FINAL REPORT

Interpretation of Event Response through Web Based Archival of TDR Signals

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Improved Interpretation of Highway Geohazard Monitoring Data Through Web-Based Management of Time-Domain Reflectometry

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INTRODUCTION

As remote geotechnical or structural monitoring of transportation facilities becomes more common, the amount of raw data available to infrastructure owners and engineers is increasing. However, acquisition of more and more data does not necessarily increase the amount of actionable information available for owners and engineers to make decisions. The Northwestern University Infrastructure Technology Institute (NU-ITI) has developed a Web-based data management system to improve the utility of remote monitoring measurements by autonomously transmitting data from the field to the laboratory, storing it in a searchable database, and making automatically-generated data plots and tables available to practitioners and researchers via a password-protected Web site.

The three critical questions for continuous remote structural or geotechnical monitoring for a transportation facility are

1) How can meaningful performance data be collected from the facility in question? That is, what engineering quantities should be measured, and by what types of instruments and data acquisition equipment?

2) How should the data be transmitted from the field to the laboratory or office? For a variety of reasons, it is often impractical to frequently dispatch an engineer or technician to download data manually at a field site. Robust methods are needed to transmit data reliably to a central location for analysis.

3) How should the data be stored and displayed for interpretation? More informally, once the data reaches the office, what does one do with it? How can the raw data be distilled into actionable information?

This paper describes the development of methodologies to address the second and third questions above, with emphasis on the third, in the context of a live field deployment along a section of Interstate highway threatened by subsidence due to an abandoned coal mine.

DATA MANAGEMENT SYSTEM DESCRIPTION AND KEY INNOVATIONS

An end-to-end data archive and display system for TDR monitoring of highway geohazards has been developed. The purpose of the system is to expand the practice of remote monitoring of highway geohazards by making monitoring data readily useful to practicing engineers. This is achieved by capturing data from the field, storing it in a relational database, plotting the data
automatically, and making the plots and raw data available to practitioners through a password-protected Web site. Key system features include:

**Sensor and Monitoring Hardware Independence**: The data management system is designed to operate with a nearly any sensor or data acquisition system, rather than intended for use specifically with one manufacturer’s hardware. This is accomplished by using an abstract framework to handle sensor data. For each data acquisition system type, a *conversion script* is written to import data into a relational database. All other aspects of the data management system take place within the framework of the database. Thus, all that is necessary to begin including data from a new manufacturer’s equipment is to write a conversion script to parse the manufacturer’s data format into the database. While not trivial, the conversion scripts are typically short and straightforward.

**Scalability**: The data management system supports an arbitrary number of sensors and data acquisition modes for a given field site. Effectively, the number of sensors on a given Web site is limited only by the number of graphs that can be reasonably displayed on the various pages that comprise the site. This limit can be circumvented by breaking the sensors into logical categories for display. Similarly, a single data management Web server can host data management Web sites for many physical field sites.

**Autonomous Operation**: All aspects of the data management system operate without human intervention. The field site is polled by an automated server nightly; the new data is immediately entered into the project database, plotted, and made available on the web site. The flow of data from the field to the lab in the context of the owner’s decision-making process is shown in Figure 1.

![Figure 1: Autonomous transmission of data from field site to management office](image-url)
Data Management Web Interface

The password-protected Web site presents a complete record of TDR waveforms for the site, allowing for easy comparison of current and baseline measurements. Typical TDR waveforms, showing the difference between current and baseline measurements, are shown in Figure 2. Other data streams (such as groundwater pressure, which will be discussed later) are also included.

Figure 2: Screen capture of the data management Web site showing typical TDR waveforms
CASE STUDY: I-70 OVER ABANDONED MINE, MUSKINGUM COUNTY, OHIO

Much of the I-70 corridor through Ohio and western Pennsylvania is underlain by shallow coal deposits. Over the past 10-15 years, several locations along this corridor have been affected by subsidence – “sinkholes” – due to collapse of abandoned mines in these coal deposits. A notable example is the March 5, 1995 collapse of a section of I-70 near Cambridge, Ohio; while there were fortunately no fatalities, three cars and a truck fell into the subsided area, and that portion of I-70 was completely closed for approximately three and a half months (Federal Highway Administration, 2003).

A subsidence monitoring system based on time-domain reflectometry (TDR) technology was installed at postmile MUS-I-70-15.31 in Muskingum County, Ohio, near the city of Zanesville. Subsidence features were first documented in April 2006 by personnel from the Ohio Department of Transportation (ODOT). In 2009 and 2010, consultants designed and installed a distributed monitoring system based on TDR cables grouted into horizontal directional drilled holes. TDR monitoring operates on the principal that movement of soil or rock around the cables will cause the cable to deform or break, resulting in a change of electrical properties which can be measured and localized by TDR pulser equipment. The theory and practice of TDR for geomeasurements is described in Dowding and O’Connor (1999).

The subsidence monitoring system consists of eight TDR cables in horizontal directional drilled holes and one vibrating-wire piezometer in a vertical borehole. The horizontal TDR cables are two to five feet below the surface of the pavement; a plan view of the horizontal TDR cables is shown in Figure 3. The piezometer is within the mine void. Figure 4 is a section view under the eastbound lanes showing the pavement, TDR cables, and mine void. Readings from each TDR cable and the piezometer are taken every six hours.

Figure 3: Plan view of horizontal TDR cables beneath east- and westbound lanes of I-70
Incorporation of Groundwater Elevation Measurement

One important innovation at the Muskingum County site was to include real-time measurement of groundwater elevation in the subsidence monitoring system. Groundwater elevation data can provide important insight into subsidence risks; Changes in groundwater elevation may influence mine subsidence in two different ways: first, a rising water table may soften the clay/clay shale stratum which often underlays coal seams, allowing coal pillars in the mine to punch through; second, a falling water table leads to increased effective stress in the mine roof, leading to roof collapse. A vibrating-wire piezometer was installed in Well B4, located in the median of I-70 at station 126+28.36. The piezometer is within the mine void at elevation 880 feet, as was shown in Figure 4. Rather than directional-drill another hole for power and communication cable, the piezometer installation is powered by a solar panel and battery and communicates with the main data acquisition system, located just under ¼ mile away (at station 138+00) and on the right shoulder of the eastbound lanes, by a point-to-point digital radio link. Figure 5 shows the piezometer installation in the highway median, and Figure 6 presents the locations of the piezometer and main data acquisition system.

The piezometer has shown variations in water table elevation over a range of ten feet over the course of a year, as shown in Figure 7. Using plots of groundwater pressure and elevation, such as those in Figure 8, ODOT engineers are able to identify times when the water table is falling and extra vigilance for subsidence due to roof collapse is warranted. Since water pressure is key to many geotechnical problems, the incorporation of automated groundwater measurements into the data management system will likely find widespread use.
Figure 5: Vibrating-wire piezometer in median with radio link to main data acquisition system, just under ¼ mile away.

Figure 6: Plan view of site showing distance from piezometer in median to data acquisition system (DAQ) on shoulder. Note match line.
Figure 7: Changes in water table elevation, August 2010 - November 2011

Figure 8: Typical piezometer data on project Web site
Quantifying TDR Activity

Individual TDR waveforms such as those in Figure 2 present a “snapshot” of the cable’s condition at a given moment in time. It may also be useful to consider the evolution of changes in TDR response at a given point along the cable over time. New TDR activity plots complement the TDR waveforms by automatically tracing the change in TDR response at a given point along a cable over time. The points are identified automatically by a numerical algorithm; TDR activity time histories are plotted for points with more than five TDR activity indicators. A typical TDR activity plot is shown in Figure 9. Because areas of change in signal are automatically identified, the development of shear zones may, in some cases, become apparent sooner on the TDR activity plot than by comparison of current and baseline waveforms.

![Typical plot of TDR activity at a given location over time](image)

**Figure 9:** Typical plot of TDR activity at a given location over time

Software Improvements Through Dialog With Users

Dialog with ODOT engineers has resulted in a number of improvements to the data management web site. For example, ODOT engineers pointed out that distance along the cable, which is commonly used as the x-coordinate for TDR waveform plots, has little meaning in terms of the physical location of possible subsidence features along the roadway. In response, the graphs were annotated to include indicators of highway stationing corresponding to important points along the graph, as shown in Figure 10.
CONCLUSIONS

An autonomous end-to-end data management system for monitoring highway geohazards with TDR has been developed and deployed at a field site. Through autonomous operation, the data management system promotes convenient and easy interpretation of real-time infrastructure monitoring data, which in turn promotes better management of transportation assets, especially in light of response to geohazards. The data management system includes data streams for several sensor types and is flexible and scalable to accommodate arbitrary numbers of sensors and sensors of all types. The presentation of data on the Web site was developed in coordination with the state highway engineers who presently use it.

REFERENCES


APPENDIX: Equipment List

*With the exception of the piezometer itself, which is sold by Geokon, all equipment below is sold by Campbell Scientific, Inc. (CSI).*

Main Data Acquisition System

Model CR1000-XT-XW-CC measurement & control datalogger (CSI Part 16130-30)

Model RF401-XT 900 MHz spread-spectrum radio (CSI Part 18101-10)

900 MHz 9 dBd Yagi antenna (Type N female) (CSI Part 14201)

Surge suppressor for 900/922 MHz spread spectrum radio (CSI Part 14462)

Remote Piezometer Installation

Model AVW206-XT 900 MHz wireless 2-channel vibrating wire interface (CSI Part 20749-2)

900 MHz 9 dBd Yagi antenna (Type N female) (CSI Part 14201)

Surge suppressor for 900/922 MHz spread spectrum radio (CSI Part 14462)

Model BP12 12V, 12 amp-hour sealed rechargeable battery (CSI Part 8065)

Model CH100-SW 12V charger/regulator (CSI Part 17369-14)

Model SP10 10W solar panel (CSI Part 5278)

Model ENC10/12-SC-NM weather resistant 10x12 inch enclosure (CSI Part 15874-46)

Model 4500AL(V) piezometer with 60 feet of lead wire (Geokon)