Chapter 1
INTRODUCTION TO TDR

This book project was written to crystallize the commonalities among the seemingly divergent specialties employing Time Domain Reflectometry (TDR) technology in geomaterials. The diversity of interest and terminology within the TDR community tends to obscure commonalities and the fact that physical principles underlying the technology are universal. It is our hope that the condensation, distillation, and integration of the varied TDR experiences in this book will provide the synergism necessary to unify the field.

EVOLUTION OF TDR TECHNOLOGY

TDR technology was first developed during the 1950s to locate and identify cable faults in the power and telecommunications industries which remain major users of this technology. TDR cable testers are now considered standard equipment by engineers and technicians in these major industries. The enormous size of the power, telecommunications, and more recently the cable TV and computer network industries provides the largest market for the development of TDR hardware.

In the 1970s, TDR technology began to be applied with geomaterials, and it is this expansion of use and technology transfer that led to the writing of this book. Now TDR technology is employed by soil scientists, agricultural engineers, geotechnical engineers, and environmental scientists as well as electrical engineers. Initial empirical methods of application in geomaterials have matured with scientific calibration and improved pulser samplers, cables, and sensors. These accelerating improvements are condensed here.

This book represents another step along the evolution of TDR technology in geomaterials from a research instrument to a robust, reliable, and economical production tool. Thus far, users of TDR in geomaterials typically have been researchers and this book attempts to clear the way for use of TDR by a variety of nonspecialists. A major effort has been made to incorporate experience and reports of field verification, and their inclusion not only substantiates TDR's usefulness, but also provides comparisons with other commonly employed technologies. The broad range of positive experience supports the assertion that TDR technology is not a passing fad but has already stood the test of time.

Shelves of articles as well as research and consulting documents have been condensed into this book to provide the perspective on application of TDR technology that is not achievable one article at a time. Basically, this book expands upon the First International Symposium on Time Domain Reflectometry in Environmental, Infrastructure, and Mining Applications that was held at Northwestern University in 1994. That symposium brought together for the first time the incredibly diverse disciplines employing TDR and allowed experts to exchange experiences. Even though these experiences were exchanged through the proceedings of the symposium, as with all such proceedings, they were not integrated. To the base of experience provided by the 1994 symposium, the authors have added their own. This additional experience has focused on many of the secondary applications rather than the currently most active one, soil moisture monitoring.

TDR'S BROAD RANGE OF APPLICATION

In general, Time Domain Reflectometry describes a broad range of remote sensing electrical measurements to determine the location and nature of various reflectors. TDR is similar in principle to radar which consists of a radio frequency transmitter (which emits a short pulse of electromagnetic energy), a directional antenna, and sensitive radio frequency receiver. After the transmitter has directionally radiated the pulse, the receiver records the echo or reflection returned from a distant object such as an airplane or ship. By measuring the time between transmission and receipt of the reflection and knowing the speed of light, the distance to the object may be easily calculated. Detailed analyses of the echo can reveal additional details of the reflecting object, which aid in identification.

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.

WHAT IS THE SIZE OF THE TDR MARKET ?

By far the largest markets for TDR technology involve hundreds of thousands of units in the telecommunications and power industries. Thus equipment manufacturers have focused on these markets. Because of the large size of this communications market, many of the major companies regard the geomaterials and infrastructure applications discussed in this book as niche markets. At present, use of TDR in geomaterials is dominated by the study, monitoring, and control of soil water content for conservation of agricultural water. Since the potential number of soil moisture or irrigation control systems is measured in terms of a hundred thousand worldwide, it is no wonder that several firms have been formed to serve this potential market.

There are a number of applications of TDR technology that are rendered potentially commercially viable by the infrastructure provided by the level of activity in the areas of telecommunications and soil moisture. In order of decreasing numbers of potential installations they are:

- leak detection and contaminant monitoring
- water level measurement
  - hydrological and contaminant transport
  - water pressures
- deformation and stability monitoring of
  - mines (abandoned and operating)
  - slopes (rock and soil)
  - structures (bridge scour, earthquake degradation)

The leak detection market alone is estimated to be in the hundreds of thousands in the United States with the requirement of monitoring systems for all petroleum storage facilities over one thousand gallons. Added to that is the potential to employ TDR technology for the detection of other chemical and polluting liquids. The water level market is estimated to be in the tens of thousands and is also important for monitoring safety of water diversion structures. The market for deformation monitoring is estimated to be in the thousands and could be larger if and when automated telecommunication systems become robust enough to be installed and maintained by local personnel.

Broadening the market for TDR technology is critical for generating the enthusiasm needed to ensure the continued development of necessary components such as miniaturized pulsers and specialty cables and probes. Our interaction with original equipment manufacturers (OEMs) and venture capitalists has indicated that markets of 100s to 1,000s hold no promise for investment, no matter how helpful the technology. Markets of 1,000s to 10,000s attract attention but little investment from OEMs (at this level forgivable, supplementary funding from Federal sources is necessary to attract OEM participation). Only at the 10,000 to 100,000 unit threshold is there significant interest. It seems that the markets for leak detection and soil moisture measurement, which when combined could approach multiple hundreds of thousands, justify the continued development of TDR instruments as well as specialty cables and transducers.

WHO SHOULD READ THIS BOOK

Because of the broad spectrum of measurement possible with TDR, this book should be of interest to a wide variety of scientists, engineers, and contractors. Consider the following list of disciplines and applications of TDR technology:

- soil scientists and agricultural engineers monitor soil moisture,
- mining engineers monitor rock mass deformation,
- chemical engineers and facility managers monitor chemical and petroleum spills,
- civil engineers monitor water content of landfill covers and water pressures beneath dams, and
- geotechnical engineers monitor soil slope movements.

While the greatest number of installations are employed to monitor soil moisture (water content) and chemical and petroleum spills, use of TDR to monitor deformation is growing. Needs of all these disciplines are addressed in this book.

Material is presented at a professional level; it is assumed that the reader is college educated. Thus the book is appropriate for professional practice and graduate level courses in engineering and soil science. As far as possible, the presentation follows an observational or empirical rather than mathematical approach. However, the basic physics and quantitative nature of signal interpretation and computer processing will of necessity require some mathematics.

FUTURE DEVELOPMENTS

This chapter began with a short history, and the introductory process can be completed by concluding with an estimate of future developments. In addition to symmetry there are several important reasons to peer over the horizon. First, assessing future developments places in perspective the accomplishments chronicled herein. Second, contents of all books lag the forefront of research because they must be frozen for editing and publication at least a year before they are available for sale. Thus in a sense there are two time frames relative to this book. Near-term developments which are already well underway and long-term developments which are conceptual. Perhaps most important, TDR is an emerging technology for use in geomeasurements which is on the accelerating portion of the development curve. Its potential should not be judged solely by the snapshot in time represented by this book.

So what does the future hold? It will definitely involve many more users. For instance in the last year, the authors have installed cables to monitor deformation in unusual geo-materials for a number of new clients. Kilometers of leak detection cables and hundreds of moisture sensors are being installed at new sites each year. These clients in turn will use it on more projects and development of new products will accelerate.

Continued miniaturization of digital telemetry makes remote monitoring a practical reality. The inherent digital nature of TDR measurements will further accelerate its use for remote monitoring. Already, GeoTDR and Northwestern University have been involved with remotely operable systems at more than a dozen sites world-wide.

Smaller, less expensive pulser-samplers are being developed. For instance, the HYPERLABS instrument has already been modified and is being marketed. Another TDR unit has been developed as a plug-in card for use with portable field computers.

There will be new specialty cables and new uses for existing cables. Work has begun at Northwestern University to build a large-diameter compliant cable for use in soft soils. Prototypes could be installed within two years. Air-dielectric cables are being used to retrofit existing piezometers as described in Chapter 9.

Deformation-monitoring cables are being placed in obstructed inclinometer casing to extend the useful life of these installations.

There will be new probes and calibration techniques for measurement of soil moisture. Inexpensive methods are being developed to field calibrate moisture probes for specific soils. TDR is emerging as a viable alternative to nuclear techniques for measurement of *in situ* density of soils.

Look for greater use of TDR probes and cables to monitor contaminant migration. Already, air-dielectric cables are being employed by GeoTDR to monitor changes in subsurface oil pools. In this application, the difference of dielectric properties of oil and underlying ground water allows the thickness of oil to be measured directly. Companies are continuing to develop new specialty cables for leak detection and more cables will be employed to retrofit existing installations.

Finally, new analytical techniques will be developed. As described above, soil moisture probes are being calibrated for specific soils. Likewise, models are being developed that allow more sophisticated analysis of TDR signatures generated by cable deformity. For example, work will be completed this year at Northwestern on a numerical model that incorporates frequency dependent signal loss with transmission distance. This model will allow calibration of cables as well as analysis of multiple reflections.

INTERNET SUPPORT

This book 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. It can be reached at

http://www.iti.nwu.edu/clear/tdr/index.html

and an annotated bibliography is maintained on

http://www.geotdr.com

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.nwu.edu

while there is another list server which addresses the needs of researchers involved principally in monitoring soil water content at

owner-sowacs@aqua.ccwr.ac.za

ORGANIZATION AND CONTENT OF THE BOOK

Chapters were kept small and focus on separate areas of application. Discussion of principles is separated from that of case histories of application for soil moisture and rock deformation because of the large amount of material and large number of examples of application. A short introductory paragraph and outline of topics for each chapter follows to more fully describe the contents. Rapidly changing information is included in Appendices such as Contact Information for Vendors, as well as Cable and Grout Properties.

CHAPTER 2. BASIC PHYSICS

TDR operates like radar in a coaxial cable. Distances to reflectors along the cable are calculated by time of flight, and characteristics of reflectors along or at the ends of a cable can be discerned from details of their respective reflected signals. This chapter describes the basic physics of signal generation, transmission, and attenuation along the coaxial cable. Also described are the physics of signals reflected by changes (both single and multiple) in the transmission path (along the cable) and by changes at special probes (at the end of the cable). Reflections produced along the length can lead to measurement of fluid levels and their presence as well as cable deformation produced anywhere along the cable. Those produced with specially constructed probes at the end of a cable can be employed to measure changes in moisture content of soils. Particular attention is paid to the physics of multiconductor probes and changes in dielectric constant because of their importance in the measurement of soil moisture or unsaturated water content.

CHAPTER 3. MONITORING 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 lead to its widespread adoption in agricultural study, irrigation control, and the study of unsaturated particulate material in general. The dielectric constant, $K = e/e_0$, of air is 1, ranges from 3 to 5 for most soil mineral grains, and is approximately 81 for water (at 20°C). 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. This chapter describes probe design and procedures for their calibration as well as the variation in probe responses to changes in water content and soil mineralogy.

CHAPTER 4. 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. After presentation of typical agricultural field validation studies, additional case studies are presented to demonstrate use of TDR to measure spatial and temporal changes in soil moisture associated with the performance of landfill covers, compacted fills, and pavement subgrades.

CHAPTER 5. MONITORING LOCALIZED DEFORMATION IN ROCK

Measuring rock deformation with TDR developed naturally from the original purpose of this technology, namely, identification of cable faults or deformities along telephone and power cables. TDR cables were first installed in holes drilled into rock masses around mining operations simply to locate cable breaks which correlated with the extent of complete rock mass failure. During one such application it was noticed that the TDR reflection waveforms changed incrementally with rock mass deformation before failure. Subsequent laboratory studies indicated that it was possible not only to quantify the magnitude of deformation but also, in some cases, to distinguish shearing from tensile deformation. This chapter presents variations in waveform characteristics associated with cable deformation, cable calibration, and installation techniques for metallic cables installed in rock.

CHAPTER 6. FIELD EXPERIENCE AND VERIFICATION OF ROCK DEFORMATION MEASUREMENT

To date more than several dozen TDR deformation monitoring systems have been installed worldwide, which underscores its growing acceptance in the mining community. A number of case histories are presented to demonstrate the possibilities of quantitative evaluation of TDR waveforms for rock mass deformation. Comparisons are made with direct measurement of displacement in shallow boreholes, as well as those computed from inclinometer measurements. They are also made with indirect assessments based upon beam bending principles and cumulative horizontal displacements. This chapter closes with a number of case histories that illustrate the variety of environments wherein TDR measurement has been successfully employed.

CHAPTER 7. MONITORING SOIL DEFORMATION

It is possible to install a compliant TDR cable/grout system that will deform with localized soil shear zones in a manner similar to that observed with shearing of stiffer cable/grout systems by displacement along rock joints. In addition to developing the rationale for the use of compliant cable, this chapter presents several cases that demonstrate use of TDR cables in soil as well as weathered and soft rock. Remote monitoring of slope movement in soils has been inhibited by the manually operated nature of instruments commonly employed for this task, namely, the inclinometer or slope indicator. Inclinometers include down-hole electronics that must be manually lowered down a borehole and are thus difficult to operate remotely. TDR cable surveillance by its digital nature is automatically accomplished remotely and in addition is able to detect very thin shear zones.

CHAPTER 8. MONITORING STRUCTURAL DEFORMATION

This chapter presents the use of both metallic cable (MTDR) and optical fiber (OTDR) to monitor response of structures. While OTDR is not the focus of this book, a brief introduction to its physics and use is presented. Like its metallic counterpart, OTDR can be employed to monitor large volumes with a single fiber. While shorter wavelengths of optical signals allow measurement of elastic stress and strain, the location of the measurement must be known because the small strains can only be measured at selected locations. The chapter begins by describing use of MTDR for two aspects of structural response: 1) internal deformation, which involves monitoring localized response of individual structural members, and 2) external deformation, which involves monitoring the overall movement of a structure. It then closes with an overview of OTDR measurement of stress and strain within a structure.

CHAPTER 9. AIR–LIQUID INTERFACES

This chapter develops the background necessary for TDR measurement of fluid levels and discrimination of fluid types. TDR methods are compared with other approaches to measure pore water pressure near critical structures such as dams, as well as changes in ground water table elevation. Measurements are easily made via TDR because of the very large reflection that occurs at the air–water interface when water rises within the annular space of a hollow coaxial cable. In addition, TDR technology that identifies liquid presence is being extensively deployed to detect leakage of a variety of liquids over large areas or within large volumes. Leakage detection is possible with specially designed coaxial cables that selectively allow designated liquids to penetrate the outer conductor and permeate the dielectric material.

CHAPTER 10. ELECTRONICS

While various components of TDR systems can be acquired from a variety of suppliers, their functional relationship is constant and they can be described as a series of components. Since the state of the art in instrumentation is dynamic and is expected to be constantly changing, the attributes of each component are discussed in a generic manner. Discussion in this chapter begins with the sensor/transducer components followed by connections from the sensors to the TDR pulser/sampler. Next, the system control methods are discussed, followed by components for storage and downloading of TDR data. Finally, power requirements for remote monitoring are addressed and detailed examples of systems that have been used to monitor rock deformation and soil moisture are summarized.

CHAPTER 11. SOFTWARE

The wide variety of software available for transmission and analysis of TDR signatures is summarized in this chapter. Some software is designed specifically for control of pulser/samplers and some specifically for analysis of TDR waveforms, while a third category serves both functions. In order to elaborate on the capabilities of available software, common details of programs are described. Discussion in this chapter begins with general control and acquisition software, followed by a description of programs that have been developed specifically for analysis of soil moisture measurements and cable deformation measurements.