TELEMETRIC AND MULTIPLEXING ENHANCEMENT OF TIME DOMAIN REFLECTOMETRY MEASUREMENTS

by

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ABSTRACT

This paper describes development of computer and telecommunication technology that links a central data monitoring and processing station with multiplexed time domain reflectometry (TDR) cables in the field by modem or other telemetric means. TDR technology has been employed successfully in geotechnical applications, such as monitoring of rock mass deformation and subsidence in a variety of geometries, and measurement of water level, water pressure, and soil moisture content. Human operation at a site, however, still requires a major effort to collect and analyze records. Manual reading at weekly to monthly intervals prohibits continuous tracking of cable or wire response. Under such manual schemes, monitoring has been achieved by moving the TDR unit from place to place and attaching cables/wires one at a time. Visual analysis software [Northwestern University TDR Signature Analysis (NUTSA)] developed by Northwestern University can be used to visually compare up to three TDR waveforms quickly and easily. The graphical user interface is necessary to compare and analyze large numbers of TDR signatures. Complete TDR waveforms, for coaxial cables up to 650 m long, in formats such as Tektronix[3] SP232 and Campbell Scientific CR10, can be read. Amplitude and width of voltage reflections can be computed automatically, and results can be tabulated and saved in an ASCII file.

INTRODUCTION

Time Domain Reflectometry (TDR) is an electrical pulse testing technique originally developed to locate breaks in power transmission cables *(16)*.[4] This technique has been employed successfully in many applications in geotechnical engineering, such as rock mass deformation and water level changes *(6-12)*. However, typical operation still requires human interaction to collect and analyze records.

There is a need for TDR to warn of impending subsidence at critical facilities over abandoned mine lands *(2)*. It was reported that cable response to small movements has

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

[4]Italic numbers in parentheses refer to items in the list of references.

been demonstrated for early warning; however, manual reading schedules at weekly to monthly intervals prohibited continuous tracking of the cable response prior to failure. It was recommended that TDR should be monitored as frequently as possible, such as every 2 to 4 hours, during periods of active subsidence. Bauer *(2)* recognized that an intense monitoring schedule will enable the calculation of rates of shear in a potential failure zone and documentation of progressive fracture in the overburden.

Need for the capability of remote, real-time monitoring is best illustrated with the experience gained from the Dorris School installation *(2)*. As shown in figure 1*A*, the TDR system was installed on June 22, 1989, and movements associated with less than 6.35 mm of surface settlement by July 5 had changed the crimp signature to extension, as shown by the decrease in spike amplitude of the second signal in the insert to figure 1*B*. The extension nature of this movement is substantiated by the laboratory experimentation reported in *(11)*. Subsequent small movements failed the cable some time between July 5 and September 19, 1989, at a depth of 24.8 m, as shown by the truncation of the signal at that depth on September 19.

Had real-time monitoring been employed at this site, it would have been possible to precisely measure the rate of signal change between July 5 and September 19. Missing data that could have been obtained with the system described in this paper would have allowed determination of the amount of shear and extension deformation and the exact time of cable failure. Changes in the TDR waveform would have been observed prior to surface movements as local movements below ground would have produced deformation of the cable.

Consideration of economic factors demonstrate the need for multiplexing and can be illustrated best with the example shown in figures 2*A* and 2*B*. Assume that the surface facilities are partially underlain by an abandoned room and pillar mine. For long-term considerations, it is necessary to monitor subsidence caused by the collapse of the abandoned mine. One approach to optimizing the measurement system involves multiplexing of several cables from one pulser for early detection of surface subsidence. In this example, the monitoring program would involve installation of four vertical coaxial cables and seven inclined cables to monitor both localized and areal subsidence.

If the system had to be monitored manually, an operator would be required to visit the site once a month or even once a week to interrogate cables one at a time and collect a large number of hardcopy cable signatures for later analysis. If remote operation was utilized but no multiplexer employed, it would be necessary to use a TDR tester for each cable. Thus, a centralized, multiplexed, telemetric system decreases both the labor component of data collection and high cost of multiple cable testers as well as maintenance costs.

In the geometry of this example, only one TDR pulsing unit and two multiplexers would be required. Remote polling of the cables via telecommunication would allow movement to be monitored hourly if necessary and eliminate the need for field personnel to operate. The operating costs would be a telephone bill for data transmission and a maintenance contract with a local TV repair service to periodically check the system.

BACKGROUND

TDR equipment now available from Tektronix allows the required frequency of data acquisition *(17)*. Addition of an RS232 interface to the digital TDR cable tester *(18)*

A

B

Figure 2.-Single multiplexing unit at location (A) allows TDR pulsing of multiple cables. *A*, Plan view with cable radiation from central location; *B*, cross section xx' showing cable inclination.

allows remote interrogation and data retrieval. This development, without substantial cost increase, provided a missing link for continuous monitoring. Only development of specific application software and field testing of the system were required for demonstration of the system's capability.

Data communication can be achieved via modem, cellular, radio, or satellite. With this telecommunication flexibility, remote field sites can be linked to the central station for real-time monitoring. Data can be acquired at will, as frequently as necessary, via telemetric transmission. Furthermore, the system can be expanded to poll multiple cables remotely with the addition of multiplexers. Such a multiplexing system can be further deployed as a centralized or dispersed multiplexing system to match the measurement geometry.

A number of researchers have developed systems for recording reflections from multiple sensors in the field. Most of these are based upon linking the Tektronix 1502B cable tester with the Campbell Scientific CR21X datalogger and multiplexer *(1,13,14,20)*. Unfortunately, these systems to varying degrees fell short of the goal of the project: development of a remotely operable system that could receive instructions via a telecommunication link and poll multiple sensors from one TDR tester. Some of the systems are not remotely operable, some have no communication links, and some do not allow flexible multiplexing.

APPARATUS FOR REMOTELY MULTIPLEXED OPERATION

This paper describes telemetric and multiplexing enhancement of TDR measurements *(15)* in three phases. The first phase involved development of a remote, real-time data acquisition system. The second phase involved automation of data manipulation. Finally, the third phase involved expansion of the remote, real-time data acquisition system to a centralized, multiplexing data acquisition system. Future development and modification of these systems are also discussed.

Real-Time, Remote Data Acquisition

As described earlier, a real-time, remote data acquisition system is necessary to avoid loss of critical data from insufficient tracking of cable response. As schematically illustrated in figure 3, the remote field site requires installation of a cable tester with a RS232 interface and modem (1,200 bps) in a weather-proof enclosure with access to 120 Volt AC power and a telephone line. The central site, which in the demonstration was 500 km away, requires a 386 IBM-compatible computer with CGA or EGA/VGA monitor and modem (1,200 bps). Although a higher baud rate such as 2,400 bps may be used, the lower rate has been chosen to minimize data transmission errors due to high line noise.

Figure 3.-Remote, real-time TDR data acquisition system prevents critical data loss due to non-telemetric data collection (after *(15)*).

Communication protocols to combine the 251-word data blocks produced through the RS232 interface were implemented using the SP232 Host Application Program *(19)*. This series of command switches allows the operator to select the data sampling intervals, number of data blocks, and transmission switchs to properly digitize the TDR voltage reflection signal and transmit the data blocks upon request. The Northwestern University Modem Communication System (NUMOD) is the protocol developed to provide a data structure compatible with the TDR waveform analysis program *(15)*.

The system can only be used to poll a single cable, but the objective was to acquire waveforms whenever desired at a remote site. For example, such a system was deployed to detect early subsurface horizontal displacement above a longwall mining operation *(9)*. Horizontal displacements measured by surveying at the ground surface are compared with those acquired at depths of 48 m and 66 m along the cable in figure 4. The face was advancing at a rate of 10 m/day, and subsurface movements could be recorded on an hourly basis, as shown by the data density at a depth of 66 m. Thus, in addition to early detection of the subsequent surface movement, the remote operational aspect of the TDR system allowed readings to be taken at intervals that could be varied to match the rate of ground movement without human presence at the site.

A

B

C

Figure 4.-Comparison of horizontal shearing displacement that shows early detection of movement at depth by TDR. *A*, Surface survey; *B*, depth of 48 m; *C*, depth of 66 m (after *(9)*).

Automation of Data Manipulation

TDR waveform data may be processed with a wide variety of approaches. The simplest is the generation of a raw reflection signature as hardcopy. The next level of processing includes proper scaling of the signature for simple visual comparison with other waveforms. These scaled comparisons can be displayed graphically on a computer for easy manipulation and visual comparison. Finally, analytical programs can be developed to interactively analyze individual spikes on a signature or compare one signature with another.

These computerized analytical capabilities have been implemented in NUTSA, an interactive TDR analysis software with on-line help developed by Huang *(15)*. NUTSA is designed to allow visual comparison of up to three TDR waveforms quickly and easily. Various user-specified processes can then be employed to quantitatively compare the data. This approach maximizes the efficiency of human decision-making and visual acuity by providing a rapid means of comparison and calculation.

Development of NUTSA was motivated by the need to analyze and interpret large numbers of TDR records obtained when monitoring long (up to 650 m) cables on a daily basis. The location, amplitude, and width of changes in the signature can be visually compared and significant differences quantified. This approach avoids development of signal interpretation routines and facilitates human judgement. The most recent version of NUTSA can read data obtained using either a Tektronix SP232 or Campbell Scientific CR10 datalogger.

Dowding and Huang *(9)* have reported that TDR signatures acquired when monitoring rock mass deformation measurement may show slight variations of signature locations from record to record. In the past, operators aligned all TDR waveform hardcopies and manually searched for variation of spike location. With NUTSA, this challenge is overcome simply with a few key strokes. By moving the cursor to the peak of the spike location of the first waveform and then to the peak of the next waveform, the variation of the peak location can be quantified. This quantification reduces the processing time required for a large number of TDR waveform files.

For example, consider changes between two signatures from the above project shown in figure 5. NUTSA displays both waveforms as well as the arithmetic difference in the lower window. It is intended that function keys and commands be used to locate and characterize changes, and a simple algorithm for quantifying the difference in spike width was incorporated to allow for a gross quantification of change. By moving the cursor to the location of the difference spike apex, which is located at 30.12 ft, the excursion amplitude of -15.00 m 2 ft are displayed at the left, as shown in figure 5. The program searches from the peak position (30.12 ft) to the left until a difference amplitude of zero is reached. If a difference amplitude of zero is reached, NUTSA considers this point as the left end point. It then searches from the peak position to the right until a difference amplitude of zero is reached. If a difference amplitude of zero is not reached after incrementing over 10 data points, NUTSA then considers this point as the right end point. The location, magnitude, and width of each reflection in the difference can be stored for further analysis.

This computational assistance is the first step in developing an expert system or an artificial intelligence program for analyzing changes in TDR signatures. It not only

Figure 5.-Screen displayed by NUTSA showing the spike width of the arithmetic difference waveform (after *(15)*).

facilitates data interpretation, but also facilitates quantifying and synthesizing of large volumes of acquired data. More sophisticated methods need to be developed to interpret large data bases of TDR signatures that result from either long or multiple cables. Unfortunately, the large variation in shapes requires a significantly complex expert system to replace visual inspection by a human "expert".

Multiplexing Data Acquisition System

Field placement of TDR instruments is envisioned to be either centralized or dispersed. Equipment for placement at centralized sites must provide a comparatively protected environment for the TDR pulser, multiplexer, telemetric device, and remote controller. Equipment for placement at dispersed sites must be sufficiently robust or power-independent to allow dispersed deployment in remote and hostile environments typically associated with geotechnical, mining, environmental engineering, and infrastructure monitoring. So far, no robust, dispersed system exists.

An example of a centralized, multiplexed system is illustrated in figure 6. The main components at the remote site are a TDR cable tester, a datalogger, one or more multiplexers, data storage modules, and a modem *(3)*. Based upon various functions, the system can be separated into three main subsystems that are responsible for multiplexing, automation, and telecommunication.

A 50-ohm coaxial cable carries microwave pulses from the TDR pulser to the input channel of the multiplexing unit *(3)*. Up to eight channels can be connected to cables or wires for polling with one multiplexer. If more than eight channels are required, the multiplexing unit can be expanded up to three levels and up to 512 switching channels by connecting one of the switching channels to the input channel of

Figure 6.-Equipment for placement at centralized site provides a protected environment for the TDR system, which allows automatic, remote, multiplexing data acquisition (after *(15)*).

another multiplexing unit, as illustrated by level 2 in figure 2.

The datalogger is controlled by a datalogger program *(4)*, which is downloaded from a computer remotely or directly. With the datalogger program active in datalogger's memory, it executes the following sequence: (1) turns the TDR pulser power on, (2) acquires TDR waveforms from one channel, (3) switches to the next channel in multiplexing unit, (4) acquires TDR waveforms from the second channel, (5) repeats the data collection sequence until all channels are polled, and (6) finally turns the pulser power off. This process is totally automatic and requires no operator in the field.

Telecommunication tasks can be achieved via telephone line and modem links as well as other forms of telecommunicating systems, such as radio, cellular telephone, or satellite *(5)*. A three-channel prototype of this multiplexing system has been constructed and tested. It is envisioned that a multiplexed site may be arrayed to monitor water level or piezometric pressure *(10)*, shear deformation *(11,12)*, and/or failure detection via TDR technology, as illustrated in figure 7. Each measurement type will require a different data block and data density structure.

SUMMARY

Equipment and software is available for telemetric and multiplexing enhancement of TDR measurements. Visual analysis software, NUTSA, that incorporates both Tektronix and Campbell Scientific data formats, is described. These hardware and software enhancements of existing TDR data acquisition systems not only support TDR measurements in geotechnical engineering, but also allow the complete system to be employed in a variety of other applications. Based upon these developments, the following conclusions are advanced:

1. Remote control of TDR measuements via modem over existing telephone lines with serial communication modules is available but requires appropriate software to acquire and analyze the high density of data acquired.

2. Remote polling allows collection of TDR data at any desired time interval.

3. The TDR data analysis software, NUTSA, provides graphical, user-friendly visual analysis with on-line help which facilitates waveform analysis of a large number of TDR waveforms.

4. The automatic, remote, multiplexing TDR data acquisition system proved to be flexible enough to allow a variety of measurements simultaneously, such as water level monitoring, soil/rock shearing, and failure detection.

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REFERENCES

1. Baker, J.M. and R.R. Allmaras. System for Automating and Multiplexing Soil Moisture Measurement by Time Domain Reflectometry. Soil Society of America Journal, v. 54, No. 1, 1990, pp. 1-6.

2. Bauer, R.A., C.H. Dowding, D.J. Van Roosendaal, B.B. Mehnert, M.B. Su, and K.M. O'Connor. Application of Time Domain Reflectometry to Subsidence Monitoring. Office of Surface Mining, Pittsburgh, PA, Final Report, 1991, 48 p.

3. Campbell Scientific, Inc. (Logan, UT). TDR Soil Moisture Measurement System Manual, February, 1992, 11 p.

4. _____. CR10 Measurement and Control Module Operator's Manual, November, 1992, 195 p.

5. _____. PC208 Datalogger Support Software Instruction Manual, November, 1992, 69 p.

6. Dowding, C.H. and F.C. Huang. Water Pressure Measurement with Time Domain Reflectometry. U.S. Patent Application, 1993, 9 p.

7. _____. Ground Water Pressure Measurement with Time Domain Reflectometry. Proceedings of the First Symposium and Workshop on Time Domain Reflectometry, Northwestern University, Evanston, IL, 1994, 12 p.

8. _____. Remote Piezometric Water Pressure Measurement with Time Domain Reflectometry. Submitted for publication, Geotechnical Testing Journal, ASTM, 1994, 25 p.
9. _____. Early Detection of Rock Movement with Time Domain Reflectometry. Accepted for publication, Journal of Geotechnical Engineering, ASCE, v. 120, No. 8, 1994, 28 p.
10. _____. Automatic, Remote, Multiplexed Geotechnical Measurements with Time Domain Reflectometry. Accepted for publication, First Congress on Computing in Civil Engineering, ASCE, Washington, DC, 1994, 8 p.
11. Dowding, C.H., M.B. Su, and K.M. O'Connor. Measurement of Rock Mass Deformation with Grouted Coaxial Antenna Cables. Rock Mechanics and Rock Engineering, v. 22, No. 1, 1989, pp. 1-23.
12. _____. Principles of Time Domain Reflectometry Applied to Measurement of Rock Mass Deformation. International Journal of Rock Mechanics and Mining Sciences, v. 25, No. 5, 1988, pp. 287-297.
13. Heimovaara, T.J. and W. Bouten. A Computer-Controlled 36 Channel Time Domain Reflectometry System for Monitoring Soil Water Contents. Water Resources Research, v. 26, No. 10, 1990, pp. 2311-2316.
14. Herkelrath, W.N., S.P. Hamburg, and F. Murphy. Automatic, Real-Time Monitoring of Soil Moisture in a Remote Field Area with Time Domain Reflectometry. Water Resources Research, v. 27, No. 5, 1991, pp. 857-864.
15. 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. I.C. 9346, U.S. Bureau of Mines, Washington, DC, 1993, 42 p.
16. Moffitt, L.R. Time Domain Reflectometry: Theory and Applications. Engineering Design News, November, 1964, pp. 38-44.
17. Tektronix (Beaverton, OR). 1502B Metallic Time Domain Reflectometer Operator Manual, 1989.
18. _____. SP232 Serial Extended Function Module Operator Manual, January, 1989, 103 p.
19. _____. SP232 Host Application Program User Guide, December, 1990, 11 p.
20. Wraith, J.M. and J.M. Baker. High-Resolution Measurement of Root Water Uptake Using Automated Time-Domain Reflectometry. Soil Science of America Journal, v. 55, 1991, pp. 928-932.

A

B

Figure 1.-Small movements in rock mass between July 5 and September 19, 1989, failed the cable at a depth of 24.8 m (81.5 ft) and resulted in missing important data that could be overcome by telemetric data acquisition. *A*, Surface settlement versus time; *B*, cable

response versus time (after *(2)*).

A

B

C

Figure 7.-Example of multiplexed site for multiple applications. *A,* Water level monitoring; *B,* rock/soil shearing monitoring, and; *C,* failure detection are simultaneously implemented.