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TDR Based Alarm Systems

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Abstract

Alarm systems based on geotechnical measurements have been in place for dams for many years. Geotechnical applications of TDR are continuing to evolve and usage is increasing, particularly for monitoring slope movement. It has evolved into real time monitoring with alarms and a variety of notification schemes. This has created the need to develop action plans based on various alarm levels.

When geotechnical measurements are used for activation of alarm systems, the rationale for the measurements is significantly different from the rationale for monitoring performance. Measurements must be made in real time and be available to several responsible parties simultaneously. Algorithms can be programmed into dataloggers or it may be more efficient to implement the algorithms at base stations. Action plans are developed and refined as data is collected and action levels are refined. The data collected varies from real time downloading of large data files to real time reception of a small data packet.

Action plans define action levels and responsible parties. Fully automated systems detect when measured values have exceeded specified magnitudes and/or rates, and initiate phone calls to responsible parties. These parties evaluate the measurements and make decisions relative to implementation of the next step in the action plan.

Monitoring a phone 24/7 is reactive and can lead to "burnout" when alarm levels are being exceeded frequently. Historical data for police, fire, and Taiwanese debris flow alarms show false alarm rates of 70% to 90%. The reactive approach of responding to alarms creates apprehensive and irrational decision making. Proactively looking at trends is (a) the much "kinder" approach and (b) cuts down on "burn out" of responsible personnel. Web-based data display for proactive monitoring of measurements, in combination with automated dialing to cell phones and email notification when alarm thresholds are exceeded, is representative of the current comprehensive alarm system approach. Assignment of responsible personnel (outsource vs. in-house) is an issue that must be addressed as well. Inexperienced personnel are often surprised by the commitment required.

Key Words cable deformation, subsidence, earth fissures, dam stability, alarm systems

Alarm System Development

Action Plan – The Big Picture

In reality, users should be considering the overall project objectives. As discussed by Zaluski et al (2003), a well-organized action plan is required to maintain control of the situation, minimize loss of life, prearrange notification of authorities, and limit liability. For example, landslide and debris flow warning systems in Rio de Janeiro (Ortiago and Justi, 2004), Hong Kong (Chan and Pun, 2004), and Taiwan (Wu, 2005) involve an extensive network of remote automated rain gages (and other sensors) that transmit data to a central location maintained by government agencies. Alarm levels for these systems are based on proven models or empirical relations in combination with empirical databases. A decision to notify the public of an emergency situation is made by a team composed of individuals from several agencies.

Table 1. Sites Where Alarm Systems Have Been Installed.

Location	**Reason to Monitor**	**Communication Interface**	**Transmission Medium**
Washington, PA (O'Connor et al, 2001)	Active mine subsidence	CSI datalogger and Modem/voice synthesizer	Phone line
Summit County, OH (O'Connor et al, 2002)	Abandoned mine subsidence	CSI datalogger and Modem/voice synthesizer	Phone line
Plasterco, VA (O'Connor et al, 2004)	Abandoned mine subsidence	CSI datalogger and Autodialer	Phone line
Fort Dodge, IA (Crawford et al, 2004)	Abandoned mine subsidence	CSI datalogger and Autodialer	Phone line
Manhattan, KS (Trimbath, 2005)	Dam seismic stability	CSI datalogger interfaced to Geomation CMU	Radio
Phoenix, AZ (Weeks and Greenslade, 2006)	Earth fissures at dam	CSI datalogger and ALERT system modem	Radio

The list of sites in Table 1 illustrates a range of applications for which TDR systems have been used. In each case, the primary objective was protection of the public, but the mode of deformation being monitored was different. The layout of the sensing cables was based on empirical experience (and occasional numerical modeling) by a project team. In contrast, the action plan was developed, implemented, and updated during the project. Consider the following action plan that was implemented for a project in which the concern was subsidence along a highway over an abandoned mine (O'Connor et al, 2004).

Action Level 1:
- Receive call from remote datalogger
- Down load data, identify cause of alarm condition

Action Level 2:
- Visual inspection of alarm location
- Increased frequency of data acquisition
- Confirmed movement
  - (based on visual inspection and/or redundant measurements)
- Alert management

Action Level 3:
Accelerating movement
Confirmation with visual evidence or redundant data
Shut down highway

Action Plan Implications

This type of action plan is based on a reaction to an alarm call from the remote monitoring system. It inherently involves:

- decision making within a compressed time frame,
- 24/7 on-duty personnel, and
- limited preparation for alarm conditions.

The task of 24/7 monitoring and response is typically assigned to salaried in-house personnel to control costs and to expedite the decision making process. Since this assignment in is addition to other tasks which must be accomplished within project schedules, it creates a lot of stress to make decisions as quickly as possible.

Defining an Alarm Condition

Definition of an alarm condition requires experience with TDR technology. Applications are only limited by the creativity of users, and they have included (O'Connor and Dowding, 1999; Campbell Scientific Inc., 2006; Dowding et al., 1996; and PermAlert, 1995):

- quantify and locate deformation along coaxial and parallel conductor cables
- quantify changes in water content and conductivity
- quantify changes in fluid levels and solids along coaxial cables and parallel conductors
- quantify moisture intrusion in special cables
- quantify hydrocarbon intrusion in special cables

Within the scope of quantifying cable deformation, the applications have included monitoring (O'Connor et al, 2001, 2002, and 2004; Francke et al, 1994; Kane and Beck, 1999; Su et al, 2005; Weeks and Greenslade, 2006; Trimbath, 2005):

- strata movement in boreholes and trenches over active and abandoned mines
- strata movement in boreholes within mines and engineered openings
- movement in boreholes within sliding masses
- movement in trenches across earth fissures
- movement in trenches along the toe of dams

The definition of an alarm condition is obviously dictated by the application, the site conditions, the liability if the alarm condition is reached and exceeded, the aversion to risk of the project owner and personnel, and a variety of other factors.

Alarm Algorithm

For the projects listed in Table 1, alarm conditions have been based on the *change in magnitude* of a TDR reflection associated with cable deformation (except the project in Washington, Pennsylvania where the alarm was based on tiltmeter measurements). The action plans were based on the *rate of change* in magnitude of the reflection.

An algorithm that has been used for detection of an alarm condition (Table 2) is the following:

1. Acquire and store baseline (optionally specify a single reference value)
2. Acquire current waveform
3. Calculate difference point by point
4. Check if difference exceeds alarm level
5. Store waveform (optional)
6. Store alarm time stamp, cable ID, distance along cable
7. Datalogger initiates phone call to programmed numbers
8. Repeat steps 2 to 7 at specified time

As indicated by the earlier listing of applications, TDR reflections can be associated with a variety of causes. The above algorithm will not distinguish the cause of the reflection. It will only alert responsible personnel to the fact that a condition exists in which the reflection magnitude at a measured distance is greater than the specified alarm level magnitude. The reaction of responsible personnel to this alarm condition is dictated by the action plan.

Table 2. Data Acquisition and Alarm Methodology

Location	**Cables**	**Data Density**	**Interrogation Interval**	**Alarm Baseline**	**Alarm Algorithm**
Washington, PA	5 cables, 246 ft to 505 ft	50 points per meter	48 to 72 hrs	Store baseline reading (tiltmeter only)	Difference from baseline (tiltmeter only)
Summit County, Ohio	8 cables, 9260 ft	1 point per meter	3 hrs	Store baseline waveform	Difference from baseline
Plasterco, VA	3 cables, 2268 ft 3 cables, 1498 ft 6 cables, 1999 ft 6 cables, 1974 ft	3 points per meter	3 hrs	Store baseline waveform	Difference from baseline
Fort Dodge, IA	5 cables, 1850 ft	3 points per meter	3 hrs	Store baseline waveform	Difference from baseline
Manhattan, KS	5 cables, 8030 ft	2 points per meter	0.2 hrs (10 min)	Store baseline waveform	Difference from baseline
Phoenix, AZ	5 cables, 6303 ft 3 cables, 3103 ft	20 points per meter	24 hrs	Specify single reference value per 100 m section	Difference from reference value

Algorithm Refinement

The decision making process is less stressful when the reliability of the alarm call is maximized. In the case of a TDR-based alarm system, the reliability increases with the level of experience of the personnel as well as the level of refinement of the alarm algorithm, which is a combination of:

- software,
- hardware, and
- data analysis and interpretation.

System Sensitivity and Reliability

False Alarms – Historical Perspective

TDR-based alarm systems are susceptible to the same rate of false alarms as systems based on other technologies and in other applications. Historical data for commercial alarms, residential alarms, police alarms, and debris flow alarms show the following false alarm rates:

Location	Alarms	Reference
Bellevue, Washington	75% - 90% filtered out	AIREF, 2002
Columbus, Ohio	90% false alarms	Andes, 2005
Taiwan debris flow	70% false alarms	Wu, 2005

The listing in Table 3 shows experience with two TDR based alarm systems. The false alarm rate varied from 0 to 100% during each one month period.

Table 3. TDR Alarm Activity

Period	Total Alarm Calls	Due to Deformation	False Alarm Calls	
Summit County, Ohio				
AUG 2001	10	4	6	60%
SEPT 2001	82	40	42	51%
Plasterco, Virginia				
JUN 2002	5	0	5	100%
JUL 2002	17	4	13	76%
AUG 2002	14	2	12	86%
SEPT 2002	7	0	7	100%
OCT 2002	2	2	0	0
NOV 2002	0	--	--	--
DEC 2002	52	0	52	100%
JAN 2003	6	0	6	100%
FEB 2003	0	--	--	--
MAR 2003	108	49	59	55%
APR 2003	42	3	39	93%

False Alarms – Caused by Data

A significant feature of a TDR-based alarm system is that you have the option to store waveforms in addition to being alerted when an alarm condition exists. Systems are currently installed that take advantage of this capability.

Typically, the alarm call provides on-call personnel with a time stamp, cable ID, and distance along the cable where the alarm condition exists. This information alone may be sufficient for the person to determine if the alarm is associated with credible movement or an identifiable spurious condition.

When this information is not sufficient, personnel must download the most current waveform data and compare it with historical data to evaluate the alarm condition. The sensitivity of the system is dictated by a number of parameters including distance along the cable, magnitude of deformation, and number of data points per cable (e.g., 100 points per meter versus 2 points per meter). There is a limitation due to the available memory in the datalogger. As the cumulative length of cable being monitored increases, the number of data points per unit cable length must be reduced (Table 2). The influence of increasing the number of data points on the waveform is illustrated by a comparison of Figures 1 and 2.

There is a wide variation of approaches that have been used to maximize the number of data points (Table 2). If a reference waveform is stored on the datalogger, this will limit the memory available for acquiring the current waveform. Alternatively, web based data displays and access to historic data have been used but this is based on visual analysis by experienced users (Dowding et al., 2003).

An approach used to reduce the use of available memory is to use a single reference value for segments of a cable rather than acquiring a baseline waveform. Datalogger memory is made available for acquiring the current waveform using a maximum number of data points (e.g., 2000 data points). By interrogating a cable in segments and using the maximum number of data points for each segment, the resolution of the waveform is maximized.

False Alarms – Caused by Hardware

The waveforms shown in Figure 1 illustrate conditions associated with reflections created by hardware conditions (A, C, and D) and cable deformation (B and D). A common source of reflections is poor quality connectors or moisture in connectors. Another problem has been the impact of freezing temperatures on battery voltage. Switches within the coaxial multiplexers have also created high magnitude reflections especially during freezing conditions.

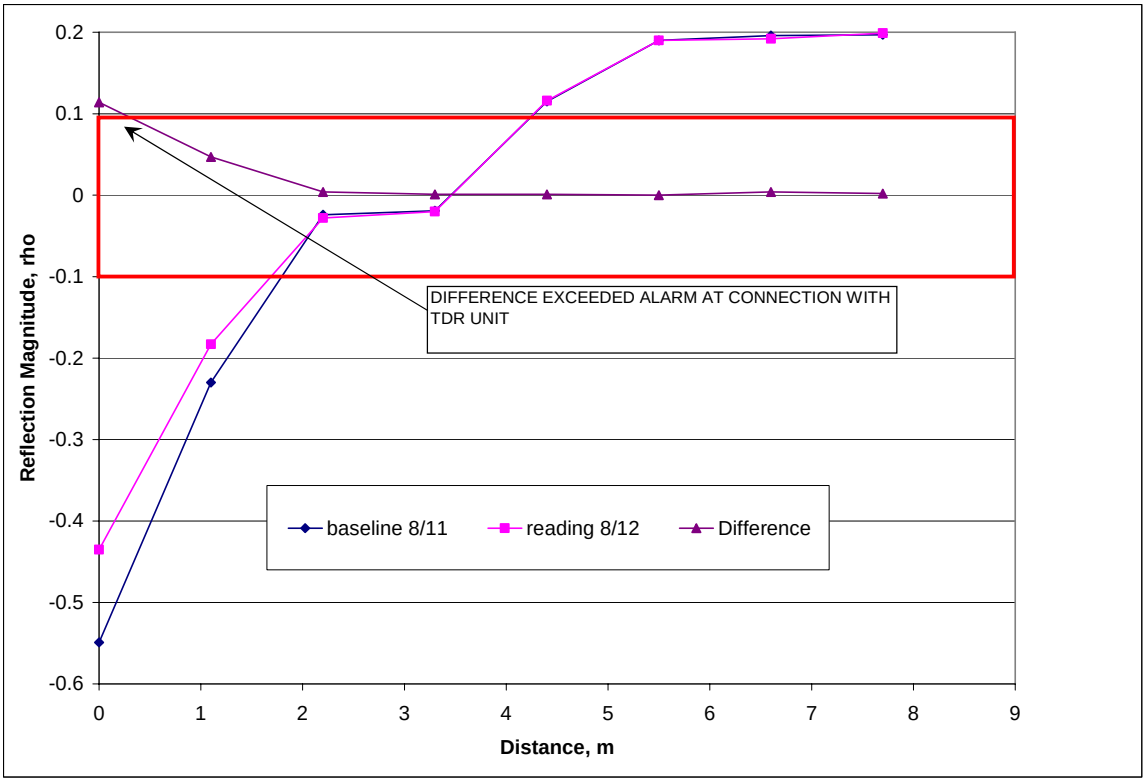
The philosophy for the system installed in Summit County, Ohio (O'Connor et al, 2002) was to have an alarm condition if the cable was severed. However, it was decided to initially set the alarm threshold at a much lower level and then increase the threshold as experience was gained. Examples of the types of cable faults that exceeded the lower alarm threshold, and associated waveforms, are as follows:

1. Poor Connector and Splice (Figure 1: A and C). Problems developed with connectors between lead cables and transducer cables, and with splices along the transducer cables.

2. Cable damaged by Backhoe (Figure 1B). The end of the cable was damaged by a backhoe digging in this area. After that point in time, this end of cable was exposed and the outer conductor was damaged.

3. Cable Severed by Drilling (Figures 1D). Since the system was intended to detect subsurface movement induced by the mine backfilling, it was necessary to have the cables installed prior to drilling grout injection holes. Cable locations were not well marked on the highway pavement and several drill holes intercepted the cables.

4. Electrical Noise (Figures 1D). Sometimes electrical noise associated with poor connections was sufficient to exceed the alarm threshold.



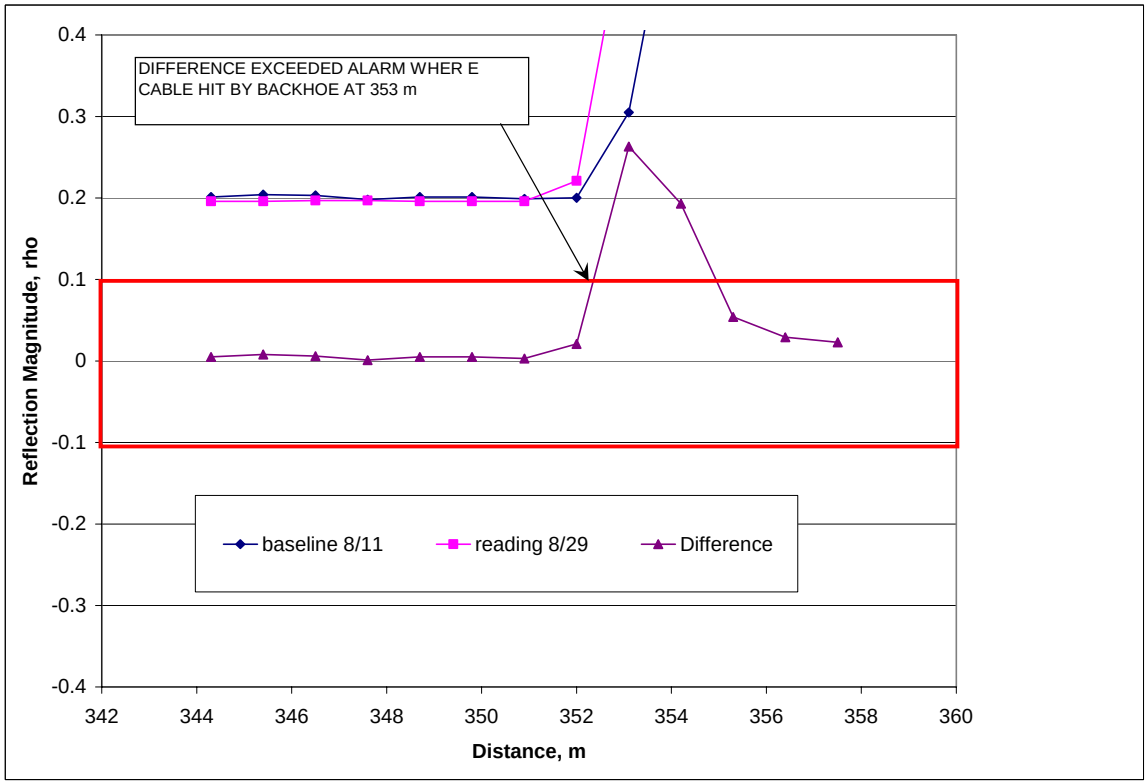
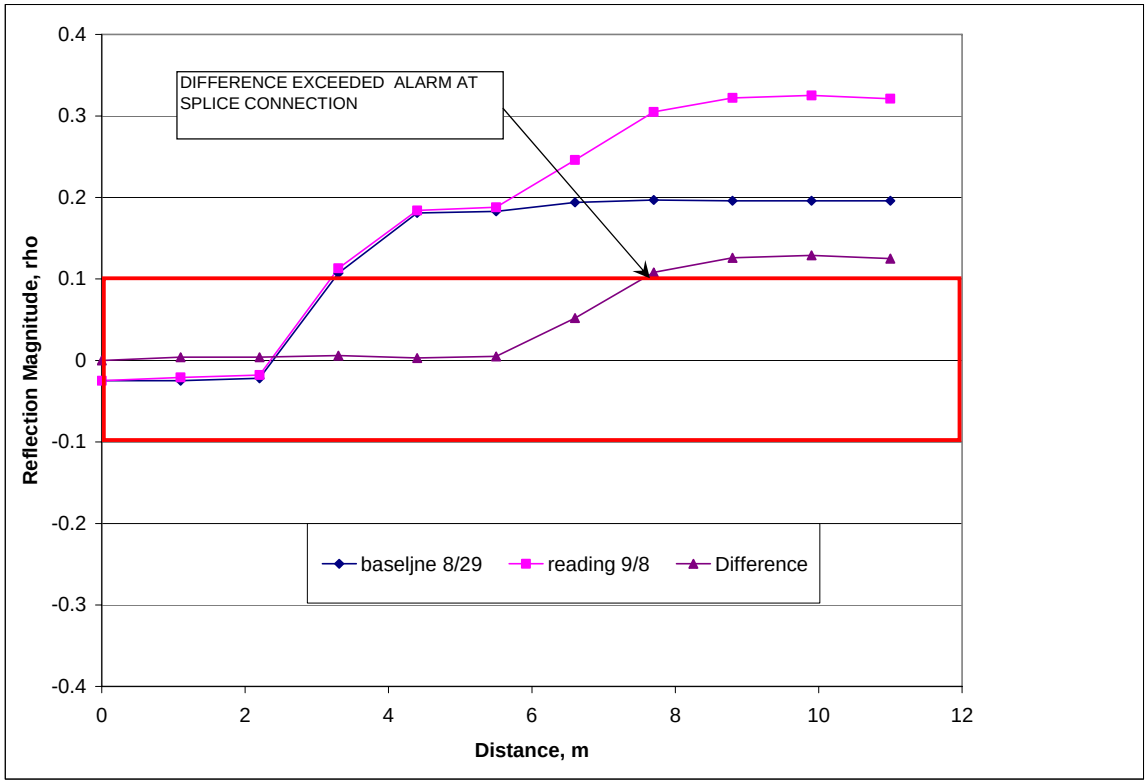


Figure 1. Waveforms acquired with 1 point per meter (O'Connor et al, 2002).



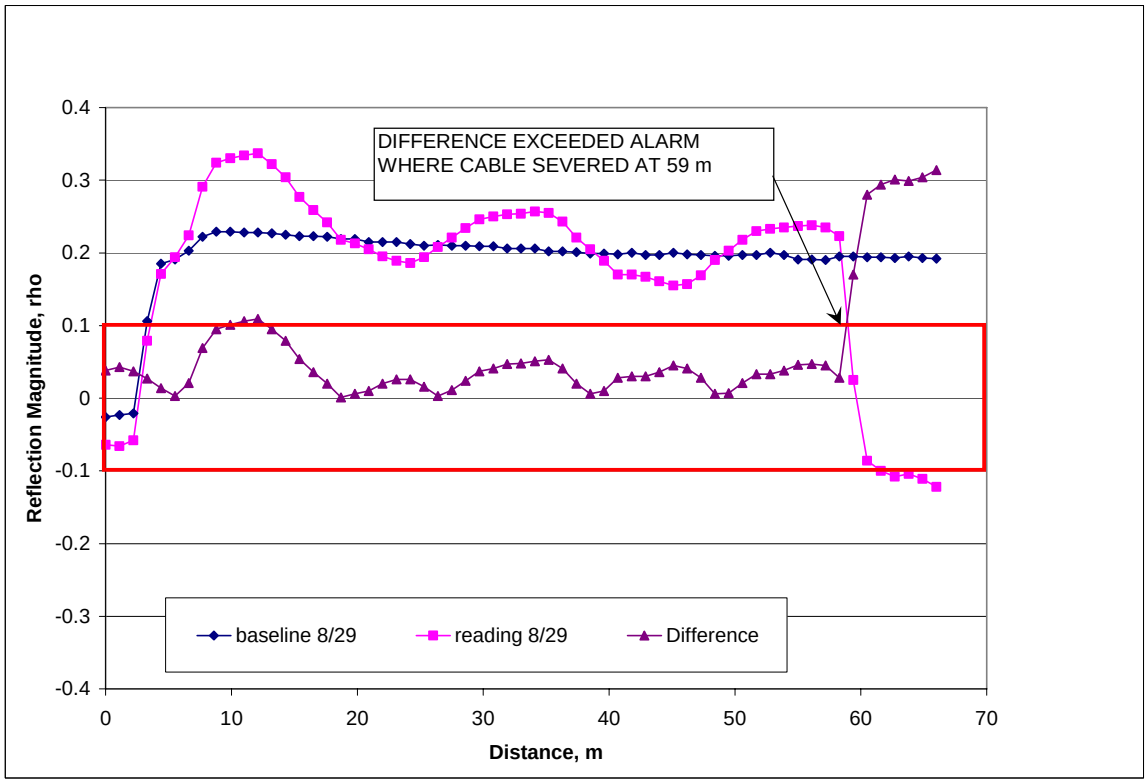


Figure 1 (continued). Waveforms acquired with 1 point per meter (O'Connor et al, 2002).

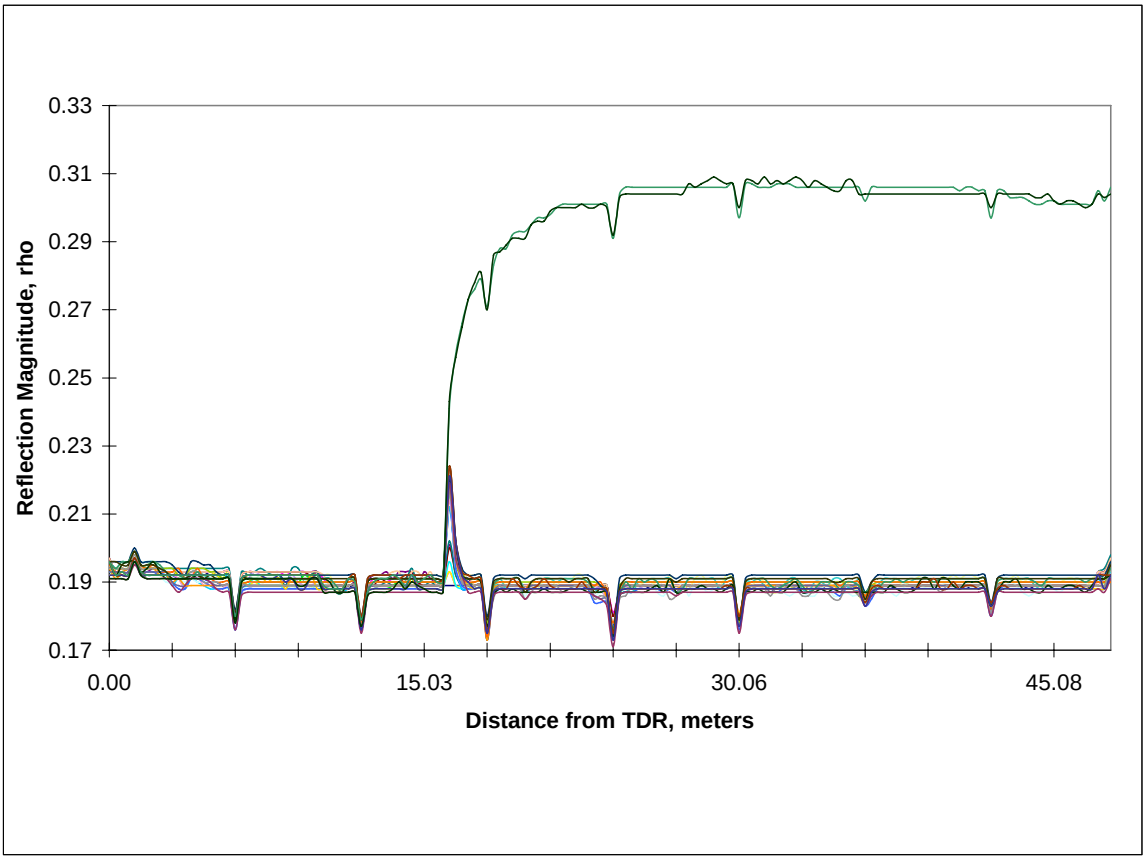


Figure 2. Waveforms acquired with 3 points per meter (O'Connor et al, 2004).

Alarm Level Refinement

Imagine that you are driving a car that uses an alarm rather than a dial fuel gage or digital fuel gage. Since you made a decision to monitor the situation using this approach you would quickly learn how much fuel is left in the tank when the alarm is activated, and you would have a feeling for how much farther you could drive before you empty the tank. You would adjust the alarm as you became more familiar with the system.

For the systems listed in Table 1, a default value for the alarm threshold was established by experience on previous projects. This threshold value was set independently for each cable and it was adjusted periodically as responsible personnel gained experience with the system and changing site conditions. For example, the threshold would be temporarily increased for a cable during periods when noise levels on that cable are high and then lowered as conditions stabilized. The objective was to keep the threshold as low as possible to maximize sensitivity to changes from the baseline waveform.

In response to alarm calls from the TDR monitoring systems installed at Plasterco, it was vital to isolate the cause. It was necessary to download and analyze TDR data files to determine if the alarm condition was associated with ground movement and the rate at which movement was occurring. Based on this information, it was possible to make an informed decision when talking with site personnel about the appropriate plan of action. Once it was determined that the alarm call was triggered by a condition that is persistent, it is typical to validate the condition using on-

site manual interrogation of the coaxial cable, identify the physical location, conduct a visual assessment, and develop a plan of action.

The summary of alarm calls in Table 3 illustrates how alarm calls would continue over a period of time. Often this was deliberate to verify that a condition was not intermittent and there was a high probability that it was associated with cable deformation. Alarm calls were received until the alarm condition was rectified or the alarm was deliberately terminated. For example, in Dec 2002 there were problems with cold weather impacting the system and alarms were not associated with movement. In March 2003, there were problems with the connector on one cable. However, at the same time there was deformation occurring on two other cables. Each alarm condition had to be identified and appropriate action taken for each of the three cables.

System Refinement

Systems have been installed with features that reduce spurious alarms. In Manhattan, Kansas, redundant cables were installed in a single trench, and alarm conditions must exist simultaneously on both cables to activate an alarm call to the base station. The interrogation cycle needed to be repeated once every ten minutes, so data is not stored during each cycle (Table 2). It is only stored once every three hours, and the alarm notification is sent to another remote acquisition system which then requires notification by several other sensors to activate a system.

In situations where communication between the base station and remote datalogger is via radio or cellular phone, it is not feasible to download large data files. In Manhattan, Kansas and Phoenix, Arizona, data is stored and downloaded periodically from an external storage module. This is done by maintenance personnel when they visit the site and eliminates the need to download large files

Personnel Resources

As indicated earlier, 24/7 monitoring is typically done by in-house personnel to control costs and limit the chain of command in the decision making process. Since this monitoring is another task assigned to these people, they must be flexible to set aside other tasks and projects to properly respond to an alarm situation (i.e., drop everything to respond to an alarm, if necessary). As discussed by Dunnicliff (1988), selection of personnel may govern success or failure of a monitoring program.

Typically, responsible personnel have experience with instrumentation and have been involved with monitoring during the current project and previous projects. If they do not have prior experience with TDR, there is a learning curve. First, they must become familiar with the technology. Then, they must become familiar with interpretation of the data to recognize credible deformation. As they gain experience, they can quickly identify an alarm as associated with a spurious source or credible movement.

Personnel Learning Curve

The learning curve for personnel involved with TDR based alarm systems is repeated for each new project or client. The individuals begin with cursory knowledge of the technology and a vague concept of the application for their particular situation. They approach the situation based on their existing knowledge that has been acquired using other technology (that cannot provide the same type of information obtained using TDR technology), and typically without the

experience of acquiring data remotely. Very often there is a reluctance to use remote monitoring since having people "on the ground" is a vital component of their current mode of operation.

Technology Learning Curve

The process begins with a "hands-on" demonstration with a short length of cable and a TDR cable tester. The individuals gain familiarity and a feeling for what TDR technology can do. This is done in conjunction with a PowerPoint presentation of past case histories to allow the individuals to get an idea of how the technology will be implemented and the issues that must be addressed for implementation in their particular situation. The presentation is structured as an interactive discussion in which participants ask questions as their thoughts are toggled and they get more focused on how they would like to see TDR implemented. There is not a set pattern to the process since the presentation is being made to people with different perspectives: geotechnical engineers, engineering geologists, geologists, instrumentation technicians, project manager, communication system managers, division managers, and a variety of other individuals.

There have been cases in which project managers have implemented the technology without the benefit of a progression from bench testing to prototype testing to full scale implementation. This has been a cause of consternation when details become apparent that should have been addressed. The situation becomes compounded when inexperienced personnel attempt to resolve the issues.

Data Management Learning Curve

The typical approach progresses from limited implementation by installing cables in one or two boreholes or in a single trench. Data is typically acquired by on-site project personnel and stored in a directory on a project computer. Typically, waveform data is imported into a spreadsheet and plotted to allow visual analysis by superimposing several waveforms on single plot. Graphical scales are changed to allow analysis to progress from visual assessment of the overall waveform down to analysis of individual TDR reflections. Preliminary analysis begins with quantification of reflection characteristics, in particular, reflection magnitude and width. As the volume of data increases it becomes readily apparent that macros (or even stand-alone programs) must be developed to easily import, plot, and analyze TDR waveforms. Web-based programs have been developed to allow several users to view and compare waveforms (Dowding et al, 2003).

Experienced Users

As the process of data acquisition and analysis advances, users become familiar with quantification of TDR reflection magnitude to quantify the magnitude and rate of cable deformation. It is a logical progression to allow software perform this analysis, identify locations where changes are occurring, and plot a time history of the change. However, a vital component of the analysis remains to be visual assessment by experienced users.

Once users have acquired familiarity with TDR technology, how it is implemented, how data is acquired and stored, and how data is analyzed, they then pursue expansion of the network of monitoring cables. As the network expands, the time involved in data acquisition becomes burdensome and users actively pursue the use of automated monitoring with remote dataloggers. Once data is being acquired in this manner, it is a logical progression to have analysis done by the datalogger.

Action Plan Learning Curve

This is a logical approach for users becoming familiar with TDR technology; however, it is not a logical approach for users who are implementing TDR-based alarm systems. An inherent assumption when working at this level of sophistication is that the user is aware of the technology and is looking at the bigger picture of overall project objectives. At this level a user should not be asking questions like: How sensitive is TDR? What can use you measure using TDR? The user should be asking questions like: Do I ask the sheriff to close the road when an alarm sounds? Who needs to be in the loop when an alarm sounds? What is the first thing we do when the alarm sounds? If movement is confirmed what do we do? If the alarm is spurious what do we do?

The alarm system design should be driven by the action plan which evolves as personnel gain experience with TDR and movement that is being detected. Typically, users will set alarms at a very low reflection magnitude with the expectation that they don't want **any** deformation to occur without being made aware of it. After dealing with several false alarms, action plans have been modified so personnel proactively download data on a regular basis and look at data plots to assess if movement is occurring before an alarm condition exists. Additionally, alarm levels are adjusted and monitoring of specific cable segments may be intensified.

Summary

Prudent application of TDR-based alarm systems should begin from the perspective of project objectives, liability, and risk aversion. The technology is capable of monitoring movement over large lateral extents and to great depths with a high density of monitoring points. Automated remote monitoring can be done 24/7 with responsible personnel alerted by a datalogger-initiated phone call. Similar to other systems, it should be expected that 70% to 90% of calls will be "false" in that an alarm condition exists that is spurious and not associated with actual deformation. Responsible personnel must gain experience with the system and develop the ability to make decisions using minimal information followed by more detailed analysis of the TDR waveform.

A gentler approach is to be proactive in downloading data and analyzing waveforms to assess developing movement that has not activated an alarm. This creates an environment in which an alarm call is anticipated but personnel have formulated a response.

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