REAL TIME MONITORING OF INFRASTRUCTURE USING TDR TECHNOLOGY: CASE HISTORIES

Kevin M. O'Connor* and Charles H. Dowding^

*GeoTDR, Inc., Apple Valley, MN 55124; kevin@geotdr.com
^Department of Civil Engineering, Northwestern University, Evanston, IL 60208;
c-dowding@northwestern.edu

ABSTRACT

Time Domain Reflectometry (TDR) is a versatile technology amenable to a variety of measurements and nondestructive monitoring of infrastructure conditions. It can be utilized to monitor deformation of soil/rock and structures, monitor changes in fluid levels, and monitor water content of soils. Furthermore, this monitoring can be automated using systems controlled by a datalogger that acquires and stores data that can then be retrieved via phone line or telemetry. The principles involved in TDR measurements are presented in a companion paper and this paper focuses on case histories in which TDR was used to monitor deformation. These cases include, 1) cables in rock supporting a highway at one site, and a school building at a second site, subject to mine subsidence, 2) cables through scour critical bridge footings, and 3) cables in a deforming rock pedestal supporting a highway. These case histories demonstrate installation techniques, remote monitoring capabilities, and typical results. Other applications are briefly summarized to illustrate the diverse uses of TDR technology.

TDR GEOMETRY, DATA ACQUISITION AND INTERPRETATION

As shown in Figure 1, a metallic coaxial cable can be crimped at specific intervals, placed in a drillhole, and anchored to the walls by tremie placement of an expansive cement grout. When movements occurring in the rock or soil are sufficient to fracture the grout, cable deformation occurs. The cable is periodically interrogated with a TDR cable tester to locate the deformation, quantify the magnitude of deformation, and distinguish shearing from tensile deformation (O'Connor and Dowding, 1999). Note that crimping the cable prior to placement in the hole creates TDR reflections at known locations and these reference reflections improve the accuracy with which deformation locations can be determined.

Monitoring can be done manually by moving a TDR unit and interrogating cables one at a time as shown in Figure 2. However, a major advantage of TDR technology is automated remote monitoring. Cable testers are available that allow for serial communication and have low power requirements (Dowding et al, 1996b; Nicholson et al, 1997; Campbell Scientific, 2000). These units can be interfaced with a programmable datalogger which controls power, acquires and stores data, and allows the data to be downloaded over a phone line (Figures 3 and 4).

Whether the data is acquired manually or automatically, it is in a digital format that can be analyzed both qualitatively and quantitatively. When monitoring deformation of coaxial cable, traces are acquired with a resolution of 1 data point per 25 mm of cable in order to maximize resolution of reflection location and magnitude. TDR units are available that can acquire 251 data points or 2048 data points so the cable can be interrogated in segments of 6 m or 50 m. For long cables, it is necessary to acquire data from a sequence of cable segments and software has been developed which concatenates these incremental traces into a continuous trace (Huang et al, 1993). This makes it possible to quickly locate reflections due to deformation and to quantify the magnitude of these reflections.

For purposes of presentation and qualitative analysis, the traces can be imported into CAD files as shown in Figures 6, 9, 11 and 14. Note that geometric and geologic conditions can be superimposed as shown in Figures 6 and 9 so that these can be correlated with reflections that develop due to cable deformation. The series of traces can also be compiled as a time-lapse

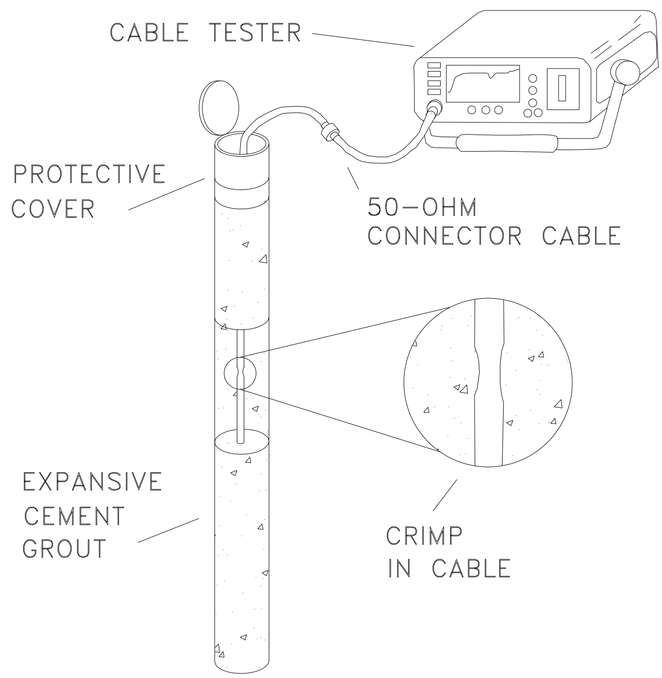


Figure 1. Schematic of cable installation and monitoring.

Figure 2. Interrogating cable with cable tester. Cable was installed to monitor abutment slope movement.

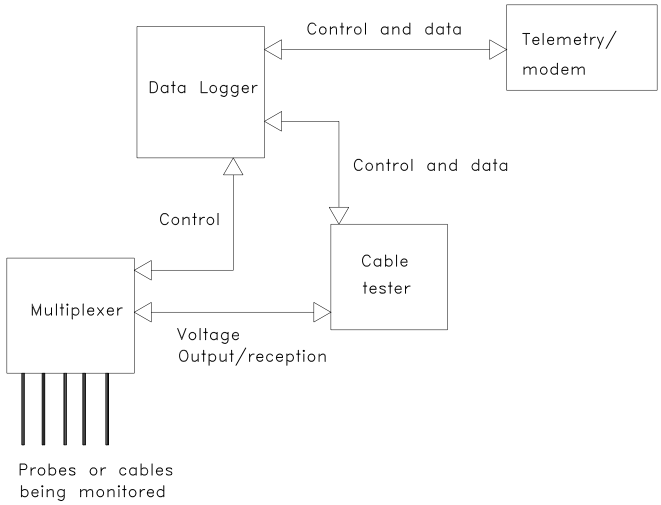


Figure 3. Schematic of system used for remote monitoring using a programmable datalogger. Stored data is downloaded via telemetry or a phone line.

Figure 4. Remote system installed to monitor subsidence along a highway over an active coal mine.

Figure 5. Installing coaxial cable in hole drilled into an abandoned mine in Ohio.

animation that can be replayed using a computer, or recorded for video display (O'Connor, 1995). This enhances visual analysis of the correlation between deformation and temporal changes in site conditions. Such visual analysis is a very powerful tool for rapid interpretation of the TDR data and provides an excellent means for conveying this information to all interested parties.

ABANDONED MINE SUBSIDENCE BENEATH HIGHWAYS

The pits, sags, and troughs that develop on the surface over abandoned underground mines are the ultimate result of subsurface strata movements. In the case of important structures located over abandoned mines, it is not enough to say that subsidence is imminent. In some critical areas, a means must be provided to detect strata movements and quantify the rate at which they are occurring so that appropriate measures can be taken to mitigate damage. TDR monitoring of cables embedded in strata overlying abandoned mines provides a means of locating and quantifying subsurface deformation which is a precursor to surface subsidence (O'Connor and Murphy, 1997).

A need for such monitoring occurred when the eastbound driving lane of Interstate Route 70 in Guernsey County, Ohio collapsed in March 1995. Subsidence was initiated in response to dewatering of an underlying abandoned coal mine. In spite of periodic visual monitoring, a 5 m diameter hole, 3 m deep suddenly opened and three cars and a truck were damaged (Ruegsegger and Lefchik, 1997). The remediation effort involved air rotary drilling of approximately 1,800 boreholes down to mine level at a depth of approximately 20 m to tremie approximately 18,000 m^3 of flyash grout into the voids. Two land bridges, having lengths of 215 m and 34 m, were constructed over areas where the drilling and grouting program encountered high concentrations of caved and broken material in the mine interval. It was decided to monitor, rather than grout, remaining voids. In January 1996, two coaxial cables were grouted into holes drilled down to mine level (Figure 5).

A comprehensive summary of TDR measurements is available from another site in Illinois experiencing active subsidence over an abandoned coal mine (O'Connor and Murphy, 1997).

At this site, monitoring was done as part of the site selection process for locating a new school building. The abandoned mine is approximately 60 m below the surface, overlain by 30 m of glacial material and 30 m of Pennsylvanian shales and limestones. This site was known to be undergoing subsidence and it was necessary to determine if subsurface deformation was active. Coaxial cables were installed in three holes drilled from the surface down into the mine and connected to a data acquisition system (similar to that shown in Figure 4) which interrogated the cables daily. Data was downloaded via phone line weekly and then analyzed monthly over a period of three years.

By virtue of TDR traces obtained from the coaxial cables, it was determined that they were being subjected to shear and extension at a depth of 42 m as shown in Figure 6. This corresponded with the bottom of a fractured shale stratum that is also an aquifer. In order to explain what this means in terms of subsidence, consider characteristics of TDR reflections (O'Connor and Dowding, 1999). When a cable is subjected to shear, the reflection is characterized as a distinct spike. When the cable is subjected to tension the reflection is more trough-like. Looking at the plot of reflection magnitude versus time in Figure 7a, the trend is indicated with lines that are either sloping upward (positive change in magnitude), flat (no change), or sloping downward (negative change or decrease in magnitude). The slopes can be expressed in units of mrho per month and the plot of their value versus time indicates different episodes of cable deformation (i.e., shear deformation or tensile deformation as shown in Figure 7b). When the reflection magnitude is increasing at a rate greater than +1 mrho/month, this is indicative of shear deformation. When a decrease in reflection magnitude occurs at a rate greater than -1 mrho/month this is indicative of cable tension. Strata separation (↕) will cause this tensile deformation and is indicative of the progression of subsidence.

Note that this approach is tailored to monitoring localized occurrence of subsidence beneath important structures. In order to assess the risk of subsidence over an entire mine, GIS techniques must be used to integrate the data acquired by TDR and data acquired by surface survey monitoring. However, for purposes of intensive local monitoring, TDR is listed in the Ohio Department of Transportation risk assessment manual (Ruegsegger, 1997) as one of the available state-of-the-art technologies that is acceptable.

BRIDGE FOUNDATION SCOUR

In 1997, a steel truss bridge supported on piers and spread footings over the Klamath River in Horse Creek, California was found to be cantilevered over a 2 m deep scour pocket beneath the pier on the west side of the river. Under an emergency contract, the pocket was filled with concrete, drilled pier foundations were constructed, and the bridge was leveled. The California Department of Transportation decided to install coaxial cables through the foundation of the pier on the east side end of the truss in order to measure movement that might result from scour of the graphitic schist supporting the spread footing (Dowding and Pierce, 1994). Working from the bridge deck as shown in Figure 8, a hole was drilled through the footing to a depth of 8 m into the schist. 100-mm diameter steel pipe was then installed which extended from the top of footing to the top of pier. Coaxial cable was lowered through the pipe and footing down into the open hole and grouted into place (Figure 9). Precision tiltmeters were also installed at the top of the pier to monitor rotation (Marron, 2000).

In addition, a 25-mm diameter slotted steel pipe was attached to the larger pipe and an air-dielectric cable was installed to monitor changes in river level. In the case of water entering an air-dielectric cable, there is a characteristic negative reflection at the air-water interface and by converting the travel time to distance it is possible to monitor changes in the river level (Dowding et al, 1996a, 1996b; Nicholson et al, 1997; O'Connor and Dowding, 1999).

The TDR deformation and water level "sensor" cables, and the tiltmeters, were connected via lead cables to an automated data acquisition system installed at the west abutment. Data

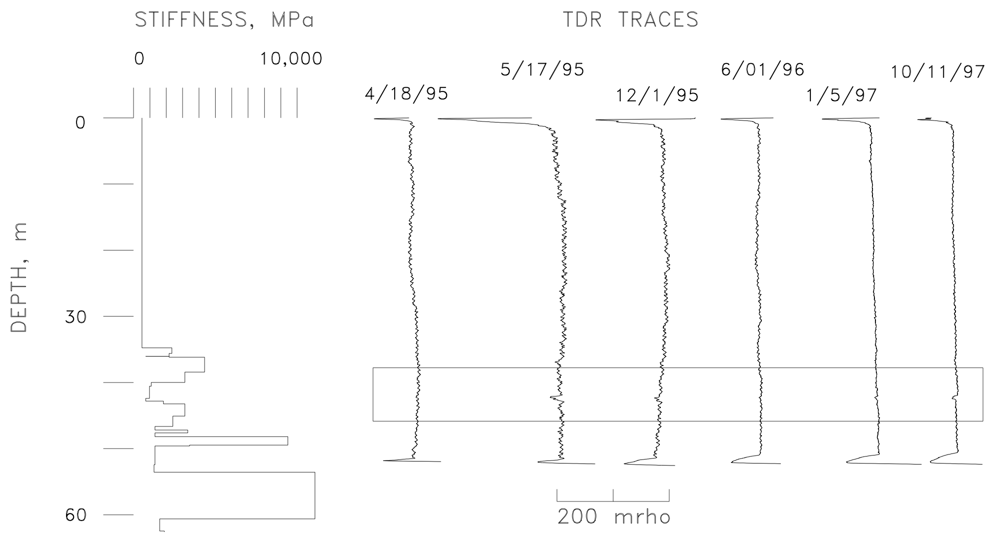
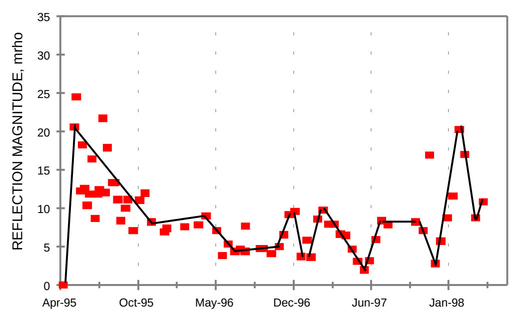


Figure 6. TDR traces acquired over an abandoned mine in Illinois. The reflection at a depth of 42 m is associated with deformation along a clay seam at the bottom of a fractured shale stratum.



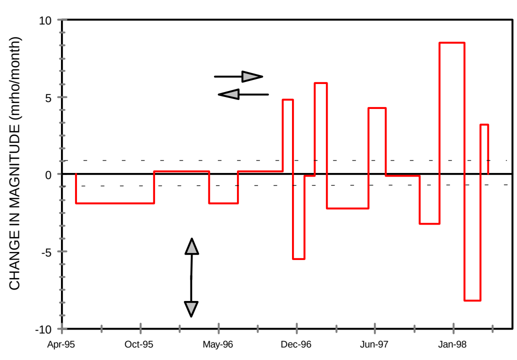


Figure 7. Time history of TDR reflection at a depth of 42 m; (a) reflection magnitude; (b) correlation between rate of change in reflection magnitude and mode of deformation

Figure 8. Installing cable from bridge deck. Preparing to pump grout through PVC tremie pipe.

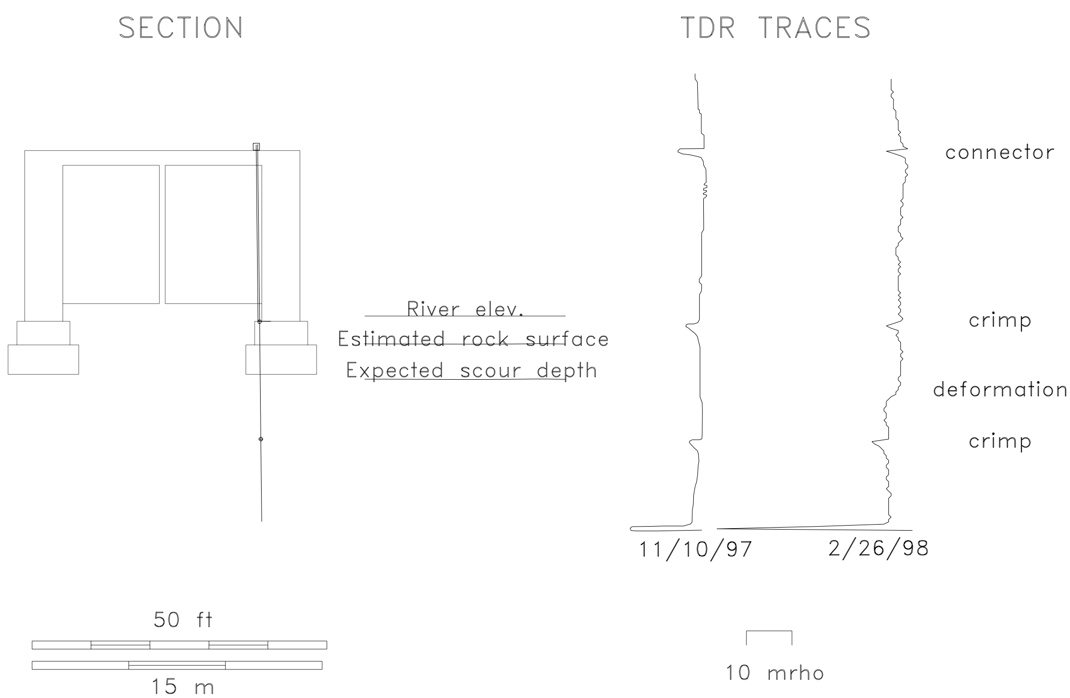


Figure 9. Overview of cable installation and TDR traces.

is collected daily and downloaded weekly over the phone. As shown in Figure 9, initial cable deformation showed indication of shear along the contact between the concrete footing and underlying schist, however, the tiltmeters did not show rotation and there has been no further movement.

ROAD DISTRESS AND RETROFIT OF INCLINOMETER CASING

Distress in a limestone pedestal supporting a major highway presented an opportunity to compare TDR and inclinometer response. Movements had been occurring since December of 1997, and an instrumentation program was formulated to determine the cause of movement. Among the instruments installed to monitor subsurface movement were inclinometers and coaxial cables (Figure 10).

Comparison between the TDR and inclinometer measurements in Figure 11 shows consistent response at a depth of 76 m. Movement at this depth occurred within a zone of greater fracture density in the limestone. The reflections at depths of 113 m and 119 m were caused by movement along dolomite-shale contacts. The time history of deformation at a depth of 76 m in Figure 12 shows that there was 19 mm of cable deformation from 7/16/98 to 8/7/98 while the incremental displacement in a nearby inclinometer was 12.4 mm. When a reading was taken on 8/19/98, it was found that the cable had been terminated at this depth. Kinking of inclinometer casing at this site has provided an opportunity to demonstrate the use of TDR technology to extend the useful life of this casing. On 3/2/99 it was not possible to lower a probe down past a depth of 76 m in the nearby inclinometer hole, and on 6/25/99 this casing was retrofitted with a grouted coaxial cable to continue monitoring (Figure 13). Ultimately, five of the eight original inclinometer casings at this site were retrofitted with grouted coaxial cables, and TDR waveforms for one of these are shown in Figure 14. This hole is inclined at 30 degrees from vertical and on 8/14/98 it was not possible to get the inclinometer probe past a downhole distance of 86.6 m which corresponds with an actual depth of 75 m. The TDR waveforms acquired since 9/10/98 show that it has been possible to continue monitoring movement at this depth as well as deformation that began at a depth of 21 m as shown by the TDR trace for 9/13/99.

OTHER APPLICATIONS

The cases presented in this paper have dealt primarily with monitoring deformation in rock but TDR technology has also been used to monitor deformation in soil slopes as shown in Figure 2 (O'Connor and Dowding, 1999; Cole, 1999). The major design consideration when installing coaxial cables in soil is the stiffness and shear strength of the grouted cable. The grout must fracture so that the cable can be deformed as movement occurs within the surrounding soil (Pierce, 1998; Cole, 1999). For installation in rock, this consideration is not important due to the relatively high strength and stiffness of rock. In order to maximize sensitivity in soil, it is hypothesized that the shear capacity of the grouted cable should be less than the bearing capacity of the soil.

Another of the diverse applications of TDR technology is monitoring changes in fluid levels. This was mentioned in connection with the case involving bridge foundation scour where an air-dielectric cable was utilized to remotely monitor changes in river level. At another location in Minnesota, this same type of cable has been installed in a well to remotely monitor changes in groundwater level. Pertinent to deformation monitoring, this capability makes it possible to monitor fluid levels that are causative conditions for continued deformation (e.g., ground water levels and pressure in slopes and embankments).

A major market for TDR technology is soil moisture measurement. In addition to agricultural applications, TDR has been used to monitor the hydraulic performance of pavement subgrade (Baran, 1994; Janoo et al, 1994; Rainwater et al, 1999). Probes are embedded at different depths and locations within the subgrade to monitor migration of the freeze front and subsequent drainage as thawing occurs.

Figure 10. Installing coaxial cable in a rock pedestal supporting a highway.

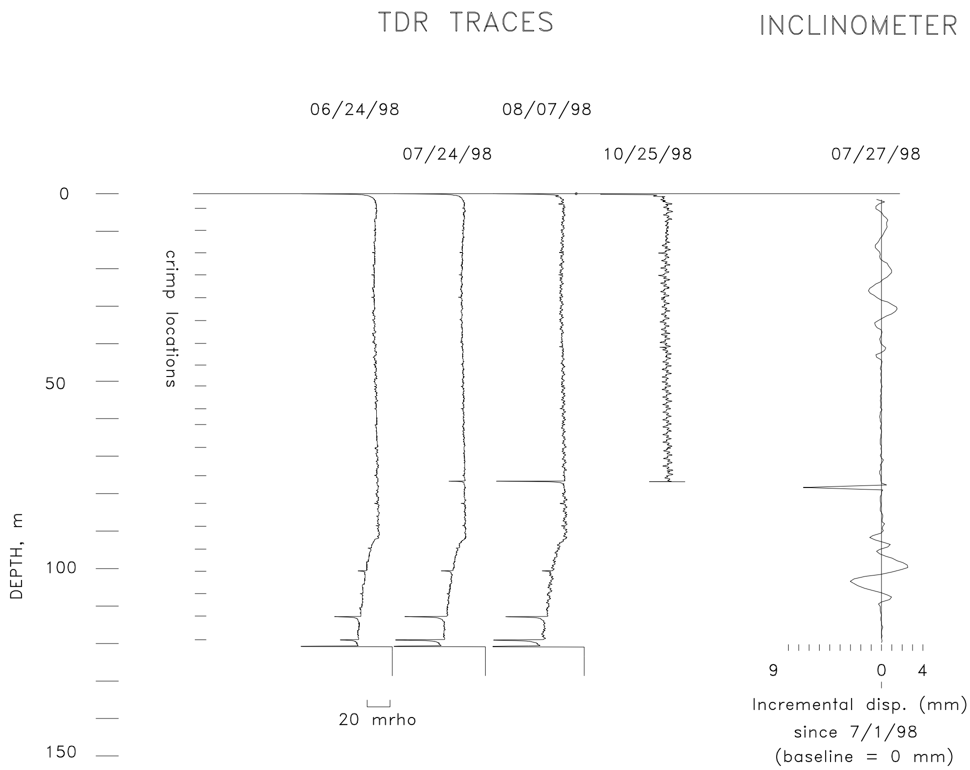


Figure 11.-TDR traces and inclinometer profile for cable installed to monitor movement within a rock pedestal.

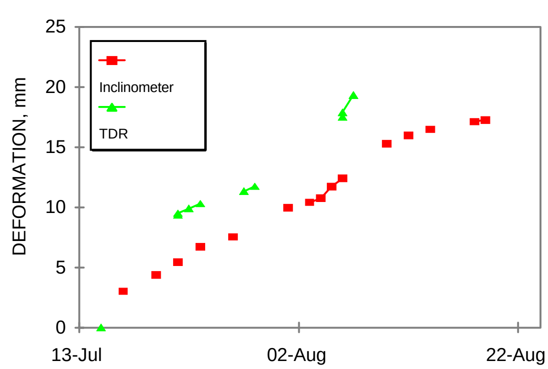


Figure 12.-Comparison of TDR and inclinometer deformation time histories at a depth of 76 m.

Figure 13. Inclinometer casing retrofitted with grouted coaxial cable.

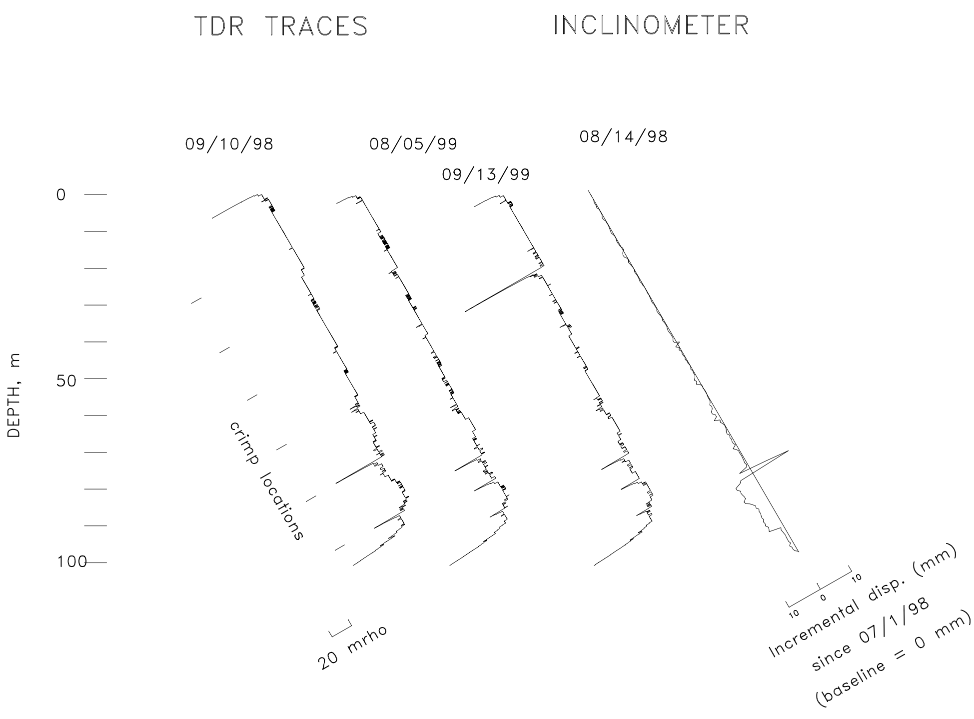


Figure 14. TDR traces acquired in retrofitted inclinometer casing within a hole inclined at 30 degrees from vertical.

SUMMARY

Three cases have been presented to illustrate some of the applications of TDR technology. These examples illustrate installation techniques, remote monitoring capabilities, and typical results for situations in which TDR was used to monitor subsidence over abandoned mines, scour of a bridge foundation, and deformation within a rock pedestal. This last case was one of several locations where it has been possible to compare TDR with inclinometers for monitoring slope movement (Dowding and O'Connor, 2000).

The results from monitoring cables installed in deformed inclinometer casing indicate the this is effective wherever this type of casing is installed —whether it be rock or soil. Such retrofitting allows continued monitoring deformation of critical structures without the need to drill additional holes.

As mentioned in the scour monitoring case summary, TDR can be used to monitor water levels. Hollow air-dielectric coaxial cable is placed in a monitoring well and the change in distance to the air-water interface is monitored remotely. For example, at the site where TDR is being used to monitor scour of a bridge foundation, it is also being used to monitor changes in river level. Although there has been no movement detected, operation of the system is verified by the measured changes in river level.

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