Instrumentation

John Dunnicliff

Introduction

This is the eighth episode of GIN. Several articles are "in the works", but only Kevin O'Connor's article on time domain reflectometry was ready by press time.

Surveying Methods

In the red book I attempted to summarize and evaluate various surveying methods (with the help of two colleagues who knew **much** more about the subject than I). But that was nearly ten years ago, and there have been many exciting developments during the past ten years.

In general, whenever geotechnical instruments are used to monitor deformation, surveying methods are also used to relate measurements to a reference datum, hence those of us involved with geotechnical instrumentation often need to interact with our surveying colleagues. I've solicited a comprehensive article for GIN, on recent developments in surveying techniques, and that will be in a later issue. In the meantime, here's a report on some recent surveying work to measure elevations using a digital level and a barcoded fiberglass staff. I was both surprised and impressed with the high accuracy achieved, hence wanted to share the information. In the first episode of GIN, in the September 1994 issue of *Geotechnical News,* I wrote:

> *Its [GIN's] purpose is to share useful information relating to geotechnical instrumentation. I intend to focus on performance of instruments. As a practitioner, I know how difficult it is to be confident that such-and-such an instrument will work well, and it seems to me that if we share performance information with each other, we will make this less difficult.*

This brief report is consistent with the "sharing" goal.

Elevation measurements were required to define a reference, against which an alternative vertical deformation monitoring system was to be evaluated. I was looking for an accuracy of ±0.01 foot (±3 mm) but, as you will see, the survey achieved a much better accuracy. The following report has been provided by Jim Peterson of BSC/Cullinan Associates, who were responsible for the survey measurements.

Equipment

Equipment consisted of Leica's Wild NA 2002 Digital level and GKNL4 barcoded dual-faced staff. The digital level is rated as a second order Class II instrument with a standard deviation (for 1KM double-run leveling) of 1.55 mm when used in conjunction with the fiberglass sectionalized staff. Digital levels operate on the principle of Charged Coupled Device (CCD) technology which is also used in video cameras. The CCD sensor recognizes the patterns of black and white divisions on the bar coded staff and forms a signal pattern which it analyzes by correlation.

The result is that the instrument is able to compute the staff reading and the distance from the instrument to the staff. A measurement consists of the following stages: point and focus, start digital measurement, coarse correlation, fine correlation, and display and record results. Data are digitally stored on a removable device called a REC (record) module which fits in the palm of your hand.

Monumentation and Benchmarks

Monumentation consisted of eighteen 1½ inch Parker/Kalon (PK) masonry nails, all within a zone 125 feet long by 10 feet wide. Benchmarks (BMs) consisted of stainless steel anchors installed with the Hilti epoxy system into bents located on a nearby elevated roadway.

The angle point in the hex head bolt was threaded in place and secured with Loctite such that an angle point of the head pointed upward, providing a well-defined surface. Four such benchmarks were installed, and leveled through to confirm their stability prior to observing the PK nails.

Observation Procedure and Initial Repeatability Test

The NA 2002 digital level is capable of recording a series of measurements and displaying a calculated standard deviation (SD) for successive observations. The field crew was instructed to record no less than four readings, not to exceed a SD of 0.3 mm.

Collimation tests were performed on the digital level prior to each set of elevation measurements. The angular difference between a true horizontal line and the line of sight from the instrument to a target is the collimation error.

The instrument is capable of storing the collimation error and applying it to all measurements, pro-rated by the distance between the staff and instrument.

An initial repeatability test was conducted prior to the start of the evaluation. The NA 2002 was situated midway between two of the BMs, a backsight observation was taken on one BM, a reading taken on the staff at each of the eighteen PK nails, and a foresight observation taken on the second BM.

The rodman plumbed the staff on the PK nail with the aid of the attached bullseye bubble. The instrument height was changed to create an independent set-up. The procedure was then repeated in reverse order with a closing observation on the first BM to determine any misclosure in the level loop.

In order to provide a high order of repeatability, the instrument was limited to a single setup and the sight distances were kept to a minimum. The BMs were approximately 180 feet apart, and the range of the sight distances to the survey monuments was 10 to 75 feet.

The above procedure was repeated in its entirety a total of four times, which produced five closed loops (ten single loops) with 36 side shots per loop. The misclosures of the five loops were 0.3, 1.0, 0.2, 0.0, and 0.2 mm respectively. This provided a check on any settlement in the level during the observation period. Each closed loop, and accompanying 36 sideshots, was independently adjusted with a least squares program which yielded five meaned elevations for each of the eighteen survey monuments.

A SD at a 95% confidence interval for the five meaned elevations was calculated for the eighteen survey monuments. The range of the SD @ 95% for all eighteen was 0.0 mm to 0.5 mm with an average of 0.3 mm for all data (90 elevations) combined.

Observations Subsequent to Initial Repeatability Test

During the evaluation to compare survey measurements with the alternative vertical deformation monitoring system, the elevations of the eighteen survey monuments were changed in 23 stages, and measurements made both with the survey system and with the alternative system. During each stage only enough time (typically less than 30 minutes) was allowed for one closed loop level run, which yielded two elevations on each monument, or one meaned elevation.

The largest misclosure of the 23 separate surveys was 0.8 mm, with an average misclosure of 0.2 mm. The largest difference observed on the same monument during the same survey was 1.2 mm, with an average difference of 0.5 mm.

Conclusion: much better accuracy than I expected (and it became important that the survey accuracy was as good as it was). If you'd like more information, please contact *James E. Peterson, RPLS, BSC/Cullinan Associates, 425 Summer Street, Boston, MA 02205-1752, tel. (617) 345-4061, fax (617) 345-8002.*

Continuing Education Courses

Two continuing education courses on geotechnical instrumentation are now scheduled.

The first will be in St. John's, Newfoundland on Saturday and Sunday, September 21 and 22, 1996, immediately preceding the 49th Canadian Geotechnical Society Annual Meeting and Conference. Elmo DiBiagio from Norwegian Geotechnical Institute will update us on instrumentation of offshore structures. For more information, see Geotechnical News, March 1996, page 44, or contact Lynn or Sandi at BiTech.

The second will be at Columbia University, New York, on Sunday, June 29, 1997, immediately preceding the International Society of Rock Mechanics International Symposium and 36th U.S. Rock Mechanics Symposium. The focus will be on rock mechanics instrumentation. For more information contact me, or *Professor Kunsoo Kim, Columbia University, 811 Seeley W. Mudd Building, New York, NY 10027, tel. (212) 854-8337, fax (212) 854-8362, or E-mail kk21@columbia.edu.*

Another Ralph Peck Video

Have you seen the new video on controlling seepage and piping in dams, starring Ralph Peck? One of the best geotechnical videos that I've seen, not only because of the technical content and presentation, but because it is far from being a mere video of a lecture. It is "produced," in the real sense, using both moving and still visual aids, for which credit goes to Frank McLean of the U.S. Bureau of Reclamation.

The video includes wise guidance on what to look for during surveillance, including:

> *It is important to keep track of.[e.g. measurement of flow over weirs] on a closely spaced basis, weekly or daily perhaps. It is not a matter of whether there are wet spots or seepages, it is whether they have changed that counts. And this means that surveillance has to be over the long haul. One has to be able to observe things throughout the year, and from year to year, to detect whether there may be subtle changes that are not associated with precipitation or snowmelt...change in the body of a dam is something to be guarded against....*
>
> *In most surveillance programs for dams, one finds instrumentation today. There are piezometers installed downstream of the toe, and sometimes within the body of the dam itself. But piezometers are something of a mixed blessing. If they indicate that something is changing, that, in itself, is important, as a sign that there may be erosion going on. But it would be a matter of pure luck if piezometers would be installed at a place where they would be affected by an advancing erosion tunnel...and so, because piezometric observations may not show anything suspicious, this is not a good reason for believing that erosion tunnels cannot be developing.*
>
> *So we see that, even with careful surveillance, there are surprises that nature can have in store for us. Nature has the upper hand, in that she knows what she's doing in that dam, and we don't. We have to try to read what signs she gives, but we also have to realize that there may be some signs that are not going to be apparent.*

A description of content is on page 60 of *Geotechnical News*, March 1996. Copies can be requested from *William Bivins, Chairman of ICODS, FEMA (MT-PD-DV), Washington, D.C. 20247-2000.* In my view, a "must see," for anyone involved with embankment dams.

THE Marathon

The 100th Boston marathon (all 38,000 of them) passed through my home town this week. What a joy to watch! The incredible Kenyans, seven of whom finished among the first eight. The air of most runners "having fun," revelling in being part of it. Nothing to do with instrumentation? Sure it is: each runner had an instrument attached to shoe laces, which recorded the time of passing over a pad at the start and a pad at the finish!

Closure

Please send contributions to this column, or a separate article for GIN, to me: *16 Whitridge Road, South Natick, MA 01760. Tel. (508) 655-1775, fax (508) 655-1840.* Serefe! (Turkey).

Time Domain Reflectometry (TDR)

I've been aware of this technology for about ten years, but always from a distance. The names most often associated with publications describing TDR seemed to be Kevin O'Connor of U.S. Bureau of Mines and Chuck Dowding of Northwestern University. I was with Kevin recently, and asked him for an article for GIN: here it is.

Kevin O'Connor became involved with TDR technology in 1982 while employed by Woodward-Clyde Consultants, and working with Jack O'Rourke to monitor subsidence over active coal mines. The fundamental relationships between rock mass deformation and TDR waveform characteristics were established in collaboration with Professor Chuck Dowding while working on a Ph.D. at Northwestern University (NU). Advances in the application of TDR continued while he was employed as an Assistant Professor of Geological Engineering at New Mexico Tech doing research in slope monitoring and potash mine ground control. Major advances in software and applications were made while he was employed as a Civil Engineer engaged in subsidence research with the U.S. Bureau of Mines (USBM) in Minneapolis, Minnesota doing cooperative research with NU. He formed GeoTDR, Inc. in January 1996 to pursue continued development of applications for TDR, following closure of the USBM. *John Dunnicliff*

Geotechnical, Environmental, and Infrastructure Applications of Metallic TDR

Kevin O'Connor

Introduction

For any geotechnical or environmental monitoring technique to be useful in field applications, it must be economical (installation cost, data acquisition cost, etc.), provide reliable information in real time, and be resistant to sabotage. There are often tradeoffs when attempting to satisfy these requirements, and techniques have been developed using a variety of mechanical, chemical, and electrical principles. Time Domain Reflectometry (TDR) is another tool in the arsenal available to researchers and practitioners. The intent of this short article is to stimulate interest by summarizing some geotechnical, environmental, and infrastructure applications of TDR technology. I anticipate that some readers would like explore these applications and have taken the liberty of suggesting papers that document case histories and the state-of-the-art.

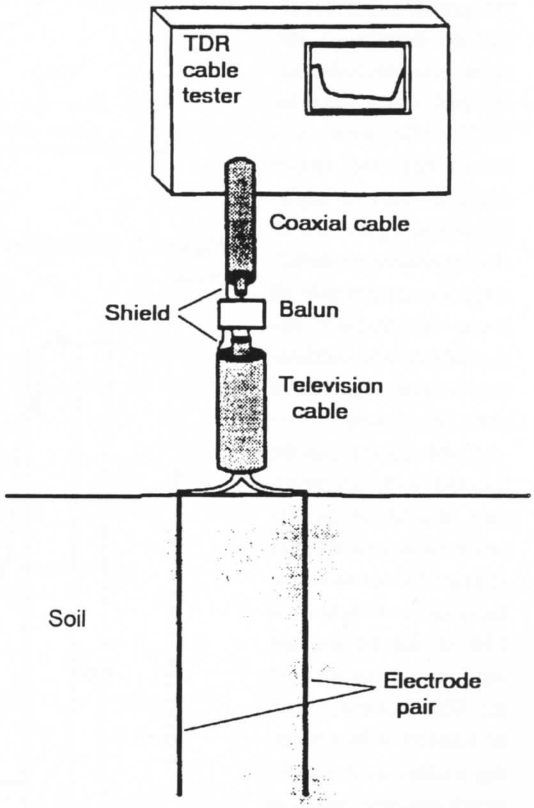

Figure 1. The basic TDR system for use in determining volumetric water content. The balun transformer allows a coaxial cable to be connected to a parallel pair television antenna cable. Electrode probes are available which can be connected directly to the coaxial cable.

What Is TDR?

It is possible to locate and track objects by transmitting high frequency electromagnetic waves and processing reflected waves. This is the operating principle of radar. Similarly, a voltage pulse can be transmitted and reflected along a waveguide embedded in soil or rock. It is possible to process the reflected voltage to evaluate changes in the rock or soil as well as changes in pore fluids. The principle is known as Time Domain Reflectometry. This article concentrates on electrical or metallic TDR (MTDR), but the same principle can be used with a light source and optical fibers (OTDR).

TDR was developed by the power and telecommunications industries to locate faults in cables. A cable tester launches a voltage pulse into a coaxial cable, parallel pair wire or twisted pair wire. Wherever there is a change in electrical properties, due to cable damage or water ingress, a portion of the voltage is reflected back to the tester which displays the ratio of reflected to transmitted voltage as a reflection coefficient. The waveform shape is a function of the type and magnitude of cable damage. The travel time is converted to distance by knowing the propagation velocity which is a property of the cable or wire. Consequently, it is possible to display all reflections and identify the type and location of cable damage. A key reference is:

Andrews, J.R. Time Domain Reflectometry. Proceedings of the Symposium on Time Domain Reflectometry in Environmental, Infrastructure, and Mining Applications, Evanston, IL, Sept, 1994, p. 4-13; NTIS PB95-105789.

Volumetric Water Content

If a probe consisting of two or more parallel rods is embedded in a porous medium, the voltage pulse can be launched along this probe (figure 1). A reflection is created at the top of the probe and a second reflection is created at the end of the probe (figure 2). Since the probe length is fixed, the propagation velocity can be computed as twice the length divided by the time required for a pulse to travel along the probe and back (figure 3). The apparent dielectric constant (permittivity) of the porous medium is simply a ratio between this measured velocity and the speed of light in free space. As the volumetric water content changes so does the dielectric constant, which is measured as a change in propagation velocity. The relationship between volumetric water content and apparent dielectric constant can be tailored to specific soils by laboratory calibration, or approximate measurements can be made using widely accepted empirical curves.

This technology has been used to monitor changes in volumetric water content in agricultural soils, pavement subgrades, grains, trees, and a variety of other applications. In pavement subgrades it has been possible to track the transition between frozen and thawed states which has increased understanding of pavement performance. This technology has also been used to monitor the performance of landfill covers by tracking changes in volumetric water content as water seeps through prototype landfills. Key references for this application include:

Topp, G. C., J. L. Davis, and A. P. Annan. Electromagnetic Determination of Soil Water Content: Measurements in Coaxial Transmission Lines. Water Resour. Res., 16(3), 1980, pp. 574-582.

Topp, G. C., S. J. Zegelin, and I. White. Monitoring Soil Water Content Using TDR: An Overview of Progress. Proc. Sym. on Time Domain Reflectometry in Envir., Infrastr. and Mining Appl., Evanston, IL, Sept. 1994, pp. 67-80; NTIS PB95-105789.

Rada, G. R., A. Lopez, and G. E. Elkins. Monitoring of Subsurface Moisture in Pavements using Time Domain Reflectometry. Proc. Sym. on Time Domain Reflectometry in Envir., Infrastr., and Min. Appl., Evanston, IL, Sept. 1994, p. 422-433; NTIS PB95-105789.

Janoo, V., R. L. Berg, E. Simonsen, and A. Harrison. Seasonal Changes in Moisture Content in Airport and Highway Pavements. Proc. Sym. on Time Domain Reflectometry in Envir., Infrastr., and Min. Appl., Evanston, IL, Sept. 1994, p. 357-363; NTIS PB95-105789.

Benson, H. B., P. J. Bosscher, D. T. Lane, and R. J. Pliska. Monitoring System for Hydrologic Evaluation of Landfill Covers. Geotechnical Testing Journal, GTJODJ, Vol. 17, No. 2, June, 1994, pp. 138-149.

Nyhan, J. W., T. G. Schofield, and C. E. Martin. Use of Time Domain Reflectometry in Hydrologic Studies of Multilayered Landfill Covers for Closure of Waste Landfills at Los Alamos, New Mexico. Proc. Sym. on Time Domain Reflectometry in Envir., Infrastr., and Min. Appl., Evanston, IL, Sept. 1994, pp. 193-206; NTIS PB95-105789.

Rock And Soil Deformation

A metallic coaxial cable can be placed in a drillhole and anchored to the walls by tremie placement of an expansive cement grout (figure 4). When movements occurring in the rock or soil are sufficient to fracture the grout, cable deformation occurs. If the cable is subjected to localized shearing the TDR reflection is a characteristic spike such as those highlighted in figure 5. It is also possible to determine the magnitude of shear deformation using laboratory calibration curves that have been developed.

Cable faults can be located with an accuracy of ±2% of the distance from cable tester to fault. For example, a fault at a distance of 150 m can be located with an accuracy of ±3 m. This accuracy can be improved by crimping a cable at some desired spacing such as 15 m prior to placement in the hole. The reflections flagged with asterisks in figure 5 are caused by crimps at known physical locations. These reflections provide control markers in the TDR records.

This technology has been used to monitor strata movements over active and abandoned mines for purposes of determining subsurface warnings of surface subsidence. It has been used to monitor movements in highwalls of surface mines and slopes along highways. It has been used for ground control purposes in active mines.

When this technology is used in conjunction with available remote monitoring systems, it is possible to acquire TDR waveforms hourly, daily, or at any desired time interval (figure 6). The waveforms can be imported into CAD files and superimposed on the geometric and geologic conditions. A series of drawings can be compiled as a time-lapse animation. These animations make it possible to observe the correlation between TDR waveform changes and the in situ conditions. Such visual

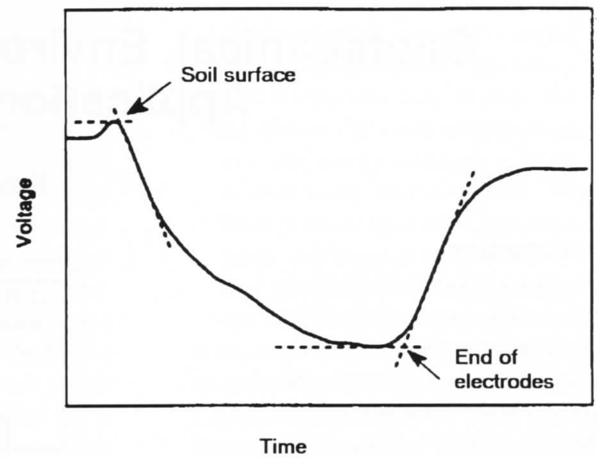

Figure 2. TDR reflections at the top and bottom of probe.

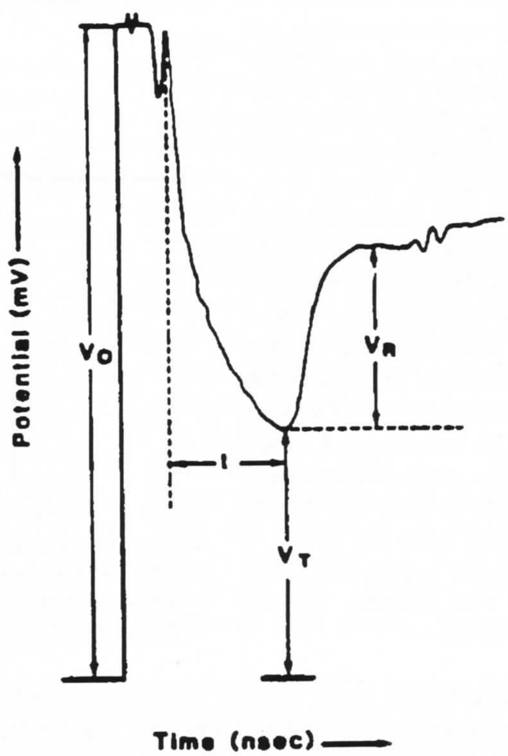

Figure 3. Parameters of a TDR waveform: output voltage, Vo, voltage transmitted along probe, VT, time for pulse to travel along probe and return, t, and reflected voltage, VR.

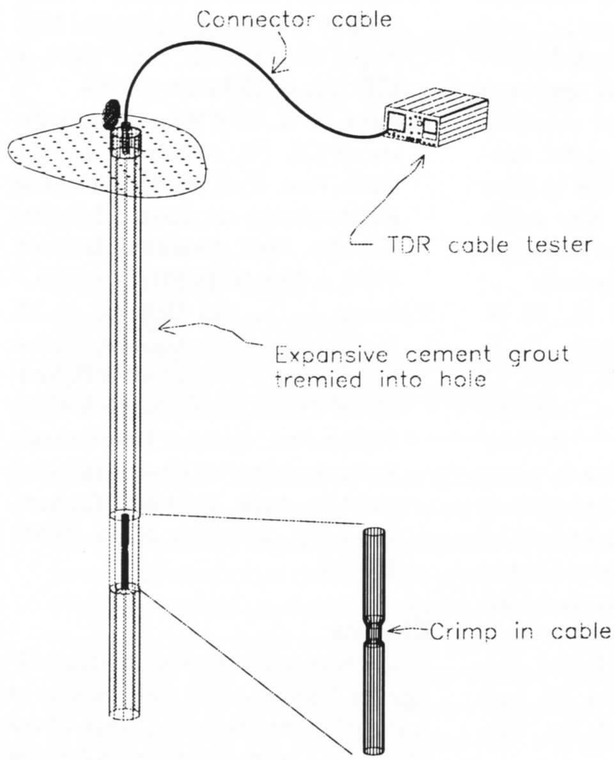

Figure 4. The basic TDR system for monitoring deformation in rock and soil.

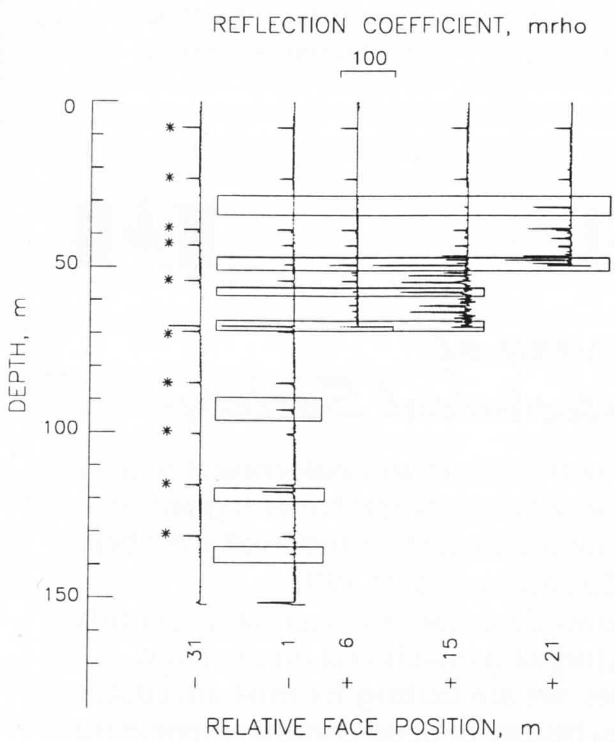

Figure 5. TDR waveforms acquired over an active mine. Asterisks indicate reference crimps. Some of the reflections due to shearing along rock discontinuities are highlighted in boxes.

analysis is a very powerful tool for rapid interpretation of the TDR data and provides an excellent means for conveying this information to all interested parties. Key references for this application include:

Dowding, C. H., M. B. Su and K. M. O'Connor. Principles of Time Domain Reflectometry Applied to Measurement of Rock Mass Deformation. Int. J. Rock Mech. and Min. Sci., v. 25, No. 5, 1988, pp. 287-297.

Huang, F.-C., K. M. O'Connor, D. M. Yurchak, and C. H. Dowding. NUMOD and NUTSA: Software for Interactive Acquisition and Analysis of Time Domain Reflectometry Measurements. BuMines IC 9346, 1993, 42 pp.

Dowding, C. H. and F.-C. Huang. Telemetric Monitoring for Early Detection of Rock Movement With Time Domain Reflectometry. J. Geot. Eng., Am. Soc. Civ. Eng., v. 120, No. 8, 1994.

O'Connor, K. M. Remote Detection of Strata Movements over Abandoned Coal Mines. Abandoned Mine Lands Research, Final Report, USBM, Minneapolis, MN, November, 1995, 93 p. and 2 disks.

O'Connor, K. M., D.E. Peterson, and E.R. Lord. Development of a Highwall Monitoring System using Time Domain Reflectometry. Proc., 35th U.S. Sym. Rock Mech. Reno, Nevada, June, 1995, pp. 79-84.

O'Connor, K. M. and L.V. Wade. Applications of Time Domain Reflectometry in the Mining Industry. Proc. Sym. on Time Domain Reflectometry in Envir., Infrastr. and Min. Appl., Evanston, IL, Sept. 1994, pp. 494-506; NTIS PB95-105789.

O'Connor, K. M. and T. Zimmerly. Application of Time Domain Reflectometry to Ground Control. Proceedings of the 10th Int. Conf. on Ground Control in Mining, Morgantown, WV, June 10-12, 1991, pp. 115-121.

Water Level Monitoring

A parallel pair wire, twisted pair wire, or air-dielectric coaxial cable can be placed in a standpipe piezometer to monitor changes in water level within the standpipe. When a voltage pulse is transmitted along the cable or wire, a reflection occurs at the air-water interface. A benchmark reference for this application is:

Dowding, C. H. and F.-C. Huang. Ground Water Pressure Measurement with Time Domain Reflectometry. Proc. Sym. on Time Domain Reflectometry in Envir., Infrastr., and Min. Appl., Evanston, IL, Sept. 1994, pp. 247-258; NTIS PB95-105789.

Contaminant Transport

When probes such as those used for monitoring volumetric water content are interrogated, the TDR reflection at the end of the probe can be attenuated (figure 3). The reflected voltage magnitude decreases as conductivity of a porous medium increases. In fact, if the medium is very conductive, it may not be possible to detect a reflection at the end of the probe and it is not possible to determine the water content. It is this remarkable capability of TDR to measure both apparent permittivity (dielectric constant) and conductivity of porous media that makes it particularly suitable for monitoring contaminant transport.

This technology has been used to monitor transport of sodium chloride,

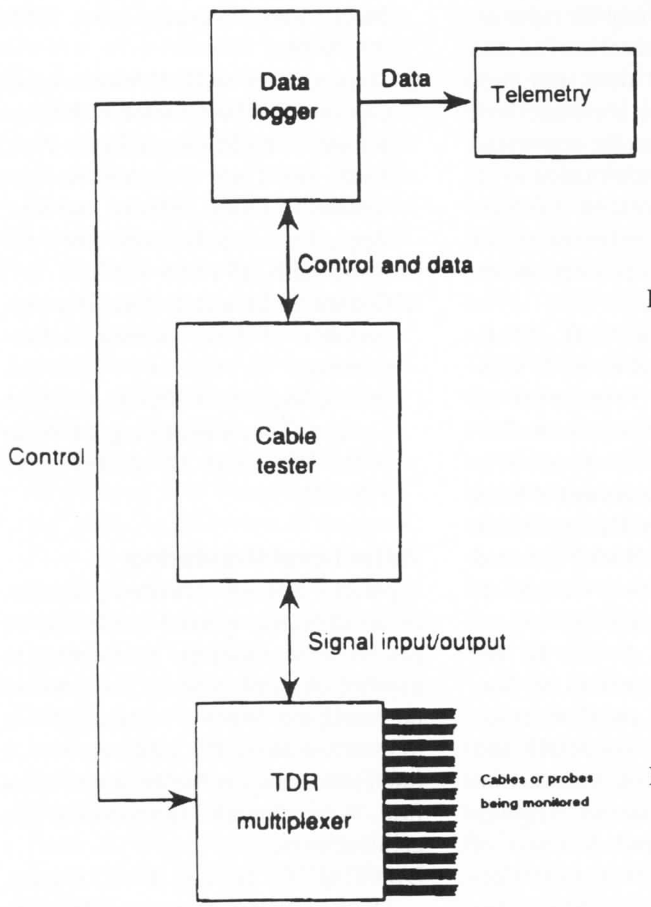

Figure 6. Schematic of system used for remote continuous monitoring.

calcium chloride, kerosene, and tetrachloroethylene. It has also been used to monitor heavy metal concentrations in mine waste. Key references for this application include:

Dalton, F. N., W. N. Herkelrath, D. S. Rawlins, and J. D. Rhoades. Time-Domain Reflectometry: Simultaneous Measurement of Soil Water Content and Electrical Conductivity with a Single Probe. Science, Vol 224, June 1, 1984, pp. 989-990.

Kachanoski, R. G. and A. L. Ward. Measurement of Subsurface Chemical Transport Using Time Domain Reflectometry. Proc. Sym. on Time Domain Reflectometry in Envir., Infrastr., and Min. Appl., Evanston, IL, Sept. 1994, p. 171-182; NTIS PB95-105789.

Norland, M. R. TDR Waveform Analysis of Cd, Pb, and Zn in Coaxial Cells. Proc. Sym. on Time Domain Reflectometry in Envir., Infrastr., and Min. Appl., Evanston, IL, Sept. 1994, p. 235; NTIS PB95-105789.

Redman, J. D., and DeRyck, S. M. Monitoring Non-Aqueous Phase Liquids in the Subsurface with Multilevel Time Domain Reflectometry Probes. Proc. Sym. on Time Domain Reflectometry in Envir., Infrastr., and Min. Appl., Evanston, IL, Sept. 1994, pp. 207-214; NTIS PB95-105789.

Closure

I have been involved with this technology for fourteen years and continue to learn about the expanding range of applications. Copies of references listed in this article can be obtained by contacting:

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