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Real Time Monitoring of Infrastructure using TDR Technology

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ABSTRACT

Time domain reflectometry (TDR) is analogous to radar in a cable. A voltage pulse is propagated along a cable grouted into place. When the pulse reaches a deformity in the cable, a portion reflects. Location of the deformity is calculated by the time of flight of the reflection. Size and character of the deformity can be interpreted from the intensity and type of reflection. For example, a cable can be installed through a foundation into the underlying soil or rock. As movement occurs at the foundation/soil interface, the grouted cable is deformed, and reflected signals increase in intensity as the deformation increases. Signal propagation and acquisition are all digital and thus inherently allows remote data acquisition and storage as well as downloading via telemetry. Case histories of the use of TDR cables to remotely monitor possible deformation are summarized. These examples include, 1) cables in roadways above possible coal mine subsidence, 2) cables through scour critical bridge footings, 3) cables in a deforming rock causeway supporting a roadway, and 4) compliant cable and grout combinations in a deforming embankment. These case histories demonstrate installation techniques, telemetric communication, remote monitoring capabilities and typical results.

TDR PRINCIPLES

TDR was developed by the power and telecommunications industries to locate faults in cables. A cable tester launches a voltage pulse into a coaxial cable, parallel pair wire or twisted pair wire. Wherever there is a change in electrical properties, due to cable damage or water ingress, a portion of the voltage is reflected back to the tester which displays the ratio of reflected to transmitted voltage as a reflection coefficient. The waveform shape is a function of the type and magnitude of cable damage. The travel time is converted to distance by knowing the propagation velocity which is a property of the cable or wire. Consequently, it is possible to display all reflections and identify

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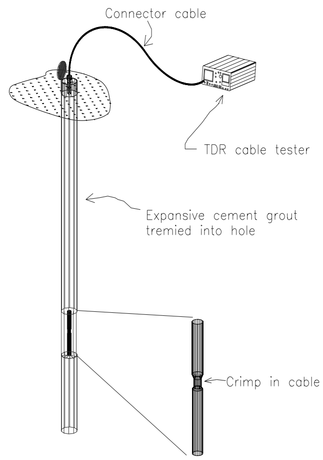

Figure 1-Schematic of cable installation and monitoring.

the type and location of cable damage. A metallic coaxial cable can be placed in a drillhole and anchored to the walls by tremie placement of an expansive cement grout (Figure 1). When movements occurring in the rock or soil are sufficient to fracture the grout, cable deformation occurs. Not only is it possible to locate deformation zones but also to distinguish shearing from tensile deformation and to quantify the magnitude of deformation (O'Connor and Dowding, 1999). The cable is crimped prior to placement in the hole. These crimps cause reference reflections which provide control markers in the TDR records.

SUBSIDENCE BENEATH HIGHWAY

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. 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).

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 15 ft diameter hole , 10 ft deep suddenly opened and three cars and a truck were damaged (Reugsegger and Lefchik, 1997). The remediation effort involved air rotary drilling of approximately 1,800 boreholes down to mine level at a depth of approximately 65 ft.

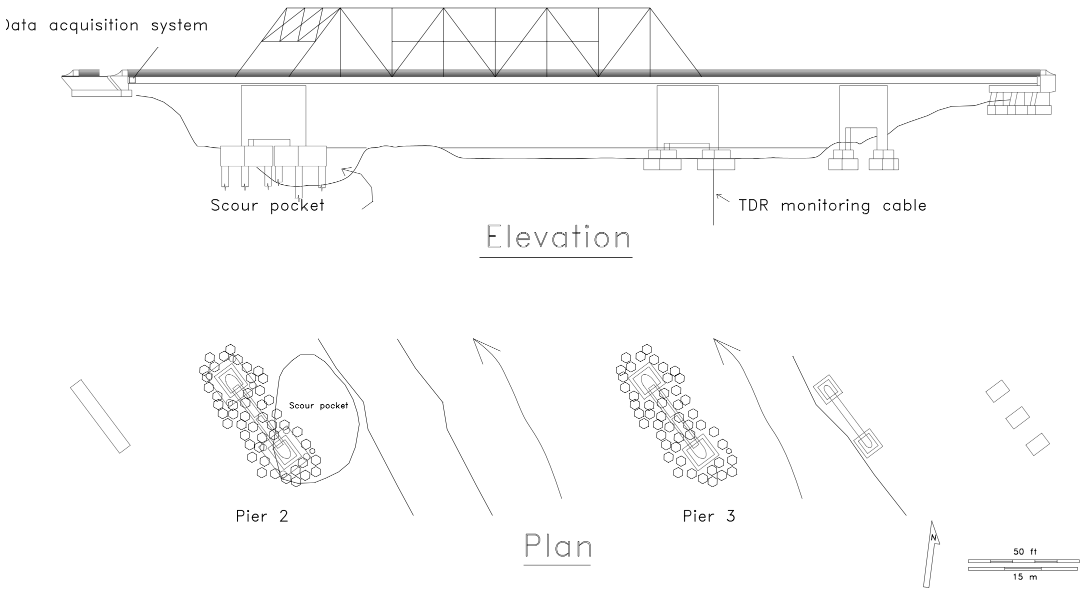

Figure 2-Overall view of bridge; TDR monitoring cable was installed in Pier 3.

The average depth of the soil-bedrock interface was approximately 47 ft. The drilled holes were cased to bedrock to allow tremie grouting of the mine voids. Approximately 18,000 cubic yards of flyash grout was tremied in the voids. Two land bridges, having lengths of 700 linear feet and 110 linear feet, were constructed over areas where the drilling and grouting program encountered high concentrations of caved and broken material in the mine interval.

In January 1996, coaxial cables were grouted into holes drilled down to mine level. TDR monitoring is done automatically on a daily basis and data is downloaded weekly which reduces costs and provides a continuous time history of subsurface movements. By virtue of this continuous record, it is possible to identify trends and precursors to surface movements. Note that this approach is tailored to monitoring localized occurrence of subsidence beneath important structures. GIS techniques must be used to integrate the data acquired by TDR and surface survey monitoring into an assessment of mine-wide subsidence risk. TDR monitoring is listed in the ODOT risk assessment manual (Ruegsegger, 1997) as one of the acceptable state-of-the-art technologies that can be used for subsidence monitoring.

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 (6 ft) deep scour pocket beneath Pier 2 on the west side of the river (Figure 2). Under an emergency contract, the pocket was filled with concrete, drilled pier foundations were constructed, and the bridge was jacked backed into position. The California Department of Transportation decided to install coaxial cables through the foundation of Pier 3 on the east side end of the truss in order to monitor for scour of the graphitic schist supporting the spread footing (Dowding and Pierce, 1994). Working from the bridge deck, a hole was drilled through the footing to a depth of 8 m (25 ft) 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 installed through this pipe to the bottom of the hole and grouted into place. In addition, precision tiltmeters were installed at the top of the pier (Prine et al, ------).

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; Dowding et al, 1996b; Nicholson et al, 1997)

The "sensor" cables and tiltmeters are connected via lead cables to an automated data acquisition system installed at the west abutment. Data is collected daily and downloaded weekly over the phone. Within a month, there was movement along the contact between the concrete footing and underlying schist which caused deformation of the cable but there has been no further movement. Performance of the system is verified by the daily changes in river level.

ROAD DISTRESS AND RETROFIT OF INCLINOMETER CASING

In May 1998, a major road was closed where it crosses a large quarry. Movements had been occurring since December of 1997. As the quarry owner was blasting to expand the pit on the north side of the road, a vertical displacement of 50 mm and horizontal displacement of 25 mm occurred and major damage to the road surface and barrier walls necessitated that the road be closed.

The instrumentation program was formulated to determine the cause of movement and to determine if the movement could be correlated with quarry expansion activities. Hole locations, orientations, and depths were chosen to maximize the likelihood of detecting movement along major joints. Among the instruments installed were inclinometers, Sondex extensometers, and coaxial cables which are monitored using TDR technology.

Comparison between TDR and inclinometer measurements is shown in Figure 3. The TDR waveforms and inclinometer incremental displacement profile show consistent response at a depth of 251 ft. The movement at this depth is occurring within a zone of greater fracture density (note lower stiffness in the histogram on the left side of Figure 3). The reflections at depths of 370 ft and 390 ft correspond with the location of dolomite-shale contacts.

As indicated by the time history plot, there was 19 mm of cable deformation at this depth from 7/16/98 to 8/7/98 while the incremental inclinometer displacement was 12.4 mm. When a reading was taken on 8/19/98, it was found that the cable had been terminated at a depth of 251 ft. Ultimately, it was not possible to lower the inclinometer probe down past 251 ft and the inclinometer casing was retrofitted with a grouted coaxial cable that is now monitored using TDR. Initially, monitoring cables

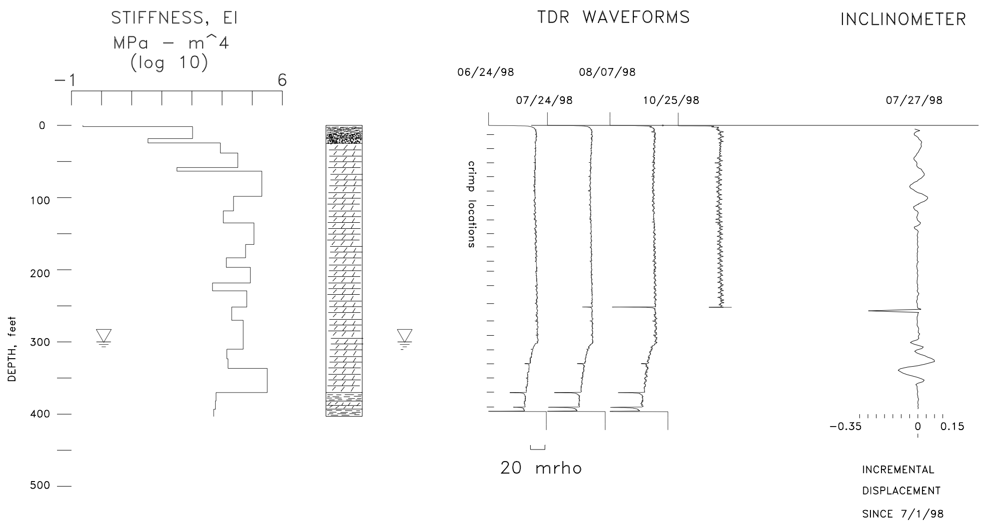

Figure 3-TDR waveforms and inclinometer profile indicating rock deformation beneath road adjacent to quarry.

were installed in only two holes while inclinometers were installed in eight holes. As movement continued and inclinometer casings were deformed to the extent that probes could not be lowered, the casings were retrofitted with grouted coaxial cables.

COMPLIANT CABLE IN EMBANKMENT

TDR technology is being used to investigate movement within the abutments of the eastbound and westbound bridges on Interstate Route 64 over the Little Blue River in Crawford County, Indiana. The westbound and eastbound bridges are continuous steel girder structures supported by Bent No. 1 on the west abutment, Pier No. 2 and Pier No. 3 adjacent to the river, and Bent No. 4 on the east abutment. The approaches of these bridges were constructed by building embankments over the existing soils and

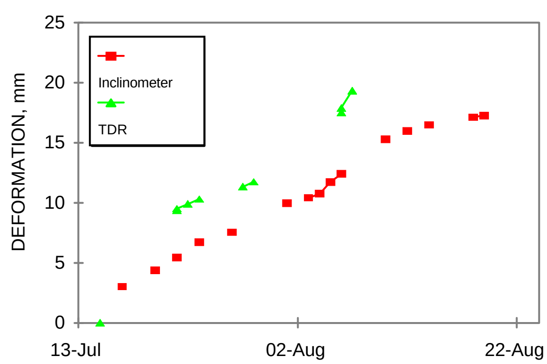

Figure 4-Comparison of TDR and inclinometer deformation time histories.

bedrock. The embankment fill consists of stiff silty clay and rock fragments, and overlies existing soft clay and loose sand. The underlying bedrock is shale and limestone. The shale is soft and easily erodible and the limestone is conspicuous as ledges in exposures along the highway.

In 1997, the bridge inspector noted that there had been displacement of one or both abutments of each bridge such that the rocker bearings had rotated almost to the maximum extent. Measurements were made of the rockers at that time. New measurements indicate little change since 1997 although the relative displacement is greater for the westbound bridge. The most striking feature is the sense of movement. On both ends of the bridges the top of the rocker has rotated toward the mud wall. In order to assess the cause of this movement, the Indiana Department of Transportation decided to install inclinometers in each embankment. In addition to the inclinometers, coaxial cables which have been installed to monitor subsurface deformation using TDR.

SUMMARY AND DESIGN CONSIDERATIONS

The major design consideration was the stiffness and shear strength of the grouted cable. The idea is for the grout to fracture so that the cable can be deformed as movement occurs within the surrounding soil (Pierce, 1988). In order to maximize sensitivity, this requires the bearing capacity of the soil be greater than the shear capacity of the grouted cable.

The strength and stiffness of the cable, grout, soil and rock for the four site described in this paper are summarized in Tables 1 and 2. Based on laboratory tests, grouted CommScope coaxial cable with a solid aluminum outer conductor (P3-75-875-CA) indicate it has a stiffness of 88 MPa and a shear strength of 1.6 MPa. This has worked satisfactorily at the sites in Ohio and Illinois where the deformation was occurring in fractured rock. In order to improve the sensitivity in soft soil a cable was manufactured by Northwestern University by stripping the solid aluminum outer conductor from the CommScope cable. The exposed polyethylene foam was then coated with silver paint and wrapped with vinyl electrical tape. This cable is being monitored at the bridge abutment in Indiana and the evaluation will continue as movement is detected.

The results from monitoring cables installed in deformed inclinometer casing indicate the this is effective wherever this type of casing is installed —weather it be rock or soil". Other (not in this article) cases indicate that the aluminum cable will deform with small 4 " holes and weak grout, ie low EI.

Table 1 - TDR Cable Details

Project	Reason for Monitoring	Sensor Cable Type	Sensor Cable Strength (MPa)	Sensor Cable Stiffness (MPa)	Sensor Cable Length (m)	Lead Cable Length (m)
OHDOT	abandoned mine subsidence	A	1.6	88.0	30	100
Caltrans	scour of bridge foundation	A			20	82
ILDOT	road distress	A			60 to 120	0
INDOT	abutment embankment deformation	A			29	0
		B	0.4	8.0	11	19

A: CommScope solid aluminum, expanded polyethylene foam dielectric, P3-75-750CA, 22.2 mm dia., 75-ohm
B: Type A with solid aluminum outer conductor removed; exposed polyethylene foam dielectric was coated with silver paint then wrapped with vinyl electrical tape, 20 mm dia.

Table 2 – Grout, Soil and Rock Properties

Project	Hole Diameter (mm)	Grout Properties† Strength (MPa)	Grout Properties† Stiffness (MPa)	Grout Mix (lb) W	Grout Mix (lb) C	Grout Mix (lb) B	Rock / Soil Properties Description	Rock / Soil Strength (MPa)	Rock / Soil Stiffness (MPa)	Installation and Comments
OHDOT	200	-	-	800	1128	0	shale, sandstone	28‡	2000‡	rotary drilled
Caltrans	102	5	-	320	376	0	graphitic schist	4	1000	rotary drilled
ILDOT	75 to 125	7	1500	1054	1983	0	fractured dolomite and shale	110	2200	rotary drilled
	75									installed in deformed inclinometer casing
INDOT	200	20	4700	240	235	15	sand and clay fill with boulders	0.1	0.1	hollow stem auger
	75	19	4300	168	329	12	shale	2	2	rotary drilled

‡ estimated
† W=water, C=Portland cement, B=bentonite

REFERENCES

1. O'Connor, K.M. and C.H. Dowding. 1999. *GeoMeasurements by Pulsing TDR Cables and Probes*. CRC Press, Boca Raton
2. Dowding, C.H., F.-C. Huang, and P.S. McComb. 1996. "Groundwater Pressure Measurement with Time Domain Reflectometry," *Geotechnical Testing Journal*, GTJODJ, ASTM, Vol. 19, No. 1, March, pp. 58-64.
3. Dowding, C.H. and C.E. Pierce. 1994 "Use of Time Domain Reflectometry to Detect Bridge Scour and Monitor Pier Movement," Proceedings of the Symposium on Time Domain Reflectometry in Environmental, Infrastructure, and Mining Applications, Evanston, Illinois, Sept 7-9, U.S. Bureau of Mines, Special Publication SP 19-94, 1994, NTIS PB95-105789, pp. 579-587.
4. Dowding, C.H., C.E. Pierce, G.A. Nicholson, P.A. Taylor, and A. Agoston. 1996 "Recent Advancements in TDR Monitoring of Ground Water Levels and Piezometric Pressures," Proceedings of the 2nd North American Rock Mechanics Symposium: NARMS'96, Montreal, June, pp. 1375-1381.
5. Nicholson, G.A., J.F. Powell, and K.M. O'Connor. 1997. "Monitoring Groundwater Levels Using a Time Domain Reflectometry (TDR) Pulser," U.S. Army Corps of Engineers WES, Final Report, CPAR-GL-97-2.
6. O'Connor, K.M. and E.W. Murphy. 1997. "TDR Monitoring as a Component of Subsidence Risk Assessment Over Abandoned Mines," *Int. Journal of Rock Mechanics & Mining Science*, Vol. 34, Nos. 3-4, Paper 230.
7. Pierce, C. E. 1998. "A Compliant Coaxial Cable-Grout Composite for Time Domain Reflectometry Measurements of Localized Soil Deformation." Ph.D. Dissertation, Dept of Civil Engineering, Northwestern University, Evanston, Illinois, December.
8. Ruegsegger, L.R. and T.E. Lefchik. 1997. "Abandoned Underground Mine Inventory and Risk Assessment." Proceedings, 48th Annual Highway Geology Symposium, Knoxville, TN, May, 1997.
9. Ruegsegger, L.R. 1997. "Abandoned Underground Mine Inventory and Risk Assessment Manual," Ohio Department of Transportation, Office of Materials Management, Geotechnical Design Section, Columbus, OH, August.

10, Prine, D.et al, -----. 199? "Automated Monitoring of Bridge Deformation using Precision Tilitmeters." ------------------------------------.