technologies have different advantages and disadvantages. For brevity, the present discussion concentrates on the issue of localized shearing.

Inclinometers and TDR sensor cables respond differently when subjected to localized shearing. TDR sensor cables are most sensitive to highly localized shear, and have been found especially useful in rock where deformation occurs along thin joints. On the other hand, inclinometers are more sensitive to general shear or gradual changes in inclination. Localized shearing of inclinometer casing causes it to kink so it cannot be profiled with an inclinometer probe. Thus in situations involving both general shear and localized shear, the two technologies respond differently. These differences have been documented for four cases in "Comparison of TDR and Inclinometers for Slope Monitoring" (Dowding and O'Connor, 2000).

There are two alternative methods of evaluating inclinometer response: 1) total displacement or deformation profile of the casing, and 2) incremental displacement or slope of the deformation profile. Dowding and O'Connor (2000) compared inclinometer incremental displacement (IID) with TDR reflection magnitude. IID is also the inclination of the inclinometer probe, and therefore a measure of the local shear strain.

The difference in response of these two approaches results from the span over which relative displacement is measured. IID is the change in angular displacement every 60 cm (2 ft) which is the wheel-base of the standard inclinometer probe. Thus a IID of 1 mm over 60 cm (0.04 in. over 24 in.) is a slope or shear strain of 0.0017. However, this shear strain is averaged over a distance of 60 cm (24 in), which is a fairly large gage length when measuring localized shear within a discrete plane or shear band.

Conversely, the sensitivity of TDR sensor cables decreases as the shear zone increases from a thin band to a large mass undergoing general shear. O'Connor et al. (1995) reported that reflections decline by a factor of 2 when the thickness of a shear zone in the laboratory was increased from 1 mm to 40 mm, and declined by a factor of 20 when the shear zone thickness was increased to 80 mm. Thus these data could be interpreted to imply that the TDR sensor responded optimally to localized shear zones with thickness of 1/100 to 1/10 times the gage length of an inclinometer.

Example Comparison: Landfill Slope Deformation

A case history involving slope movement that occurred in an industrial landfill provides a useful comparison between inclinometer and TDR response in soil. The slide mass was some several hundred meters long and tens of meters high. As shown by the soil profile in Figure 3, the landfill rests on a very thin layer of silt and sand which is underlain by 9 to 12 m of soft, glacial lake clay, and a lower stiffer clay.

In accordance with standard geotechnical practice, inclinometers and piezometers were installed to define the extent of the slide mass and assess the effective stress within the failure "plane." As a field trial of TDR technology to detect and quantify shear within soft clays, an aluminum outer conductor coaxial cable was installed in a separate borehole 35 m from an inclinometer.

The lower bulge in the IID profile at the right of Figure 3 indicates 3 mm of incremental subsurface deformation within a shear zone at a depth of approximately 30 m within the soft to medium stiff clay layer. This depth corresponds to the zone of maximum total displacement adjacent to the IID. As shown by the 07/10/98 TDR record, there is a 5 mrho reflection spike just below the distance-calibration crimp at a depth of 22 m. This is the interface between the fill material and the underlying soft clay layer. A year later, TDR reflection spikes appeared at depths of 28 m and 31 m. These reflections are located within the bulge in the IID profile between depths 27 m and 37 m. The large IID at 8 m depth may correspond with a sliding block boundary that did not intersect the TDR cable as the

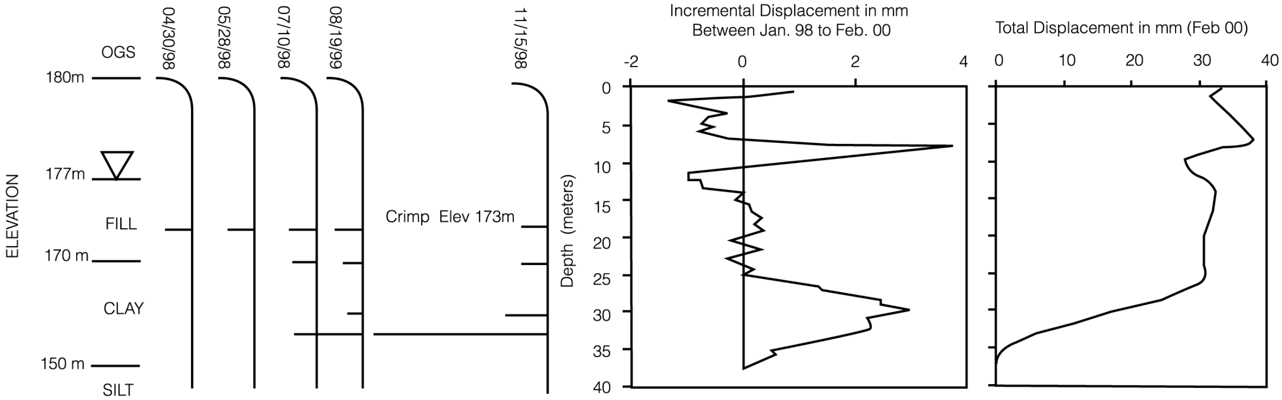


Figure 3. Comparison of TDR sensor cable and Inclinometer Response in Soft to Medium Stiff Glacial Lake Clay

inclinometer and TDR cable are separated by 35 meters.

These field measurements indicate that abrupt changes in shear strains at the boundaries of thick shear bands in soft to medium clay with large relative displacements will produce TDR sensor cable response. TDR sensor cable response and subsequent computer modeling (Blackburn, 2002) indicate that shearing is sufficiently large at this boundary to cause a TDR reflection spike at each boundary of the localized shear. The responses at 28 m and 31 m in Figure 3 may define the thickness of the failure zone at the bottom of the sliding mass. This observation is not inconsistent with that of O'Connor et al. (1995) whose laboratory data were obtained with no confinement of the grout between the laboratory shear rings. In the field the grout is confined by the soil in the shear zone, which would change the deformation regime considerably.

Summary

Both inclinometers and TDR sensor cables will indicate the location and magnitude of subsurface shear strain. TDR sensor cables are especially sensitive to shear in rock, or in soil at locations of highly localized shear strains. On the other hand, inclinometers are especially sensitive to gradual, general shear and respond to early stages of plastic deformation in soils undergoing general shear. TDR sensor cables may also respond at abrupt changes in shear strain at the boundaries of thick localized shear zones.

The case presented here illustrates that TDR sensor cable can be used to locate and quantify localized shearing in soft soil, at least when the deformations are large. Other cases (Dowding and O'Connor, 2000) demonstrate that TDR sensor cables have detected deformation at locations where inclinometers did not detect deformation and vice versa. These differences do not imply that either method is more correct, but the two methods respond optimally to different degrees of shear localization. The real challenge is to explain these different responses more precisely.

TDR sensor cables provide another instrument to supplement and/or verify subsurface deformation measured by inclinometers. One approach that has been adopted, combines the technologies by installing TDR cables and inclinometers in separate holes and remotely interrogating TDR cables using an automated data acquisition system connected to a phone or radio modem. When the TDR cable indicates that movement has occurred, an independent measurement is then made by profiling the inclinometer casing.

Monitoring Deformation in Rock and Soil with TDR Sensor Cables

Part 2. Lessons Learned Using Time Domain Reflectometry

Charles H Dowding
Matthieu L. Dussud
William F. Kane
Kevin M. O'Connor

Introduction

Listed below are the top TDR sensor cable installation and communication lessons learned from installations by Northwestern University, KANE Geotech Inc., and GeoTDR Inc. Installations involved a wide range of situations that called for TDR monitoring of the deformation of:

- Bridge piers and abutments
- Landfills & embankments
- Rock/soil masses (sinkhole and mining-induced deformation)
- Excavations in soft soils

Figure 1. Installation of horizontal TDR sensor cable in a grouted trench over a stabilized sinkhole

Top 11 "TDR Sensor Cable Installation" Lessons

1. Monitoring Large Surface Areas

Long (> 300m) TDR sensor cables can be installed horizontally beneath/beside highways, above mines, near landslides, etc. to monitor more surface area with fewer cables. Installation has been accomplished both by trenching as well as horizontal boring. Figure 1 shows the installation of a horizontal 36 m (120 ft) long TDR sensor cable in a shallow grouted trench parallel to a road subjected to sinkhole subsidence. Detailed information about this project can be found at: *http://www.iti.northwestern.edu/tdr/operational/florida.*

2. Monitoring at Great Depth

As shown in Figure 2, deep (> 500m) vertical TDR sensor cables are being installed to monitor mine-induced deformation at great depths (O'Connor and Wade, 1994).

3. Solid Aluminum Outer Conductor Coaxial Cable

The current preferred cable for installation in rock and stiff to medium stiff soil is the 75 Ohm, 22 mm diameter, bare aluminum outer conductor, foam polyethylene dielectric cable (CommScope Parameter III 875 or equivalent). In order to investigate the sensitivity of a more flexible cable in soft soil a compliant cable was made by Cole (1999) by stripping the solid aluminum outer conductor from a cable. The exposed polyethylene foam was fitted with a flexible copper braided outer conductor. Studies are continuing to assess the relative strength and stiffness of similar, more flexible cables. Photographs of the cables are in Figure 2, Part 1.

4. Cables Installed in Dedicated Boreholes

TDR sensor cables must be installed in their own hole especially in soil. **Strapping flexible cables to inclinometer casing degrades TDR sensitivity for monitoring soil deformation.** Localized shearing response is reduced by the stiffening provided by the grouted inclinometer casing. Figure 3 compares three installation geometries. The

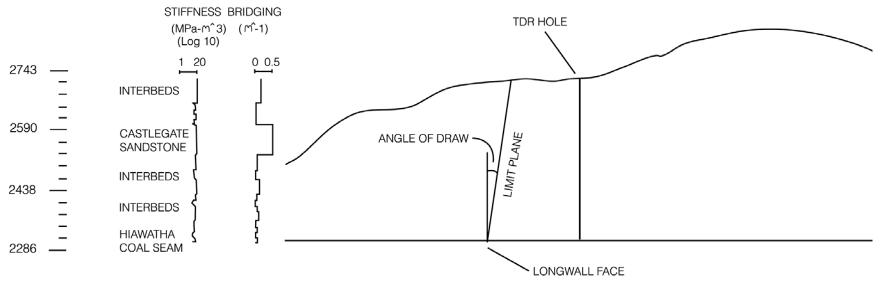


Figure 2. Cross section of the installation of a deep TDR sensor to monitor mine-induced deformation above a long wall coal mine

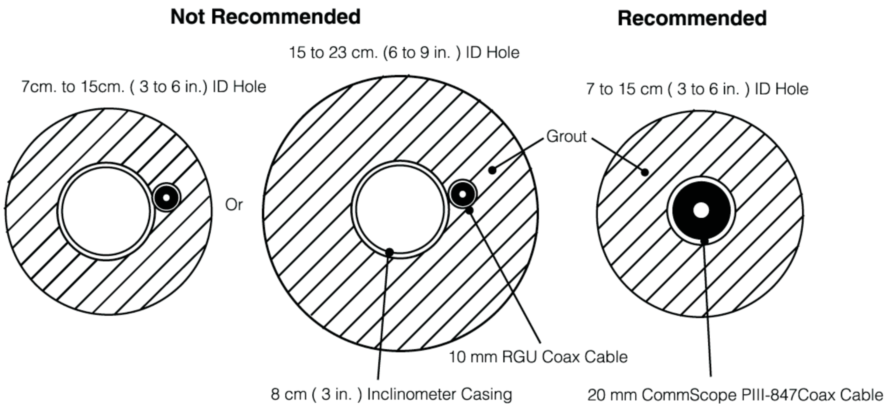


Figure 3. Comparison of geometrics of a TDR sensor cable in its own hole (recommended) and TDR sensor cable strapped around an inclinometer casing (not recommended).

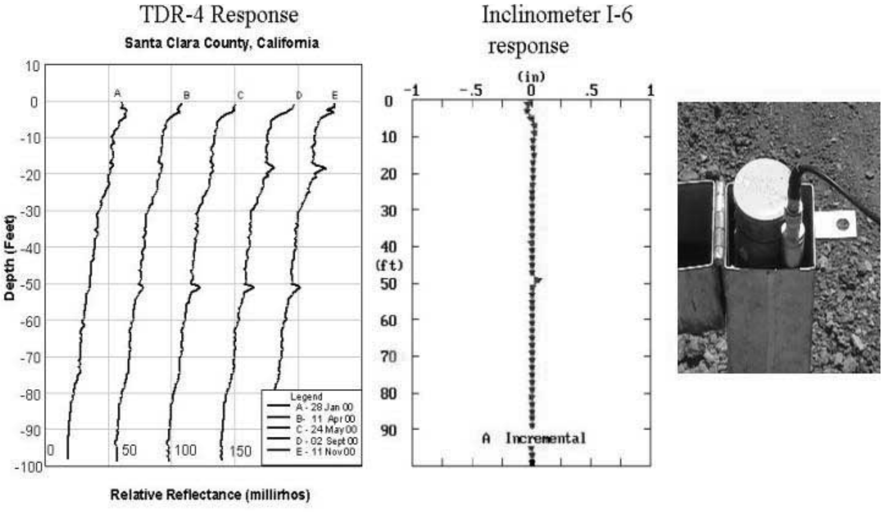


Figure 4. Comparison between response of inclinometer and strapped TDR sensor cable

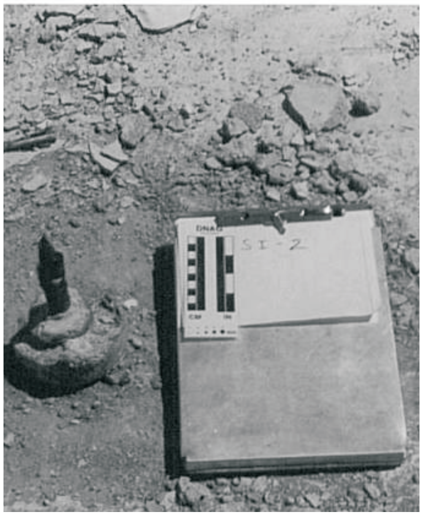


Figure 5. Installation of TDR sensor cable in sheared inclinometer casing extends the life of the monitoring borehole

leftmost two geometries are too often chosen to save the cost of two holes (one for the inclinometer and another for the TDR sensor cable) and are not recommended.

While **not recommended**, some results may be obtained in rock by strapping TDR sensor cables outside a inclinometer casing. Figure 4 compares the response of such an installation in a landslide that occurred in the California Coast Range in heavily sheared and broken Franciscan sandstone. It was particularly fast-moving and the inclinometer casing became kinked at 15.8 m (52 ft). The inclinometer probe could not be lowered below this depth after February 10, 2000. The TDR sensor cable (RG50/U), however, remained usable for some months afterward. The TDR sensor did not show a reflection until at least April 11, 2000 after a significant amount of movement occurred in the inclinometer casing. Because the TDR extended the usable life of the hole, it was able to detect an additional shear displacement at a depth of 5.5 m (18 ft) seven months after the inclinometer casing had been abandoned.

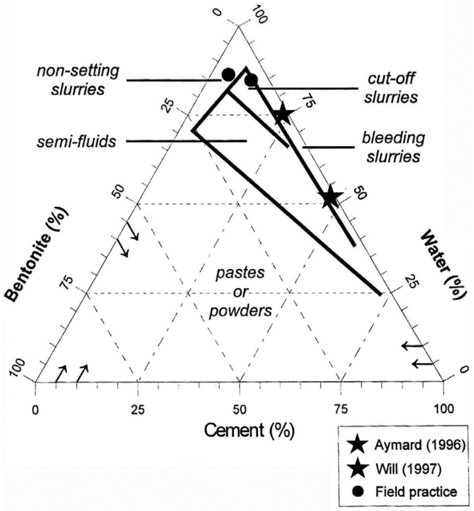


Figure 6. Principal mix proportions of cement-bentonite-water system (Aymard, 1996 and Will, 1997)

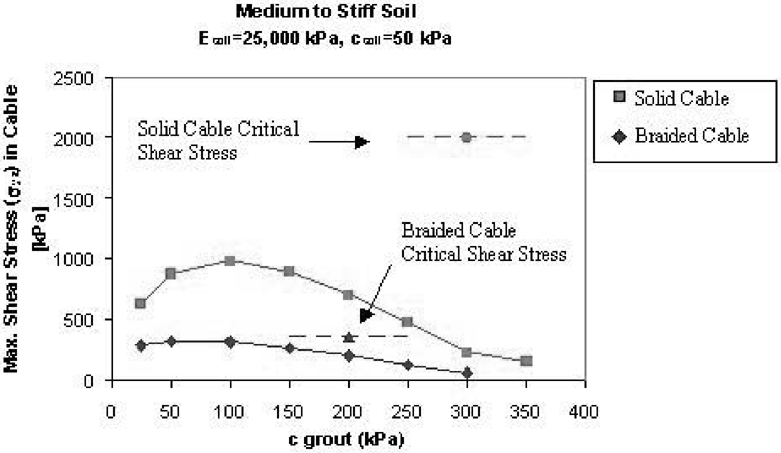


Figure 7. Plot of model shearing sensitivity of stiff and special braided flexible cable that shows there is an optimal grout strength (Blackburn, 2002)

5. *Retrofit Kinked Inclinometer Casing*

Assessment of the response of cables installed in kinked inclinometer casing in rock indicates that TDR sensor cables can also extend the useful life of existing inclinometer instrumentation holes. Such retrofitting shown in Figure 5, allows continued monitoring deformation of critical structures without the need to drill additional holes. Solid aluminum outer conductor cable must be used and, in rapidly moving rock or soil, the cable must be installed relatively soon after the inclinometer casing has been kinked to ensure that the cable can be inserted past the kink in the casing. Pushing the cable past the kink has been a problem when using flexible coaxial cable.

6. *Pumping Grout*

Specialized low strength cement bentonite grout mixtures shown in Figure 6 have been employed for TDR installation in soil (Aymard, 1996 and Will, 1997). For least installation cost, they should be able to be tremmie pumped with the drilling rig's water pump. At first these mixtures appear to be more viscous than the higher strength cement only mixtures. But low viscosities can be produced by the addition of fluidizing/expansion agents such as Intrusion Aid R. The fluidity achieved will have to be demonstrated to the drilling crew, who may not wish to pump it for fear of blocking their pump. A separate grout pump can also be used for cable installation. Refer to Mikkelsen (2002) for an excellent discussion of grout mixing procedures and strength, as well as field crews errors in using grout mixes with high water content and bleeding.

7. *Installation Using Hollow Stem Augers*

Installation with hollow stem augers

Figure 8. View of the sealed end tip of a flexible TDR sensor cable also fitted with a plastic cone to catch the PVC grout tube for insertion

Figure 9. Insertion of TDR sensor cable in CPT rods after attaching special disposable tip

may lead to degradation of response through two mechanisms. First, grout slumps into the large void left as the auger is extracted. Unless a sufficient head of grout is maintained in the auger as it is extracted, voids will exist between the cable and hole walls. Extra grout at a higher head should be available to fill the large annulus created as the auger is extracted. Secondly, extraction of the auger will disturb the soil around the TDR sensor cable (Dussud, 2002).

8. *Soil-Grout-Cable Interaction*

Use of TDR sensor cables in soft soil requires special cement-bentonite grout mixes with prehydrated bentonite and fluidizing agent which should be carefully designed to match the soil properties. The grout must be stiff enough to kink the cable, but not so stiff (strong) that it resists localized soil shearing. Special low loss, flexible cables will allow use of low strength grouts in soft soils. Model results in Figure 7 show that shearing sensitivity of stiff and special flexible grouted coaxial cable is optimal at a ratio of grout to soil strength of 1 to 5 (Blackburn, 2002). Shear stresses in the more compliant braided cable are closer to the critical value, which is the model shear stress associated with the first appearance of a TDR voltage reflection. More research will be needed to determine optimal grout mixtures.

9. *Sealing and Insertion of Cables*

Appropriate techniques for cable insertion are dependent upon cable stiffness. Flexible cables have been inserted by attaching to the cable tip a plastic cone as shown in Figure 8 in order to catch the stiff flush coupled PVC grout pipe as it is pushed in the hole. Alternatively the bottom of stiff solid aluminum coaxial cables can be fitted with a meter-long section of PVC or steel pipe (acting as a stiffener/strengthener) and then pushed down the hole. Before insertion, the bottom end of the TDR coaxial cable must be sealed to prevent intrusion of water between the inner and outer conductor.

10. *Installation using CPT Rig*

As shown in Figure 9, 12.5 mm diameter FLC12-50J cables have been in-

Figure 10. Protective enclosure for connection between a sensor and a connecting cable

serted in soft soil with cone penetrometer equipment (CPT). After determination of stratigraphy the CPT rods are reinserted and the cable placed inside. A special tip is machined for the cable and left in place as the rods are withdrawn. The hole is grouted while extracting the rods. Such technique was used in a landslide in Orange County, California to install a 25 meter deep cable. There are many situations in soft soils, such as investigation of levee stability, where the CPT method works well.

11. Crimping and Connectors Details

Miscellaneous details include: 1) making distance-calibration crimps while lowering the cable to avoid accidental kinking at the crimp during installation and 2) ensuring top-of-hole connectors are moisture-proofed and placed in a locked protective cover shown in Figure 10 (Dussud, 2002).

TOP 8 "TDR Instrumentation" Lessons

1. Integration of Data Acquisition Components

PC based data acquisition systems (DAS) with off-the-shelf components should be avoided because of integration and reliability problems. Reliable, rugged systems should be employed such as those offered by Campbell Scientific Inc. combining a TDR 100 pulser and a CR10X datalogger. These instruments, shown in Figure 11, also have relatively low power consumption, which is an advantage for operation at remote sites.

2. Alarm Call Capability

Automated surveillance of remote sites from a central polling computer (passive monitoring) as well as callback alarm notification from remote sites (active monitoring) has been successfully implemented with TDR (O'Connor et al, 2002). Figure 12 shows a typical DAS equipped with an alarm autodialer.

3. Web-based data Display

Autonomous posting of TDR waveforms over the internet on a daily basis has been successfully implemented for monitoring of deformation of multiple cables at multiple locations. Examples can be seen at http://www.iti.northwestern.edu/tdr (Kosnik and Kotowski, 2002).

4. Telemetry

Hard-wired phone and power lines are preferable at sites that involve real time monitoring and callback alarms. However, several truly remote operations are being operated using cell phone, radio communication and solar power (Dussud, 2002).

5. Low-loss Lead Cable

Long lead cables should be of the low loss, 75 Ohm F11 variety. The often employed, standard, 50 Ohm, RGU connecting cables should be kept as short as possible (<50 m) to minimize attenuation and noise. Such problems have arisen with RG58 and RG59 lead cables.

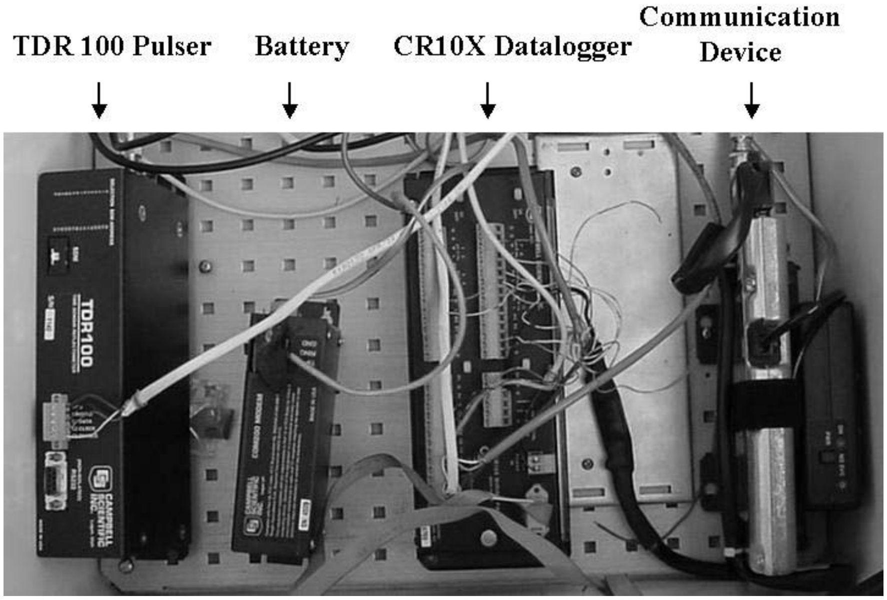


Figure 11. View of an integrated DAS comprising (from the left) a TDR 100 pulser, a 12V battery, a CR10X datalogger and communication equipment (phone modem and cellular phone)

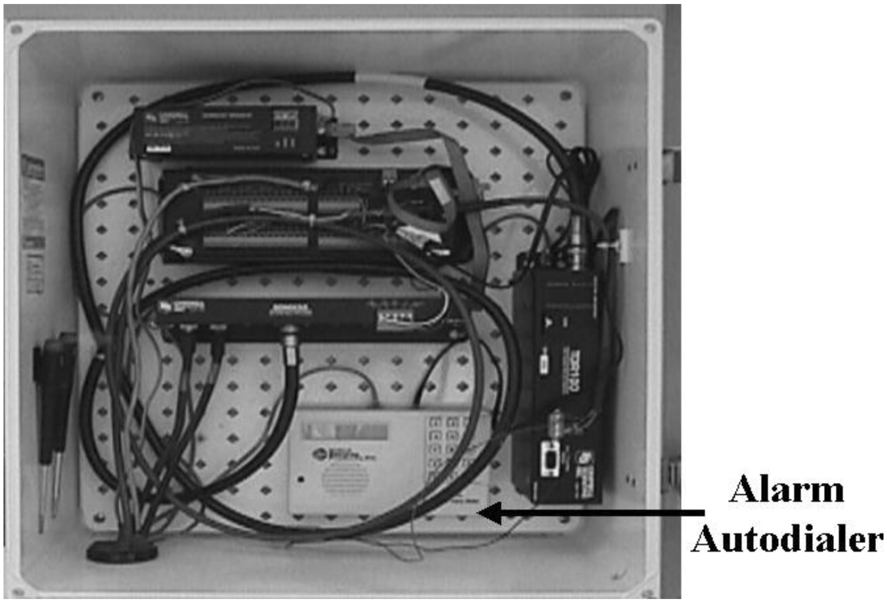


Figure 12. Remote TDR monitoring system with alarm autodialer

6. *Multisensor Monitoring Systems*

Integrated multiparameter monitoring systems have been implemented with tiltmeters and TDR sensor cables at remote datalogger-controlled installations. These have involved monitoring of bridge pier deformation from scour and from mining induced subsidence along highways.

7. *Connector Accessibility*

Connections between different cables (i.e. transmission and transducer cables) are a weak link and should be made as robust and water proof as possible. N-type connectors are recommended, but F-type have also been used. They should also be accessible for maintenance as shown in Figure 10.

8. *Digital Data Format*

If cables are interrogated manually with a Tektronix 1502 cable tester, it should be equipped with a SP232 module to acquire digital records for display, analysis and quantification of TDR reflections.

Acknowledgements

Direct financial support for development of TDR technology has been provided by the U.S. Department of Transportation funded Infrastructure Technology Institute of Northwestern University from 1993 to the present and the Civil Mechanical Systems Division of the National Science Foundation between 1995 and 2001. The authors are also indebted to the many other individuals and organizations that also have supported this development but are too numerous to mention by name.

References

Aymard, N. (1996) “Low Strength Grouts for Embedding TDR Cables in Soil,” M.S Thesis, Department of Civil and Environmental Engineering, Northwestern University, Evanston, IL USA, December.

Blackburn, J.T. (2002) Finite Element Analysis of TDR Sensor Cable-Grout-Soil Mass Interaction During Localized Shearing, M.S Thesis, Department of Civil and Environmental Engineering, Northwestern University, Evanston, IL, USA, April.

Cole, R. G. (1999) “Compliant TDR sensor cable Grout Composites to Measure Localized Soil Deformation” M.S. Thesis, Department of Civil and Environmental Engineering, Northwestern University, Evanston, IL, USA, December.

Dowding, C.H., Su, M.B. and O’Connor, K.M. (1988) “Principles of Time Domain Reflectometry Applied to Measurement of Rock Mass Deformation,” Int. Journal of Rock Mechanics and Mineral Science, Vol. 25, No.5, pp. 287-297.

Dowding, C.H. and O’Connor, K.M. (2000) “Comparison of TDR and Slope Inclinometers for Slope Monitoring,” ASCE Geotechnical Special Technical Publication, No. 106 pp 80-90.

Dussud, M. L. (2002) “Case Histories and Field Techniques for TDR Monitoring of Soil Deformation,” M.S Thesis, Department of Civil and environmental Engineering, Northwestern University, Evanston, IL, USA, Dec.

Kosnik D. and Kotowski M. (2002) “Infrastructure Remote Monitoring Software,” Infrastructure Technology Institute, Internal Report, Northwestern University, Evanston, IL.

Mikkelsen, P.E. (2002) “Cement-Bentonite Grout Backfill for Borehole Instruments,” Geotechnical News, December pp. 38-42.

O’Connor, K.M. and C.H. Dowding (1999) GeoMeasurements by Pulsing TDR Cables and Probes. CRC Press, Boca Raton, 420p.

O’Connor, K.M., Peterson, D.E. and Lord E.R. (1995) “Development of a Highwall Monitoring System Using Time Domain Reflectometry,” Proceedings, 35th U.S. Symposium on Rock Mechanics, Reno, Nevada, June, pp.79-84.

O’Connor, K.M., R. Ruegsegger, and K. Beach (2002) “Real Time Monitoring of Subsidence Along Interstate I-77, Summit County, Ohio” ITGAUM 4th Biennial Abandoned Underground Mine Workshop, Davenport, Iowa, http://www.fhwa.dot.gov///mine/oconnor.htm

O’Connor, K.M. and Wade, L.V. (1994), “Applications of Time Domain Reflectometry in the Mining Industry,” Proceedings of the Symposium and Workshop on TDR in Environmental, Infrastructure and Mining Applications, Northwestern University, Evanston, IL, USA, September, pp. 494-506.

Pierce, C. E. (1998) “A Compliant Coaxial Cable-Grout Composite for Time Domain Reflectometry Measurements of Localized Soil Deformation,” Ph.D. Thesis, Department of Civil and Environmental Engineering, Northwestern University, Evanston, IL, USA, December.

Will, D. (1997), “Cement Bentonite Grouts Compatible with Compliant TDR Cables,” M.S Thesis, Department of Civil and Environmental Engineering, Northwestern University, Evanston, IL, USA, December.

Charles H. Dowding and Matthieu L. Dussud, Professor and Graduate Student: Department of Civil & Environmental Engineering, Northwestern University, Evanston, IL 60208,
Tel: 847-491-4338,
Fax: 847-491-4338,
email: c-dowding@northwestern.edu; m-dussud@northwestern.edu

William F. Kane, President, Kane Geotech, Inc., PO Box 7526, Stockton, CA 95267-0526, Tel: 209-472-1822, Fax: 209-472-0802,
email wkane@kanegeotech.com

Kevin M. O'Connor, President, GeoTDR, Inc. 720 Greencrest Drive, Westerville, OH 43081-4902,
Tel: 614-895-1400,
Fax: 614-895-1171,
email: kevin@geotdr.com