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Internet-Enabled Remote Monitoring of Civil Infrastructure with TDR

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Abstract

Automated remote time-domain reflectometry (TDR) installations have proven to be powerful tools for monitoring civil infrastructure facilities, especially in cases of scour-critical bridges, roadbed subsidence, sinkholes, landslide areas, and seismic zones. However, continuous remote TDR sensing presents a number of data management challenges that can prevent the data from being used to its full potential. First, the large volume of data generated by continuous monitoring can quickly overwhelm a research team. Second, individual data files, which typically contain a day or week's worth of data, are difficult to interpret without a context. These two challenges can be met by providing engineers with full waveforms or histories of specific responses for comparison and decision-making.

The technology described herein seeks to autonomously present TDR data in a more useful day-to-day basis through Internet-enabled remote monitoring technology. In this system, proprietary data files from remote TDR instruments are autonomously parsed into a powerful searchable database to remove the artificial separation between data files and connect the data to historical baselines. The data are then displayed on a secure web site in an easy-to-use searchable graphical format. The system has been successfully deployed for several years in the continuous remote TDR monitoring of a scour-endangered state highway bridge, an Interstate highway subject to roadbed subsidence, and a state highway damaged by a sinkhole-like feature.

Key Words Remote monitoring, database, scour, subsidence, sinkhole, TDR

Introduction

Since the first geotechnical and structural applications of TDR in the 1970s, engineers have found that the technology provides valuable insight into the behavior of geomaterials and structural members that are otherwise not readily observed or inspected.

In geotechnical and structural applications, TDR is typically employed to detect three basic modes of displacement: simple extension, simple shear, and combined shear/extension (Charette and Beauchamp, 2001 [1]). TDR waveforms generally also indicate points where the cable has been crimped or severed; these are usually apparent from a visual inspection of the waveform. However, the cases of simple or combined shear and extension typically require side-by-side comparison of the current waveform with an initial baseline waveform, typically taken when the system is first installed. This side-by-side comparison may be made both qualitatively and quantitatively. An engineer with a basic knowledge of TDR will be able to quickly compare the waveforms visually and determine whether significant movement has taken place since the baseline measurement was acquired. If the qualitative comparison does not indicate any significant change, the engineer may immediately move on to the next task at hand. If the qualitative comparison does indicate a change, the engineer may perform a more detailed quantitative analysis to gain further insight into the issue.

Part of the importance of continuous monitoring is the ability to recognize small changes sufficiently early to enable mitigation of the potential impacts rather than waiting until a more significant failure has occurred that requires a more costly repair. In a TDR installation on a longwall coal mine, Dowding and O'Connor (1999 [2]) were able to detect subsurface movement four days before movement was measured at the surface. Data such as this could be used to plan additional proactive steps to minimize impact, but only if it is distributed to engineering staff in a timely fashion.

This ability to quickly compare waveforms and perform a detailed analysis only if necessary makes TDR a powerful tool for long-term monitoring. Very little interpretation is required to determine that the waveform has not changed since a previous measurement. However, this advantage can be lost if the responsible engineer is forced to perform the repeated menial tasks associated with collecting data and plotting it for visual comparison to the baseline waveform.

The Data Management Challenge

The issue of data collection has been addressed primarily through the use of TDR pulsers and dataloggers with remote communication capability. For sites where it is possible to connect to a telephone land line or obtain a cellular signal, any computer with a modem may be used to obtain data. In more remote areas, technologies such as point-to-point radio links or satellite communications may be employed.

Situations where there may be several or many individuals who require access to the TDR data, however, pose several challenges. First, there is the issue of providing data to various stakeholders, often in different locations. This may include researchers, managers, and practitioners in the same office or at different organizations in different locations. If multiple observers require data from a remote site, there is a significant risk that they might overwrite data that another party needs or inadvertently change settings so that other parties are not able to obtain or properly understand the data. Second, there is the issue of data parsing, archiving, and display. Typically, dataloggers will store data in files representing a test period – often the time since the unit was last reset. This test file, then, will usually contain a day's or week's worth of data. In order to make any comparison with previous data, as is particularly helpful in TDR work, one must find the test file containing the historic data, identify the data set of particular interest, and create graphs or other reports based on that data. Given that many automated monitoring facilities take data daily or hourly, the amount of data that must be searched quickly becomes overwhelming. Furthermore, the separation of data into artificially divided individual test files can make it difficult to find data of particular interest in the data set.

These issues necessitate an integrated system of data acquisition, archiving, display, and distribution that will display data from a field site in a useful format and distribute it to stakeholders in near-real time. These have been met in an Internet-enabled remote monitoring system developed at the Northwestern University Infrastructure Technology Institute (ITI) and commercialized by Civil Data Systems. This technology automates the process of collecting, parsing, archiving, displaying, and distributing data from the field to the users via a secure Web site. While there are commercial products which perform some of these tasks, the system describe herein is unique in that it provides an integrated, fully autonomous approach which brings data from the field to the Web without any human interaction, and that it has been shown to work reliably in varied deployments for years at a time.

Data Flow

The flow of data from field to end user is shown in Figure 1. A field computer or datalogger at a remote site collects data from TDR pulsers and other sensors, such as tiltmeters, temperature and humidity gauges, strain gauges, or any number of different sensor types. At some prescribed interval – typically daily, but sometimes more or less frequently, depending on the sensitivity of the site and the power requirements, among other factors – contact is made between the field site and a polling computer in a server farm that autonomously collects the data from the field. Depending on the installation, contact may be initiated by either the polling computer or the field site.

Once the data are transferred to the polling computer, a Web server operating custom software downloads the data from the polling computer, applies conversion factors as necessary, and parses it into a searchable database for archiving and display. The data are now available for viewing on the remote installation's web site. Typically, the web site is password-protected so only authorized users may obtain access to the data; password-protection is especially important when data are collected as the result of litigation, as will be discussed later. However, it will sometimes be desirable for the web site to be fully open to the public. It is also possible to make certain areas of the site public and others password-protected.

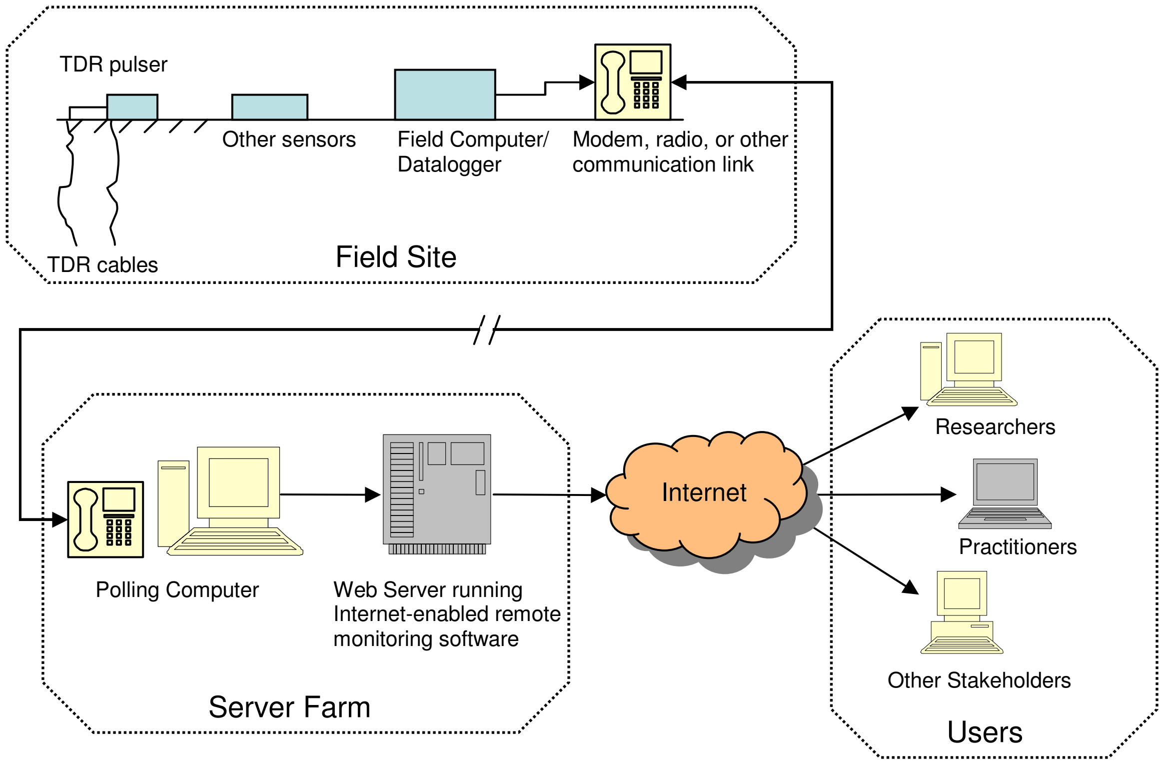


Figure 1: Data flow from the field to the Web site

The system described above employs several layers of abstraction in order to be as flexible as possible. Field computers often use proprietary data file formats which can be read only with proprietary software. The polling computer uses this software to gather the data from the field and convert it into a standard intermediate format for communication with the web server. This format eliminates the need to install additional software on the web server that may monopolize its resources or otherwise compromise its stability.

Standards for Data Exchange

The use of an intermediate format as described above allows the system to be safely abstracted from the proprietary data formats often associated with commercial dataloggers. Timekeeping is the first concern in establishing an intermediate format. In order to impose a unified timekeeping mechanism on data from different sources, all date stamps are given in Julian dates representing the local time at the remote site. Julian dates are simply the number of days that have passed since a certain epoch date. This standard is used because Julian dates are easily represented in computing as fixed-point decimal numbers and are not vulnerable to confusion between different calendar date formats

The second concern in developing an intermediate data format is that the data be readily human- as well as machine-readable. Civil Data Systems and ITI use tab-delimited text files. The result is that humans may read the data in columns, while the tabs indicate to computers the end of one field and the beginning of the next. Civil Data Systems and ITI recommend these conventions as a standard for data exchange.

Data Archiving and Display

The software on the web server parses the intermediate data into a searchable database which supports the Structured Query Language (SQL) standard. The display software then reads data through the SQL interface. The use of an SQL database as a data clearinghouse eliminates the need to modify the display software to accommodate a new type of field computer or changes to the polling software. Finally, the end-users obtain the data as HTML, text, and images through a Web interface which requires no extra software; that is, no plug-ins such as Java, Flash, Shockwave, Adobe, or ActiveX are required.

The abstraction provided by the above is most beneficial in that the system can be easily adapted to work with different hardware in the field. Internet-enabled remote monitoring sites have been successfully deployed using a variety of sensors and field computers including off-the-shelf hardware from Campbell Scientific and Somat as well as a number of custom-built devices.

Autonomous Operation

Each Internet-enabled remote monitoring installation operates autonomously; that is, data flows from the TDR pulser and datalogger in the field, to the polling computer and web server, to the end-users without intervention by human operators. This arrangement maximizes the benefits of remote monitoring by dramatically reducing the amount of time spent performing data acquisition and management tasks. Instead, all of the time spent with the data may be devoted to interpretation.

Internet-enabled remote monitoring systems are also able to autonomously notify human operators when the monitoring system or communication link themselves experience problems. For example, the polling computer or Web server may send e-mail or telephone messages to an operator when contact cannot be established with the field site. The Web server may also send alert messages when data values exceed pre-programmed thresholds. These features are not designed to replace human interpretation of the data; rather, they help focus engineers' time specifically on data interpretation by automating quality-assurance tasks.

Web Site

The primary motivation for displaying live TDR data on a Web site is to be able to easily compare current waveforms to baseline and historical readings on any computer with a Web browser. Secondary benefits include the ability to provide a universally accessible clearinghouse for all information regarding the monitoring site, the environment, and operating parameters of the monitoring system itself, such as internal temperature and battery voltage. Figures 2-4 are screenshots from a TDR web site developed for Northwestern University's Infrastructure Technology Institute. Since no special software is required to view the site, the data may be interpreted on any computer with a Web browser. The site is usable on both high-speed and dial-up Internet connections.

Current vs. Baseline Readings

Figure 2 shows that the web site for a particular TDR installation prominently displays the current TDR waveforms with the corresponding baseline readings. This page allows the qualitative side-by-side comparison of the current and baseline readings that helps an engineer quickly detect an occurrence of significant movement or something else warranting further inspection.

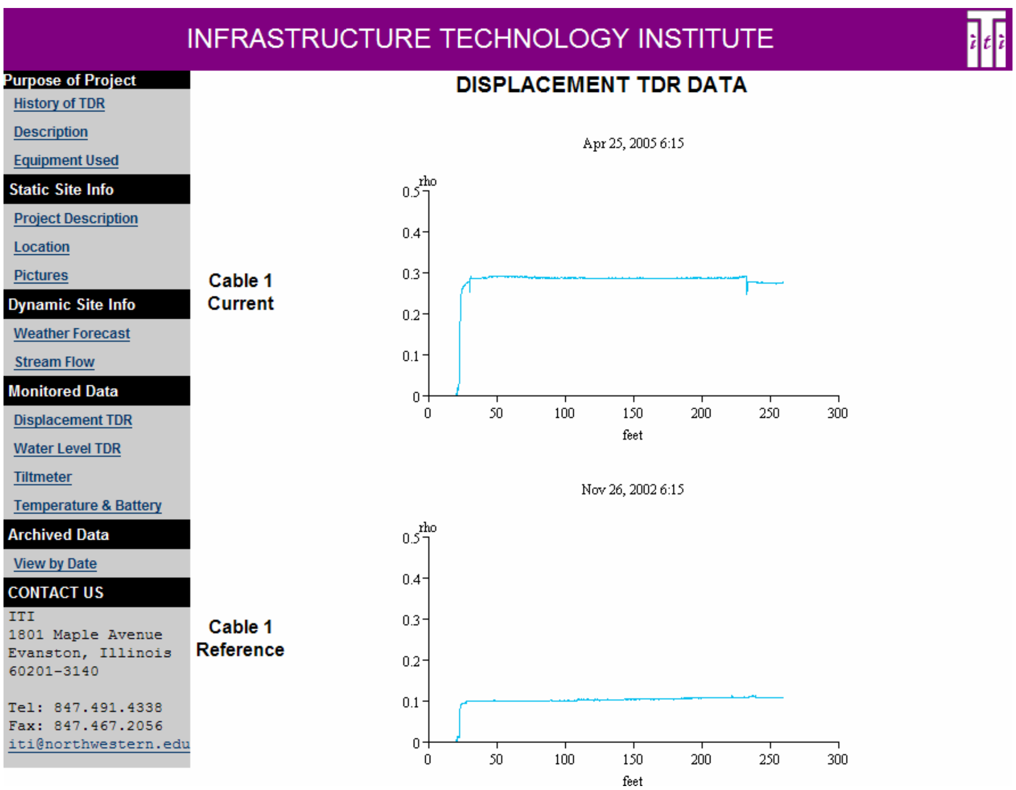
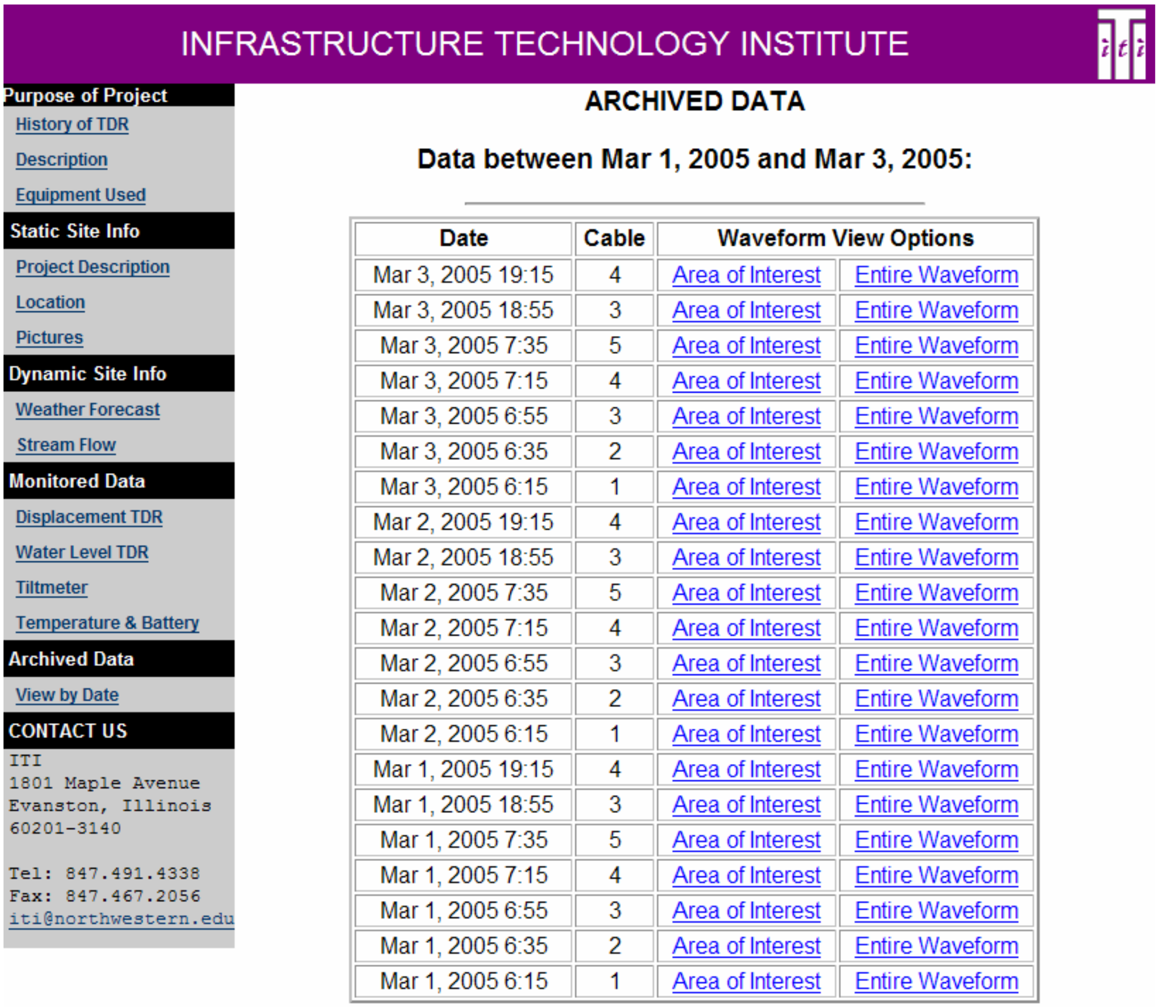


Figure 2: Current and baseline waveforms displayed on a Web site

Historical Data

The web site also provides the ability to search through historical data, as shown in Figure 3. For example, it is possible to review the record to determine when certain movement occurred. It is also possible to download a text file containing the raw data for analysis in another program, such as Matlab or Microsoft Excel.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Purpose of Project
History of TDR
Description
Equipment Used
Static Site Info
Project Description
Location
Pictures
Dynamic Site Info
Weather Forecast
Stream Flow
Monitored Data
Displacement TDR
Water Level TDR
Tiltmeter
Temperature & Battery
Archived Data
View by Date
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ARCHIVED DATA

Data between Mar 1, 2005 and Mar 3, 2005:

Date	Cable	Waveform View Options	
Mar 3, 2005 19:15	4	Area of Interest	Entire Waveform
Mar 3, 2005 18:55	3	Area of Interest	Entire Waveform
Mar 3, 2005 7:35	5	Area of Interest	Entire Waveform
Mar 3, 2005 7:15	4	Area of Interest	Entire Waveform
Mar 3, 2005 6:55	3	Area of Interest	Entire Waveform
Mar 3, 2005 6:35	2	Area of Interest	Entire Waveform
Mar 3, 2005 6:15	1	Area of Interest	Entire Waveform
Mar 2, 2005 19:15	4	Area of Interest	Entire Waveform
Mar 2, 2005 18:55	3	Area of Interest	Entire Waveform
Mar 2, 2005 7:35	5	Area of Interest	Entire Waveform
Mar 2, 2005 7:15	4	Area of Interest	Entire Waveform
Mar 2, 2005 6:55	3	Area of Interest	Entire Waveform
Mar 2, 2005 6:35	2	Area of Interest	Entire Waveform
Mar 2, 2005 6:15	1	Area of Interest	Entire Waveform
Mar 1, 2005 19:15	4	Area of Interest	Entire Waveform
Mar 1, 2005 18:55	3	Area of Interest	Entire Waveform
Mar 1, 2005 7:35	5	Area of Interest	Entire Waveform
Mar 1, 2005 7:15	4	Area of Interest	Entire Waveform
Mar 1, 2005 6:55	3	Area of Interest	Entire Waveform
Mar 1, 2005 6:35	2	Area of Interest	Entire Waveform
Mar 1, 2005 6:15	1	Area of Interest	Entire Waveform

Figure 3: Searching through historical data

Other Parameters

An additional benefit is the ability to measure and display the operating parameters of the monitoring system itself, such as internal temperature and battery voltage, as shown in Figure 4. When other sensors, such as tiltmeters, are used in conjunction with TDR, their readings can also be displayed on the web site.

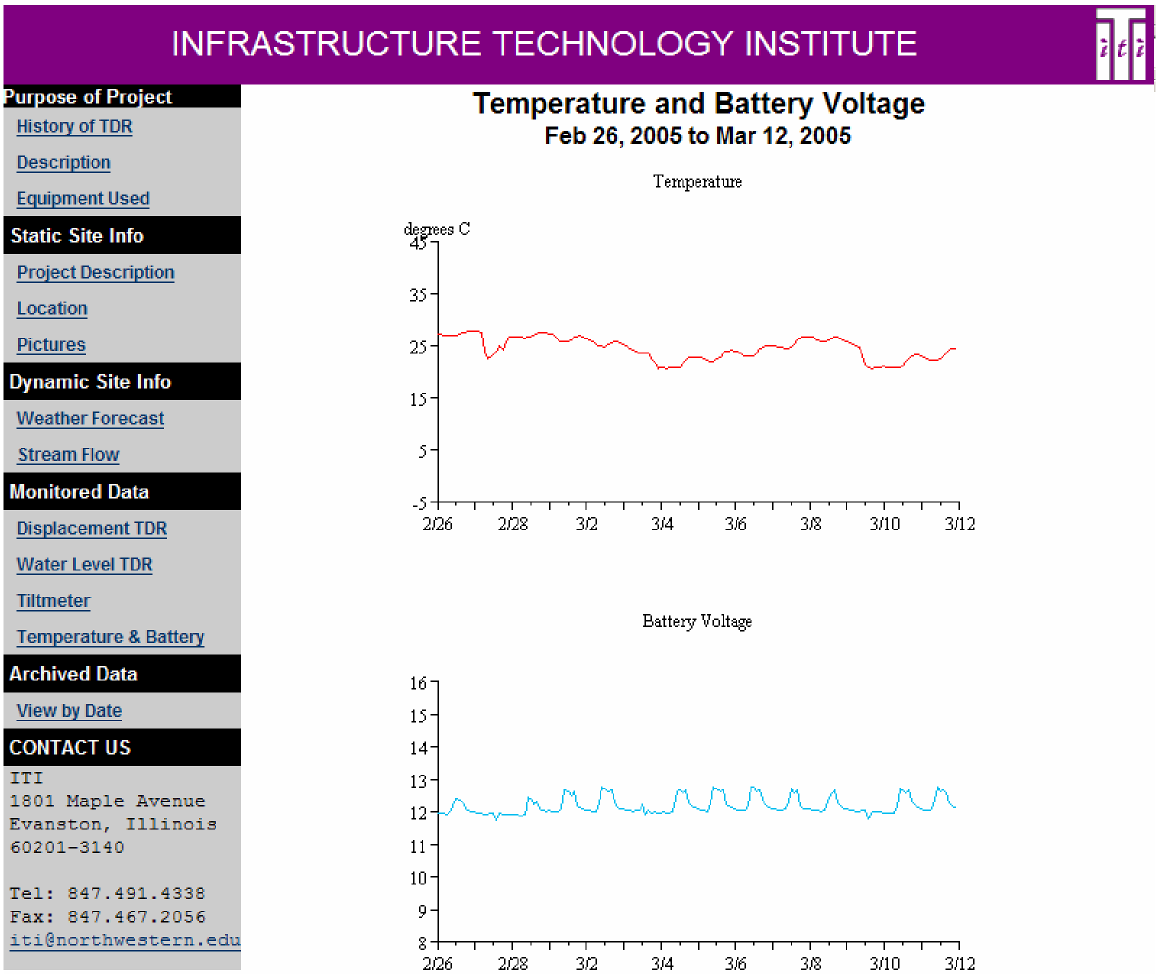

Figure 4: Temperature and battery voltage

Case Studies

SR-62 over the Little Blue River, Sulphur, Indiana

During construction of this two-lane highway bridge, one of the concrete piers tilted toward the streambed, leading to concerns of possible additional displacement. The pier was jacked back into position and two TDR cables and two tiltmeters were installed on the pier and pier cap to help provide insight into future responses (Dussud, 2002 [3]).

Figure 5: SR-62 near Sulphur, Indiana

The SR-62/Sulphur TDR site was monitored continuously from August 2001 through November 2005. The entire dataset is available on its web site:

http://data.iti.northwestern.edu/tdr/sulphur/

I-70 near Cambridge, Ohio

Figure 6: I-70 near Cambridge, Ohio

South-central Ohio was home to shallow underground coal mining operations for many years. Many of the now-abandoned mines are subject to flooding, subsidence, and collapse, and have in some cases caused damage to property and facilities on the surface as these abandoned mines subside and collapse. The potential for subsidence is compounded by maps and surveys that often fail to provide complete information about the location of abandoned mines. In one case, a sinkhole opened in the middle of I-70 just east of its junction with I-77, in the city of Cambridge. Since Interstate 70 is a trucking route of national significance, it was important that the site be monitored closely for any additional subsidence. After the abandoned mines were grouted, TDR cables were installed to monitor the site (Dowding and Prine, 1998 [4]).

The I-70/Cambridge TDR site has been monitored continuously since August 2001. The latest data and the entire historical dataset are available on its web site:

http://data.iti.northwestern.edu/tdr/cambridge/

SR-66 near Sebring, Florida

In early 2001, subsidence similar to a sinkhole formed directly under State Route 66 near the city of Sebring in Highlands County, Florida. A land bridge was built over the subsided area and the road was reopened to traffic. Since SR-66 is an important regional trucking route, it was decided that the site should be closely monitored for any future subsidence. TDR cables and biaxial tiltmeters were installed at strategic locations. The instruments were powered by a solar panel and battery (O'Connor, 2001 [5]).

Figure 7: SR-66 near Sebring, Florida

The SR-66 case study is of interest primarily because it demonstrates an additional benefit of Internet-enabled remote monitoring: the ability to easily check on the state of the monitoring system itself. In March 2005, communication was lost with the monitoring site. An examination of the recent battery voltage data on the web site (Figure 4) showed that the battery was no longer being charged during daylight hours. This strongly suggested that the solar panel had been compromised, and allowed responsible parties to focus their field visit specifically on restoring the solar panel. In a system that does not allow for easy distribution and display of remote data, the only sign of trouble is often that the remote computer or datalogger simply stops answering the phone. In that case, engineers will typically have to spend more time in the field diagnosing the problem.

Summary

TDR has proven to be a powerful tool for monitoring civil infrastructure facilities, especially cases of scour-critical bridges, roadbed subsidence, sinkholes, landslide areas, and seismic zones. TDR can be made even more effective when the facility is question can be monitored remotely, as valuable insight into the situation is provided continuously without the need for travel. However, remote monitoring with TDR presents challenges in data management that can prevent the data from being used to its full potential. These challenges include the need to manage potentially very large volumes of data, the artificial separation between data files often imposed by field computers, the menial tasks associated with parsing the data file, and the need to display and distribute the data to stakeholders in a useful form and in a timely fashion.

Autonomous Internet-enabled remote monitoring technology helps make remotely acquired TDR data more useful by autonomously parsing proprietary data files into a powerful searchable database and displaying the data in HTML-based graphical form via a secure web site. The active operation of Internet-enabled remote TDR monitoring systems for several years to continuously and remotely monitoring several civil infrastructure facilities demonstrates the effectiveness of this approach.

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Biographical Information

David Kosnik is a research engineer at the Infrastructure Technology Institute at Northwestern University and a managing partner at Civil Data Systems, both of Evanston, Illinois. He presented "Internet Examples and Demonstrations" with Daniel Marron at TDR 2001 and is active in the Midwest Bridge Inspection and Maintenance Working Group.