NORTHWESTERN UNIVERSITY

TDR Monitoring of Soil Deformation:
Case Histories and Field Techniques

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By
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Thank you Sophie and my whole family in France for your all your love and confidence.

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Chapter 1

Introduction

This thesis presents the application of Time Domain Reflectometry technology in nine case studies. Presented in detail are cable and grout installation techniques, data acquisition instrumentation and autonomous real time monitoring of soil deformation using TDR. The goal of this work is to summarize the state of the technology in TDR for geotechnical applications and also to serve as an educational tool for researchers and practitioners.

1.1 Thesis outline

Chapters 2 through 5 review case histories of TDR installation in soil. Application for monitoring bridge pier and abutment stability are presented in Chapter 2 while, landfill and embankment stability in Chapter 3, subsidence for sinkholes and mining in Chapter 4 and excavation stability in soft soils in Chapter 5. These chapters describe in detail installation techniques, cable and grout properties, data acquisition systems eventually installed in these demonstration projects, response of TDR cables is also displayed and compared to tiltmeter or Slope Inclinometer data.

Chapter 6 and 7 compare details of cable and their installation and instrumentation for data acquisition from the case studies for summary of best practice. Chapter 6 includes details on cable manufacture, grout design, mix and testing, hole drilling and cable insertion. Also summarized are field techniques and recommendations for smooth installation. Chapter 7 describes manual data acquisition in the field as well as autonomous real time data acquisition and display on the internet. Chapter 8 summarizes the findings and installation recommendations.

1.2 TDR background

General

Time Domain Reflectometry (TDR) is an electrical measurement technique used to determine the degree and spatial location of cable deformation. In concept, it is similar to radar along a cable. As shown in Figure 1-1 step b, a voltage pulse is produced by a TDR pulser, travels along a two conductor metallic cable, until it is partially reflected by cable disruptions produced by deformation. The distance to the disruption can be calculated knowing the propagation velocity of the signal and the time of travel from the disruption to the receiver. As shown in Figure 1-1 step a., rock or soil movement deforms the grout, shears the cable and thus changes the capacitance between the inner and outer conductors. This change in capacitance produces the reflected voltage pulses shown in Figure 1-1 step c. By interpreting the collected waveforms, the shearing zone can be located; the amount of shearing also increases with the amplitude of reflection.

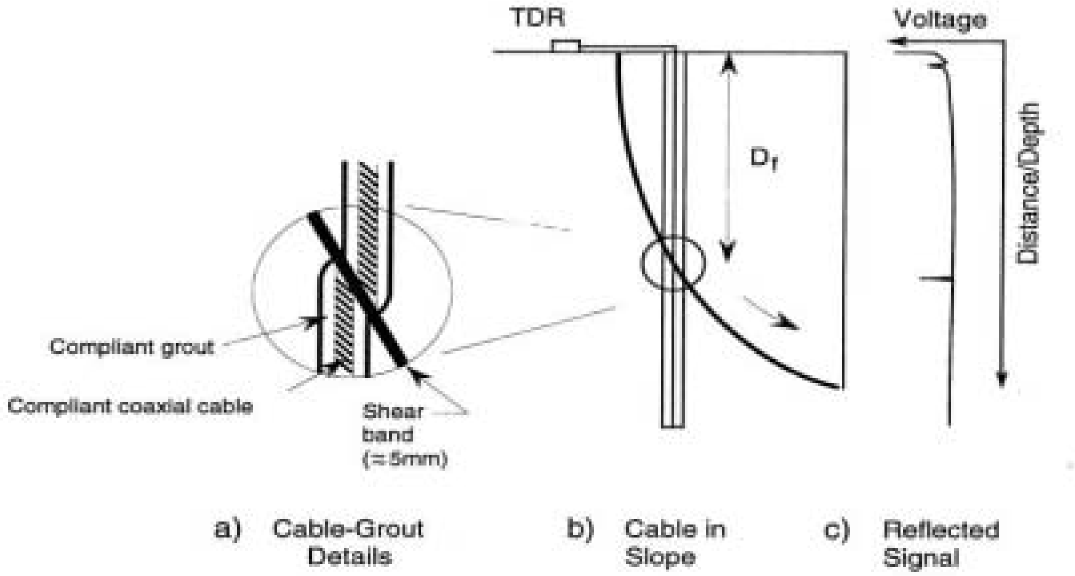


Figure 1-1: Shearing mechanism and induced reflection on a grouted TDR cable.

The ease of deployment of TDR technology varies with earth material. This technology was first applied geotechnically to monitor rock mass deformation, which occurs predominantly along joint interfaces (Dowding and Huang, 1994). The large stiffness of rock and the high degree of strain localization along rock joints allow installation with stiff cable and standard drilling and grouting procedures. As a result, the technique has been adopted world wide by the mining industry. On the opposite side of the geotechnical spectrum, the low stiffness of soft soil and the relative small strain in the early stages of failure in soft soils, greatly complicate the application of TDR technology.

For TDR to be effective in soil, a shear band must occur to produce the localized strain necessary to locally deform the cable. In this process, deformation occurring along a shear band in soil must be transferred to the cable through the grout. Thus, the composite soil-grout-cable must faithfully transfer the relative soil displacement to the cable. The grout should ideally be no more than 5 to 10 times stronger than the surrounding soil. A grout that is too strong may not fail with the soil and thus smears or widens the shear band, whereas a grout that is too weak will not kink or distort the cable.

Optimum materials and installation

TDR cable

Coaxial cables in Figure 1-2, demonstrate the best practice properties. A coaxial cable consists of a solid core (inner conductor), a cylindrical shield (outer conductor), separated by a polyethylene foam insulator. Two main types of coaxial cables are recommanded for TDR application. Bare solid aluminum outer conductor cable is the most common type; however, more compliant copper braid outer conductor cables are also being developed for use in soft soils. At this time, the stiffer cable is commercially available while the compliant cable must be made manually.

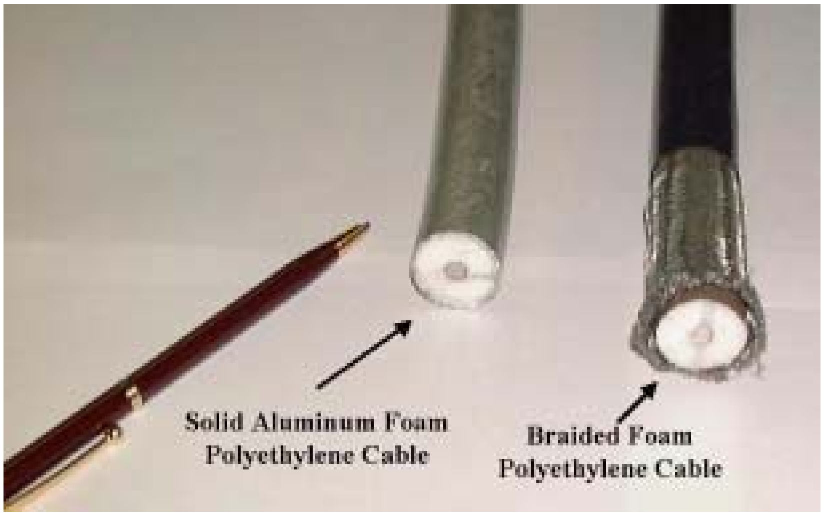


Figure 1-2: Two most common types of coaxial TDR cables (Cole 1999).

Grout mix

Grout for TDR monitoring should be low cost and pumpable with a drill rig fluid pump. It must also be strong enough to shear the cable but weak enough to be failed by the surrounding soil. Given these requirements, the best grouts for this application are cement-bentonite grout family. They are inexpensive, commonly employed by drilling crews and can be mixed to produce similar strengths to soil. To achieve sufficient fluidity, fluidizing agents such as Intrusion Aid Type R must be employed.

Installation

TDR cables must be installed in separate holes to be effective. Unfortunately, many early users have strapped small diameter TV cable to the outside of a Slope Inclinometer casing to avoid drilling an extra hole. Unfortunately these cables are lossy (high noise to signal ratio). The stiffening of the cable-grout composite by the Slope Inclinometer casing further reduces kinking of the cable.

Chapter 2

Bridge Pier Stability Monitoring Using TDR

This chapter describes the details of the installation of and equipment for TDR cables and tiltmeters to monitor the deformation of bridge piers and abutments for possible instability. In these two cases, instability arises from two differing possible mechanisms: abutment slope failure and scouring of a pier foundation. Both cases involved installation of tiltmeters as well as TDR cables to detect translation. This approach reflects a strategy to measure movement of the pier and unstable mass. Other strategies for scour surveillance have involved measurement of the scour pocket rather than the pier movement. The information contained in this Chapter come from GeoTDR Inc. installation reports (O'Connor, 2002).

2.1 S.R. 62, Indiana

Project presentation

Introduction

Significant distortion of the foundation of the bridge on S.R. 62 over the Little blue River in Crawford County, Indiana led by its eventual instrumentation by InDOT. As shown by Figure 2.1 and Figure 2.2, the bridge on S.R. 62 is a composite welded steel plate girder structure, supported by two bents and two piers founded on pile groups, parallel to the center line of the river. During construction in 1993, pier No.2 moved 21 cm (0.7 feet) at its toe towards the river and subsequently in 1999 lateral movement to the north of two girders at bent No.1 was also discovered.

Following the assumption that subsurface failure in the silty clay produced the deformations, the soil between bent No.1 and pier No.2 was removed and replaced with rock fill. After this operation, the top of the pier moved back 15 cm (0.5 ft) leaving 6 cm (0.2 ft) of residual movement.

Figure 2-1: View of S.R. 62 bridge over Little Blue River, Crawford County, IN.

Site conditions

Approaches to the bridge were constructed by building embankments over the existing soils and bedrock. Existing soils as shown in Figure 2.2, consist of silty clay on the west side of the bridge overlying alluvial sand and silty clay overlying loam on the east side. The underlying bedrock is horizontally bedded Upper Mississippian shale and limestone. The shale is soft and easily erodible and the limestone is conspicuous as ledges in exposures along S.R. 62. This is also a well known karst area.

A ledge of limestone and shale was exposed beneath bent No.1 when the slide material was excavated during remediation. The bottom of the excavation encountered sandstone 2.4 m (8 ft) below the bottom of pier No.2 footing which is 2.1 m (7 ft) above the tips of the supporting piles.

Issues of monitoring

Causes of movement at pier No.2 are unknown and InDOT decided to instrument the site. As shown by Figure 2.2, two tiltmeters (TL-1 and TL-2),Slope Inclinometers (SI-1 and SI-2) and a TDR cable (TDR-2) were installed to provide continuous monitoring of tilt and translation of Pier No.2. The Slope Inclinometer provides a comparison for TDR response.

A Campbell Scientific Instruments Inc, system was also installed by Northwestern University Infrastructure Technology Institute (ITI) in conjuction with GeoTDR Inc. in November 2001 to provide remote data acquisition. It allows remote, continuous and automatic data acquisition and storage, and a real time display on ITI website. This real time capability supplements monitoring slope deformation by manual measurement ofSlope Inclinometer response.

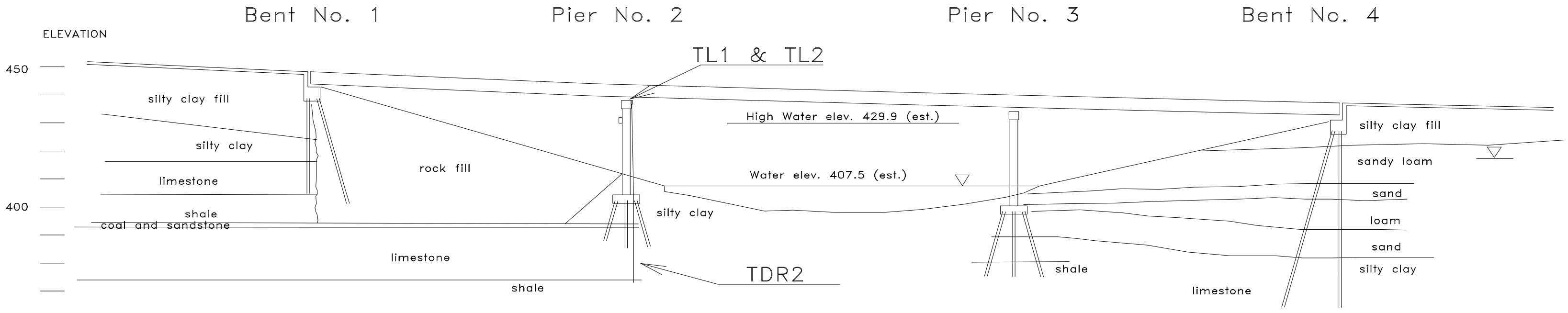
Site installation

Installation of grouted cables for monitoring deformation using TDR

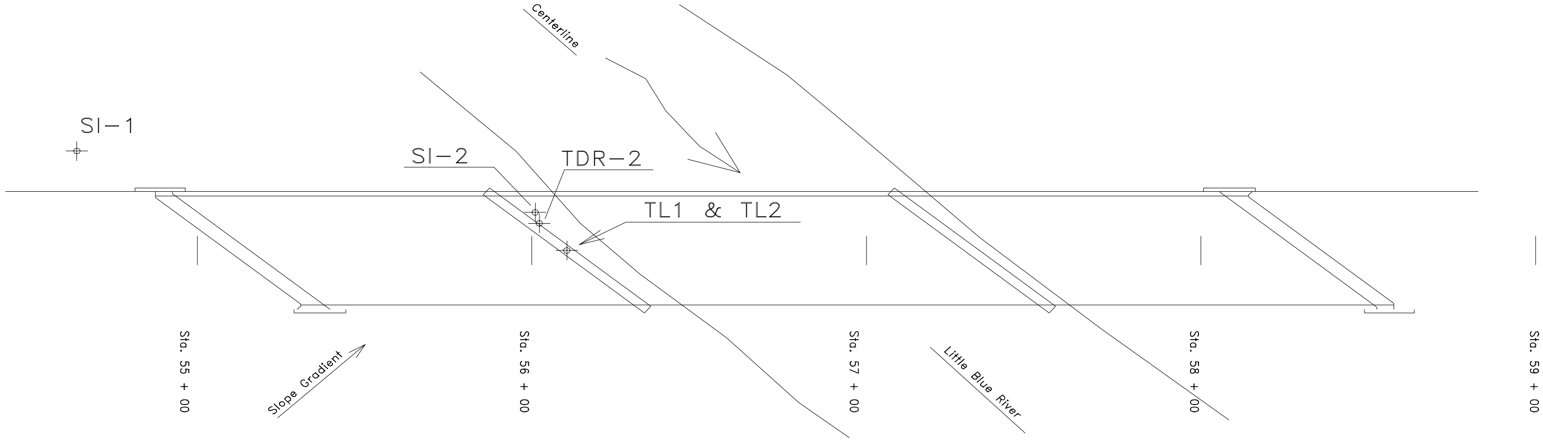
The TDR cable, CommScope solid aluminum outer conductor P3-75-875-CA, was grouted with a cement-bentonite grout mix designed to produce a predicted strength less than 0.5 Mpa. Table 2-1 compares the strength and stiffness of the materials involved in this installation.

Material	**Description**	**Strength (Mpa)**	**Stiffness (Mpa)**
Grouted cable	solid aluminum outer conductor	1.6	88.0
Grout mix	cement-bentonite mix	0.5	
Soil	silty clay below water table (N<10 blows/ft)	0.02	6.0
Soft Rock	shale below water table (N<30 blows /ft)	2.0	600.0

Table 2-1: Summary of cable, grout and soil properties for S.R. 62 bridge over the Little Blue River, Crawford County, IN.



Elevation



PLAN

Figure 2-2: Elevation and Plan view of the bridge on S.R. 62 over the Little Blue River , Crawford county, IN.

The TDR borehole was located where the pier footing would be subjected to the greatest lateral deformation during an abutment failure, as shown by Figure 2-3. It is located at the upstream (North) end of the pier as close to theSlope Inclinometer as possible, by piercing the pier footing. The cable was protected in so far as possible from floating debris during high water by installation close to the pier itself.

The footing was not accessible to drilling equipment and all operations were conducted from the bridge deck. The hole, as shown by the Figure 2-3 and Figure 2-4, was drilled by coring a 25 cm (10-in.) diameter hole through the bridge deck and lowering a 11 cm (4-1/2-in.) ID hollow stem auger to the ground surface. The auger was advanced to the top of the pier footing. The hole was then rotary drilled with a 10 cm (3-7/8-in.) bit until steel reinforcement was encountered at a depth of 60 cm (2 ft.) into the footing. The hole was finally completed with a 7 cm (2-7/8-in.) rotary bit to the required depth.

A steel conduit housed the cable between footing and bridge deck to protect the cable from miscellaneous environmental effects and floating debris. After removing the drill rod, 5 cm (2-in.) ID diameter galvanized steel conduit was lowered into the hollow stem auger. The bottom most section of conduit was 60 cm (2 ft.) long and connected to a 10 cm (3-7/8 in.) OD pipe union at the bottom. This was connected to 3 m (10 ft.) long sections which were added as the conduit was lowered down hole. When the pipe union was seated within the footing, it provided support for the conduit and allowed the bottom section to extend 30 cm (1 ft.) below the bottom of the footing as shown in Figure 2-3.

Prior to installation within the conduit, the bare aluminum 2 cm (7/8-in.) CommScope coaxial cable was spray painted with metal primer to minimize the possibility of bubbles forming due to a reaction with the hydrating cement grout and crimped. The cable was crimped at 6.1 m (20 ft.) and 12.2 m (40 ft.) from the bottom in order to produce the reference TDR reflections displayed by Figure 2-10. The cable was lowered into the steel conduit and the hollow stem auger removed .

The cement grout was mixed in a 189 L (50 gallon) barrel and tremie pumped in the hole through the drill rods. The grout, whose composition is given in Table 2-3, has an estimated strength of 0.5 Mpa. The grout was tremie pumped through a 2.5 cm (1 in.) flush coupled PVC pipe and was extracted incrementally as the grout level rose. Grout returned at the surface after pumping a volume of 0.15 m^3 (5.5 ft^3) as calculated in Table 2-4. This return implies a grout loss of 0.02 m^3 (0.7 ft^3)due to the oversized hole created by the hollow stem auger.

The top of cable and steel conduit temporarily extended above the bridge deck before being removed. The top section of the conduit was removed by unscrewing the topmost coupling and the cable was trimmed to install a connector. The steel junction box was lowered over the top of cable and attached to the bridge pier as shown by Table 2-4 so that the conduit is attached to the pier at the top and firmly seated within the footing. The total length of the cable is 19.7 m (64.6 ft) and the elevations of the cable and structure are shown in Table 2-2 below.

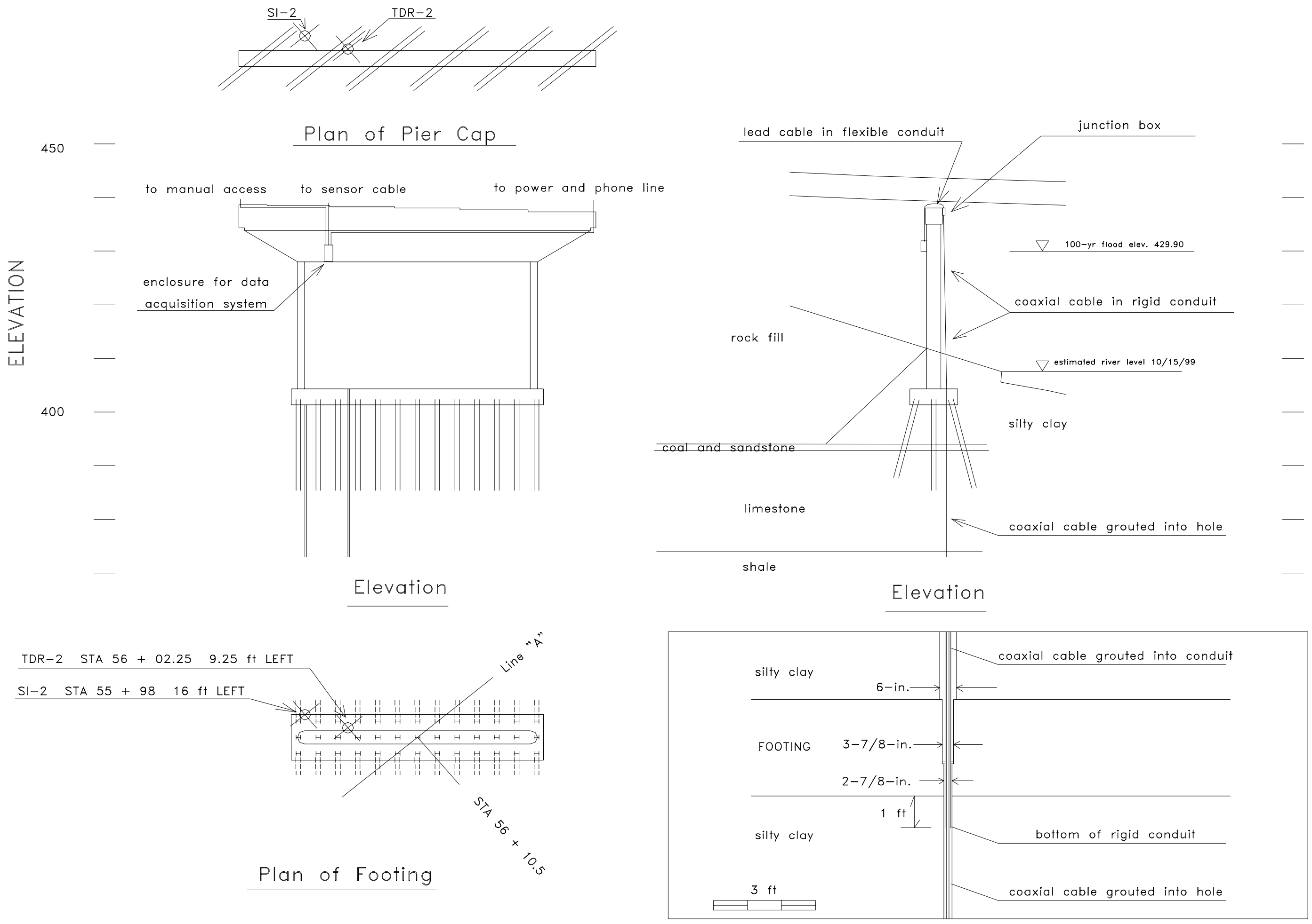


Figure 2-3: Overview of TDR cable installation for S.R. 62 bridge over the Little Blue River, Crawford County, IN.

Cable & Structure		Elevation
top of pier		elev 438.27 ft
top of cable		elev 437.6 ft
reference crimp		elev 423.0 ft
ground surface		elev 410.3 ft
top of footing		elev 404.3 ft
reference crimp		elev 403.3 ft
bottom of footing		elev 401.0 ft
bottom of rigid conduit		elev 400.0 ft
top of rock		elev 394.0 ft
reference crimp		elev 383.0 ft
bottom of pile		elev 385.0 ft
bottom of cable		elev 373.0 ft

Table 2-2: As built conditions for TDR-2 hole at S.R. 62. bridge over the Little Blue River, Crawford County, IN.

Grout Mix Component	**Quantity (in lbs)**
Water	240
Quikrete Portland cement	141
Baroid Quik-Gel bentonite	15
Specrete-IP Intrusion Aid type R	2.5
Water:Cement ratio	1.70

Table 2-3: Grout mix composition for TDR-2 hole at S.R. 62. bridge over the Little Blue River, Crawford County, IN.

	TDR-2	
	Description	**Volume**
Hollow stem auger	10 in.diam., 6 feet deep	3.27 ft^3
Rotary drilling in footing	3-7/8 in. dia., 2 feet	0.16 ft^3
Rotary drilling in footing, soil and rock	2-7/8 in. dia., 29.3 feet	1.32 ft^3
Hypothetical hole volume		4.75 ft^3
Grouted Volume pumped		5.5 ft^3
Grout Loss		-0.74 ft^3

Table 2-4: Summary of hole volumes and grout loss for TDR-2 hole at S.R. 62. bridge over the Little Blue River, Crawford County, IN.

Figure 2-4: Drilling of hole TDR-2 from the deck of the S.R.62 bridge over the Little Blue River, Crawford County, IN.

Figure 2-5: Installation of the junction box on pier No.2 of the S.R.62 bridge over the Little Blue River, Crawford County, IN.

Tiltmeter installation

Two tiltmeters were installed over the centerline of pier No.2 to measure the tilt in two directions. Location of the two Applied Geomechanics Model 801-S uniaxial tiltmeters over the pier No2. centerline is shown in Figure 2.2, Figure 2.3 and Figure 2.6. Tiltmeter 1 (TL-1, S/N 1161), measures the tilt in the transverse direction: perpendicular to the river, whereas Tiltmeter 2 (TL-2, S/N 1168) measures tilt in the longitudinal direction: parallel to the river. Positive rotation is in the direction of the lead cable as shown in Figure 2.7. The Table 2-5 below, summarizes the Tiltmeter data format for TL-1 and TL-2 as given by the data acquisition system.

Figure 2-6: Installation of tiltmeters TL-1 and TL-2 over the centerline of pier No.2 of the S.R.62 bridge over the Little Blue River, Crawford County, IN.

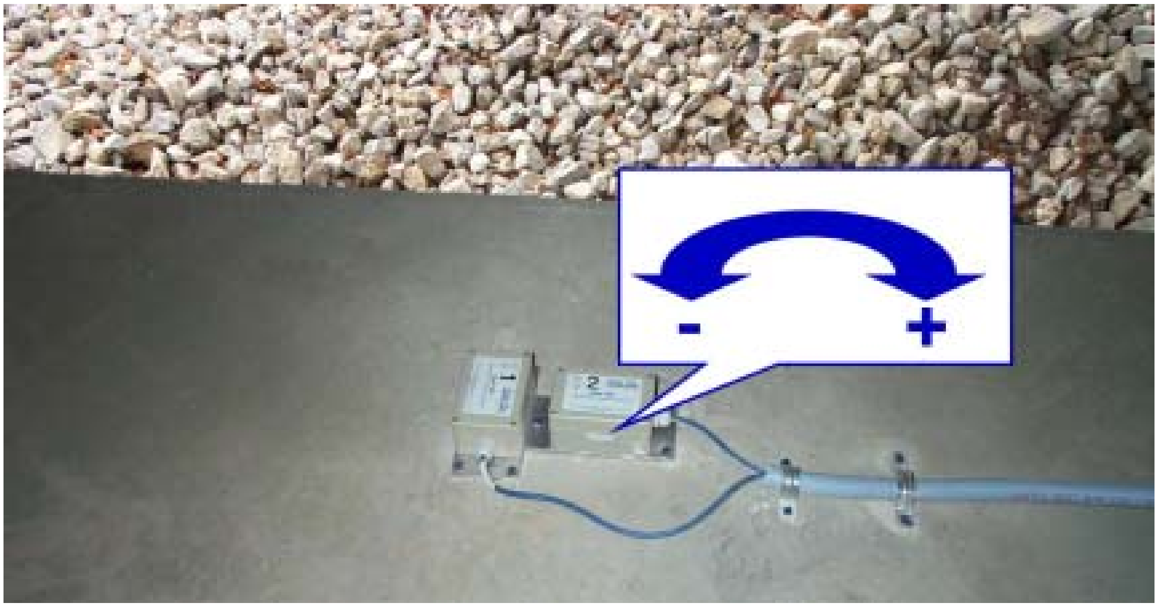


Figure 2-7: Tilt orientation of the tiltmeters over the centerline of pier No.2 of the S.R.62 bridge over the Little Blue River, Crawford County, IN.

Array ID	**Year**	**Julian Year**	**Time**		**Tilt**	**Temp**	**Baseline**	**Difference from baseline**	**Scale factor**
			hr-min	sec	arc-deg	deg-C	arc-deg	arc-deg	deg/mV
328/TL-1	2001	334	1000	.25	0.769	8.03	0.76	0.009	0.001
349/TL-2	2001	334	1005	.25	0.600	8.97	0.59	0.010	0.001

Table 2-5: Tiltmeter data format for TL-1 and TL-2 placed over the centerline of the S.R.62 bridge over the Little Blue River, Crawford County, IN.

Remote communication

Initial installation

The first data acquisition system installed in October 1999, allowed manual interrogation of the TDR cable. A flexible RG8 lead cable (Belden 8214) was connected to the sensor cable and fed through the conduit to the enclosure shown in Figure 2.8. Power and telephone line were also brought to this enclosure which is linked to a temporary junction box allowing manual data acquisition from the bridge deck with a Tektronix 1502 pulser and a field computer. This approach became unsatisfactory upon realization that access to the box was difficult and site visits too infrequent.

Figure 2-8: Enclosure housing the acquisition system, installed on the west side of pier No.2 of the S.R.62 bridge over the Little Blue River, Crawford County, IN.

Remote data acquisition system

To overcome the inefficiency of the previous system, a new remote data acquisition system based on a datalogger and a modem was installed on August 14, 2001. In order to install the new data acquisition system, the old TDR unit, the 12 V battery and the field computer were removed. The new system shown in Figure 2-9 is based on a Campbell Scientific CR10X datalogger, a newly developed TDR 100 pulser, and has a callback capability with a 9600 phone modem. This typical data acquisition apparatus is described in more detail in Chapter 6 and 7 of this thesis and a list of the hardware used is displayed in Appendix 1.

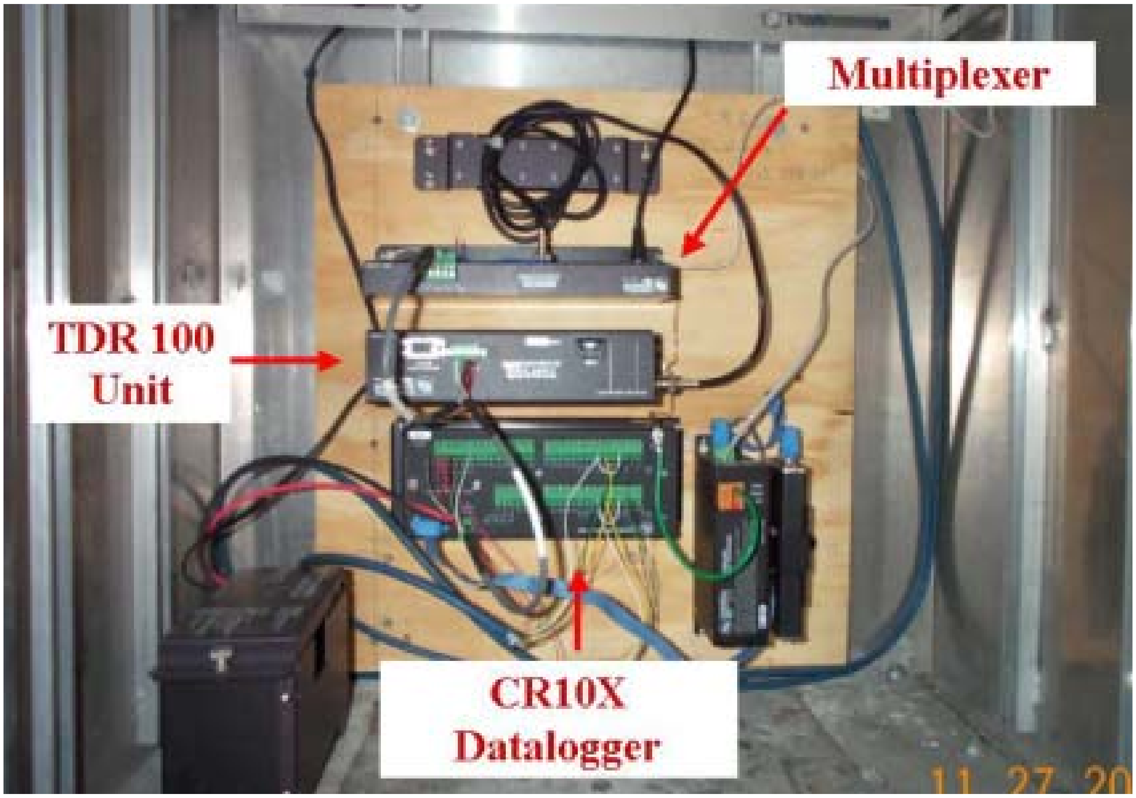


Figure 2-9: Automated data acquisition system, installed on the west side of pier No.2 of the S.R.62 bridge over the Little Blue River, Crawford County, IN.

Readings and conclusions

Readings and data display

Since the installation of the automated data acquisition system, TDR and tiltmeter waveforms are displayed in real time on the ITI website. Every morning at 8.00 AM, the polling computer at Northwestern's ITI lab calls the datalogger and collects TDR and tiltmeter waveforms from the previous day. They are displayed on the web at the following address: http://www.iti.northwestern.edu/tdr/operational/sulphur. All TDR waveforms since the initial reading have been archieved and are accessible so that it is possible to monitor changes in the reflection signal.

Even through interpretation of the measurements remains the responsibility of InDOT, a summary of instrument response is informative. Since August 14, 2001, no TDR reflection and no significant tilt movement of the pier have been observed as shown by Figure 2-10 and Figure 2-11. The comparison in Figure 2-10, between a TDR waveform taken just after the new data acquisition system was installed and a waveform from the end of July 2002, shows no reflection spike below the footing, where deformation cable would shear. No significant tilt of pier No.2 occurred as shown by the response for the month of July 2002 presented in Figure 2-11. The pier is only subject to tilt due to temperature changes as indicated by the daily sinusoidal change in tilt.

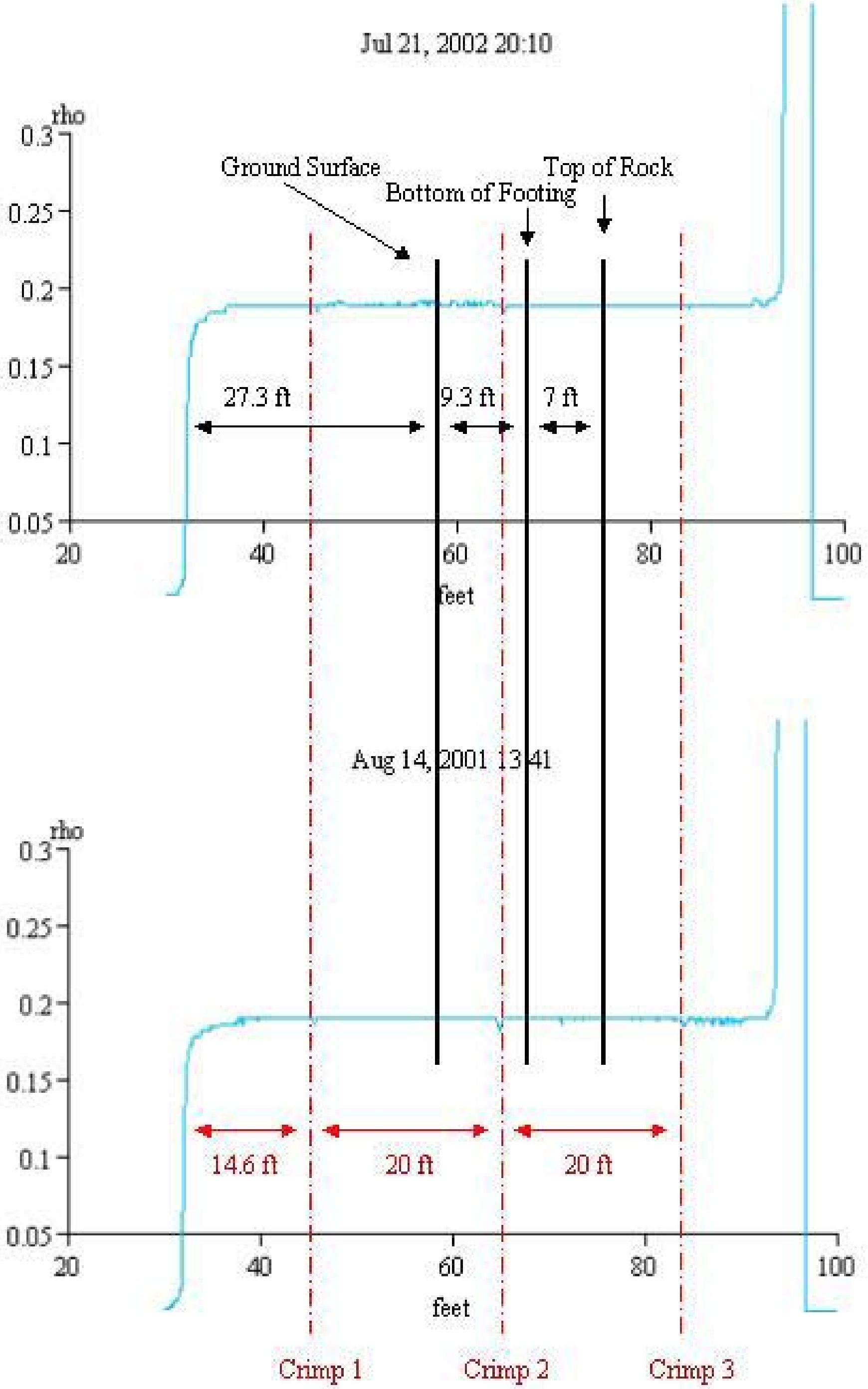


Figure 2-10: Comparison between initial and recent TDR data from TDR-2 drilled through pier No.2 of the S.R.62 bridge over the Little Blue River, Crawford County, IN. (July 2002)

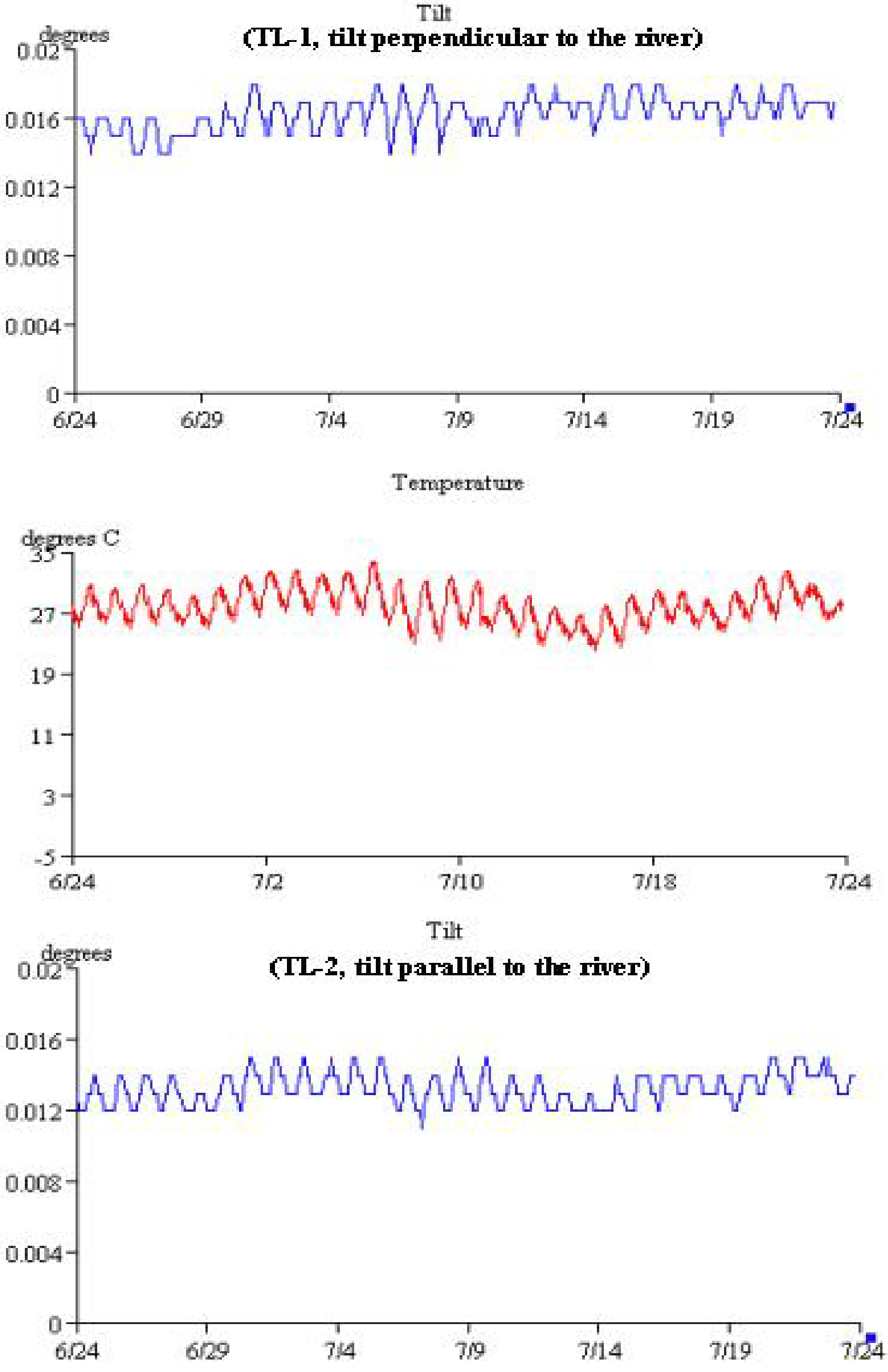


Figure 2-11: One month variation of the tilt of pier No2. of the S.R.62 bridge over the Little Blue River, Crawford County, IN.

Partial conclusion

Instrumentation of this site was challenging in both the installation of the cable itself and installation of a robust remote data acquisition system. First, the installation of a TDR cable through a bridge pier footing was a complex operation because of the required protection against the debris impact during high water. The method used on this project to drill and protect the cable with as steel conduit proved its efficiency. The remote and autonomous data acquisition system is highly reliable and the real time display of the waveform on the internet allows InDOT, ITI and GeoTDR to monitor the cable condition at all times.

2.2 Horse Creek, California (instability due to scour pocket)

Project presentation

Introduction

Deformation of bridge 02-117 over the Klamath River, California shown below in Figure 2.12, has been documented by Caltrans. Point B of Pier No.2 shown in Figure 2-14 was moving towards the river and the rocker had been rotated clockwise to within 5 cm (2 in.) of its limit rotation. During the summer 1997, a truck damaged each of the transverse truss members of the bridge and during damage inspection, it was noted that the bridge was tilted over pier No.2. Upon taking measurements, it was found by Caltrans that point C shown in Figure 2-14, had translated 30 cm (12 in.) horizontally downstream and settled 40 cm (16 in.). As shown again in Figure 2-14, a 1.80 m (6 ft) deep scour pocket beneath point D had caused movement of the spread footing supporting the pier foundations.

Figure 2-12: View of bridge 02-117 over the Klamath River, Horse Creek, CA.

Site conditions and remediation

Even through the piers were founded on rock, it had eroded. Caltrans personnel drilled exploratory borings at pier No.2 (97-1 and 97-3) and pier No.3 (97-2 and 97-4) and found that the rock foundation consist of an intensely fractured graphitic schist which crumbles easily. Although recovery greater that 60% could be obtained, as shown by Figure 2-13 the RQD for every core sample was 0%. It was not possible to test any sample of this schist.

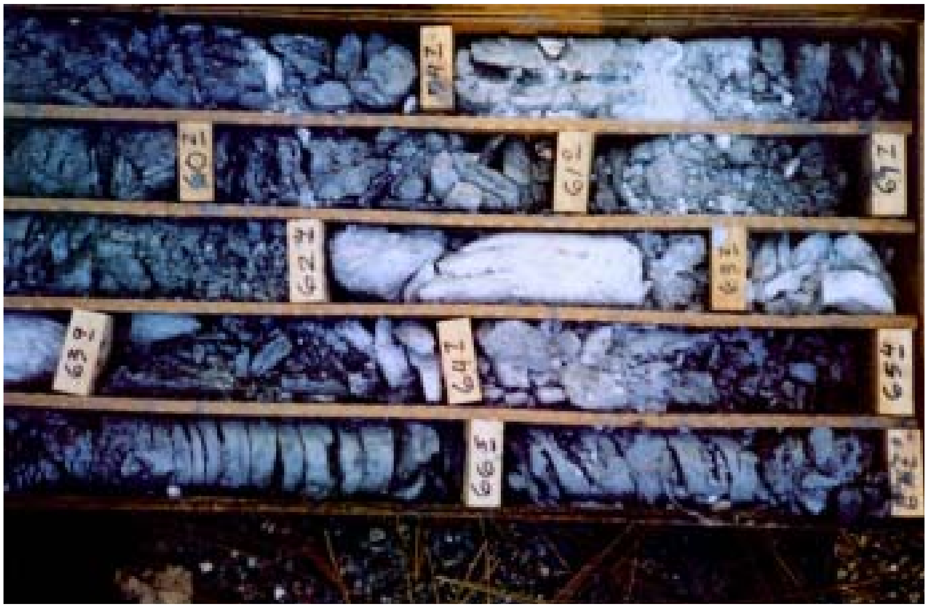


Figure 2-13: Core sample of the fractured graphitic schist below pier No.2 of bridge 02-117 over the Klamath River, Horse Creek, CA.

The bridge was releveled using cast-in-place drilled piers as a reaction to jack the pier and the bridge itself. Water was first pumped from the scour pocket which was found to be 1.8 m (6 ft) deep, 91.4 m (30 ft) wide and 18.3 (60 ft) long. Some 67.3 m^3 (88 yd^3) of concrete was required to fill the scour pocket. Eight 91 cm (36 in.) diameter by 18.3 m (60 ft) long cast-in-place drilled piers were constructed; one at each corner of the two pier footings. After releveling was completed, riprap was placed around pier No.2 and pier No.3 for scour protection as shown by Figure 2-14.

issues of monitoring

It was proposed to place one displacement TDR cable, one water sensitive TDR cable through the healthy pier (Pier No3.) and two tiltmeters on two of the pier to monitor four possible modes of deformation. The first possible mode of deformation is horizontal shearing along the interface between the concrete footing and graphitic schist. The second is shearing along a bearing capacity slip surface within the schist. Both of these are detected by the vertical TDR cable. The air dielectric TDR cable detects differences in water level through the changing level of the air-water interface between the inner and a perforated outer conductor. Measurement of water level will allow a correlation between the possible pier movement detected by the deformation cable and the tiltmeters, and the water level. Tiltmeters measure pier rotation.

Site installation

Installation of grouted cables for monitoring deformation using TDR

A major design consideration is the stiffness and shear strength of the grouted cable. A CommScope coaxial cable with a solid aluminum outer conductor (P3-75-875-CA) and stiff grout mix, was selected after study of the schist rock characteristics with a strength of less than 3.6 MPa and stiffness less than 1 GPa. The grout mix was designed for compressive strengths of 3.6 MPa and 7.2 MPa based on laboratory tests.

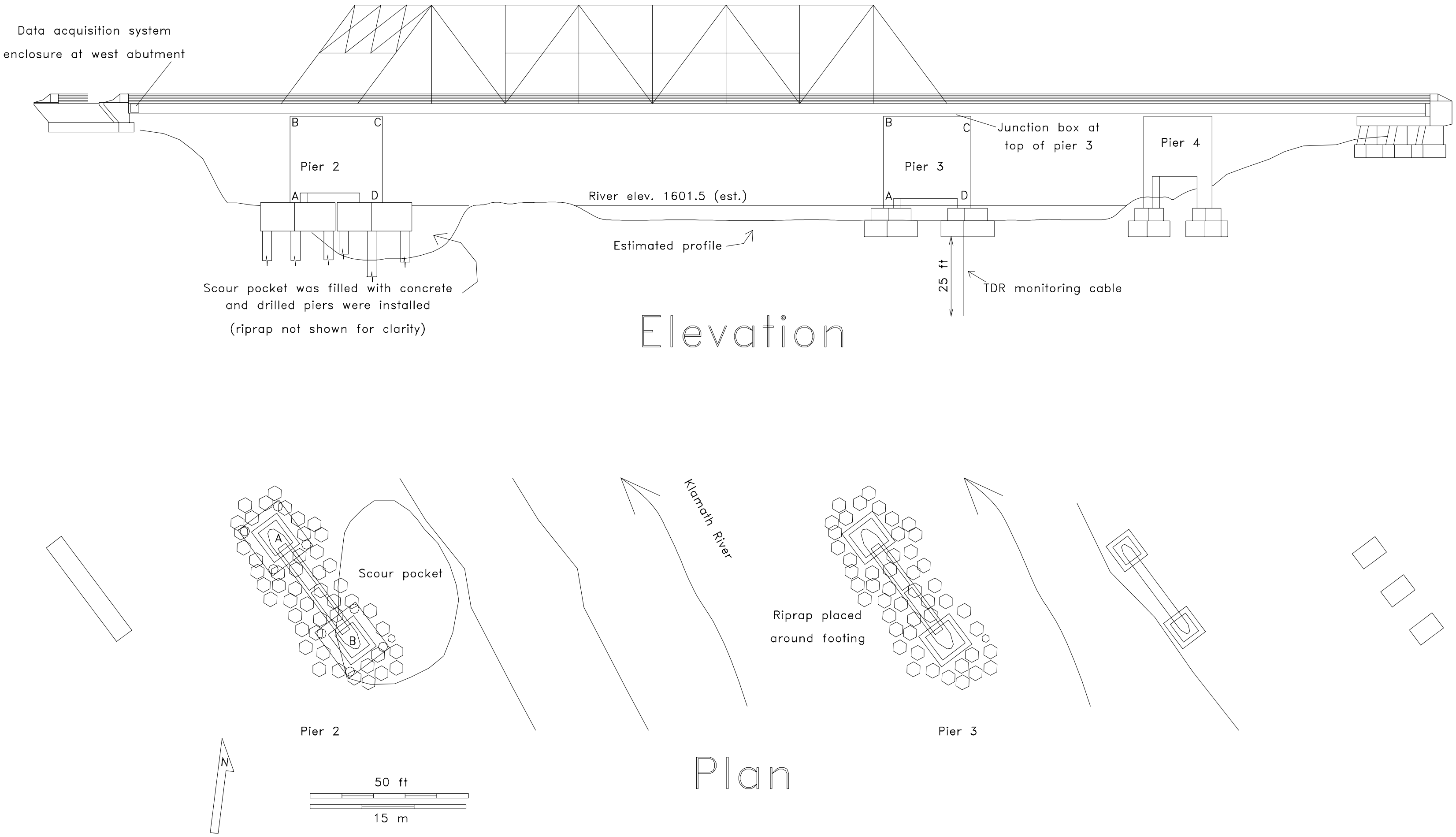


Figure 2-14: Plan view and elevation of the bridge 02-117 over the Klamath River, Horse Creek, CA

As with the bridge on S.R. 62 over the Little Blue River, Crawford County, IN, a major design and installation challenge was the location of the hole and its accessibility. The same approach as for S.R. 62 over the Little Blue River, was used. To reach pier No.2 footing, the hole was drilled through the bridge deck and drill rods were lowered between the pier curtain wall as shown by Figure 2-14. Then a steel casing was used to protect the cable from any damages.

A 12.4 cm (4-7/8 in.) diameter hole was drilled in November 1997 through the top of the concrete pier and to a depth of 30 cm (1 ft) in the concrete footing. Wireline casing was set and a 10 cm (4 in.) diameter hole was drilled through the concrete footing and tremie pad then to a depth of 7.9 m (26 ft) into the graphitic schist as shown in Figure 2-14. The casing was removed and, as shown by Figure 2-15, a protective 10 cm (4 in.) ID steel pipe was placed inside the curtain wall between the hole in the footing and the hole at the top of the pier. The cable was installed inside this steel pipe.

Prior to installation, the cable was prepared and crimped. The outer polyethylene jacket was stripped from the bottom most 7.6m (25 ft.) of cable. Crimps were made 3m (10 ft.) above the end-of-jacket location as shown by the as built condition described in Table 2-6 below. The 19.6m (64.5 ft.) long bare cable was spray painted with primer to minimize reaction with the cement grout.

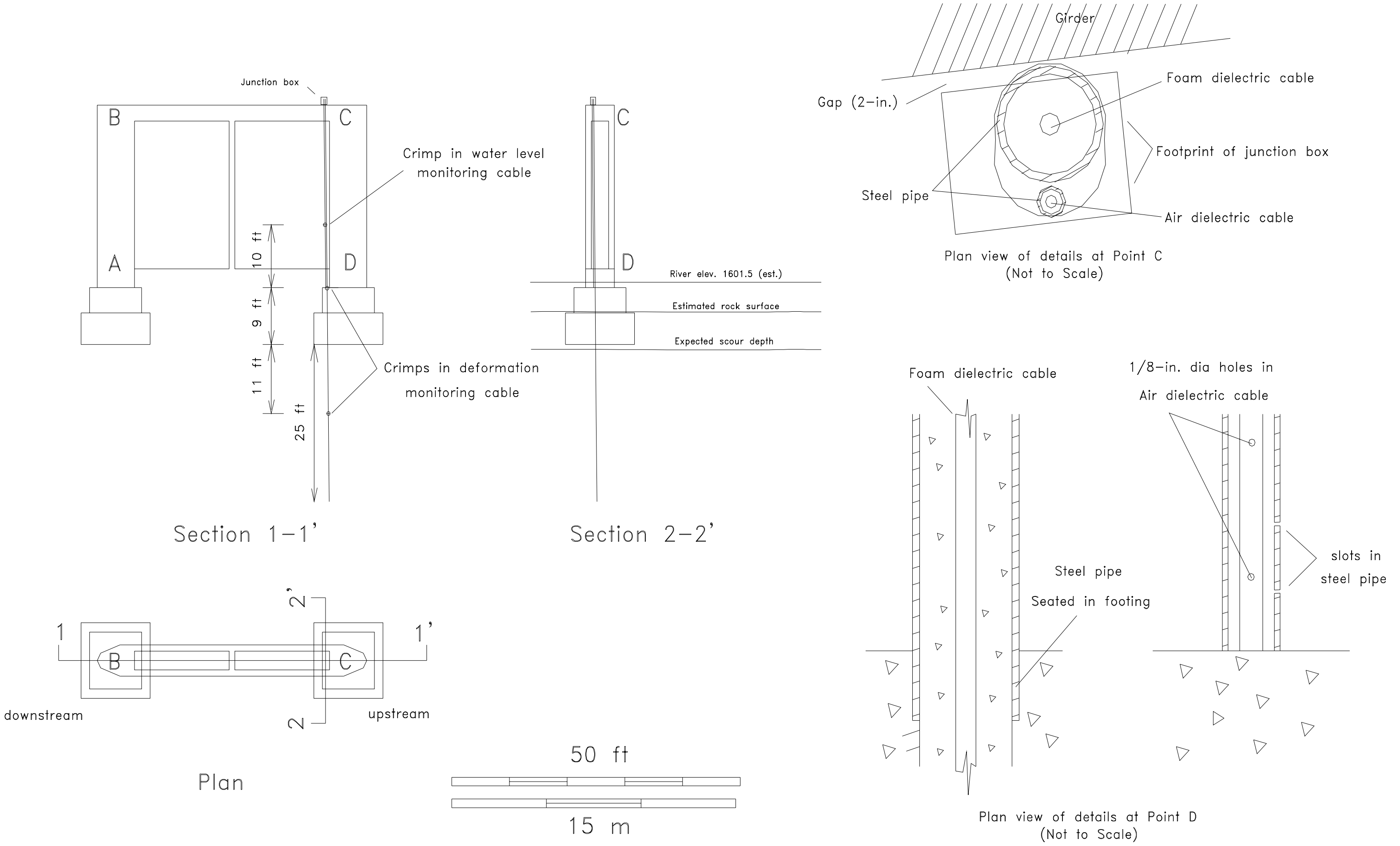


Figure 2-15: Installation details for deformation TDR cable of bridge 02-117 over the Klamath River, Horse Creek, CA

Cable & Structure		Elevation
total cable & connector length		19.6 m
Top of connector		elev 496.9 m
Upper reference crimp		elev 487.9 m
Interface concrete tremie pad / underlying graphitic schist rock		elev 485.2 m
Bottom of cable jacket		elev 484.9 m
Bottom reference crimp		elev 481.8 m
End of cable		elev 477.3 m

Table 2-6: As built conditions for deformation TDR of bridge 02-117 over the Klamath River, Horse Creek, CA.

The cable was then anchored to the borehole walls by tremie placement of grout. The cement grout mix which composition is summarized in Table 2.7, was mixed in a 189 L (50 gal) barrel. 0.14m^3 (5.1 ft^3) of grout mix were pumped through a 2.5 cm (1 in) flush coupled PVC pipe. Grout loss occurred as grout seeped out through the bottom of the steel pipe. The grout loss is estimated to have been 0.045 m^3 (1.6 ft^3), as the grouted hole volume is only 0.1 m^3 (3.5 ft^3). After grout placement, the top of grout was sounded at 1.52 m (5 ft) above the top of footing. Thus the cable was grouted throughout the movement zone.

Grout Mix Component	Quantity (in lbs)
Water	334
Portland type I-II cement	380
Intrusion Aid type R	20
Water:Cement ratio	0.87

Table 2-7: Grout mix composition for deformation TDR hole of bridge 02-117 over the Klamath River, Horse Creek, CA.

Air dielectric cable installation

As shown by Figure 2.15, the air dielectric cable was placed in a 2.5 cm (1 in) steel casing next to the casing for the deformation TDR cable. The 2.5 cm (1 in) ID steel pipe was attached to the outside of the 10.1 cm (4 in) diameter steel pipe and a Cablewave Systems HCC 12-50J air dielectric cable was placed in this pipe as displayed by Figure 2.14 and Figure 2.15. Prior to placement, slots were cut in the bottom one foot of the pipe. Also, 3 mm (1/8 in) diameter holes were drilled at a spacing 30 cm (1 ft) in the bottom 1.2 m (4 ft) of the air dielectric cable and a crimp was made 3 m (10 ft) from the bottom of the cable. The bottom of the pipe rests on the top of the footing as shown by the as built conditions displayed in Table 2.8 below.

Cable & Structure		Elevation
total cable & connector length		8.9 m
Top of connector		elev 496.9 m
Reference crimp		elev 491 m
River (11/10/1997)		elev 488.1 m
End of cable = top of footing		elev 487.9 m

Table 2-8: As built conditions for air-dielectric TDR of bridge 02-117 over the Klamath River, Horse Creek, CA.

Figure 2-16: View of the 4 in. and 1 in. casings housing the TDR cables through the deck of bridge 02-117 over the Klamath River, Horse Creek, CA

Remote communication

Initial installation

The first remote data acquisition system installed on site shown by Figure 2.17 is a PC based Comtronix Computer linked to a Textronix 1502 cable tester and two single axis tiltmeters on top of pier No3. This system is also linked to a modem and a hard wired phone line to allow remote data downloading. This system worked intermittently for two years till 1999.

Figure 2-17: View of the first DAS installed at Horse Creek, CA, with the PC on the left and the Textronix cable tester 1502 on the right.

Second installation

The first DAS system installed was hit by a lightning and the computer damaged. The phone line is also unreliable. A second DAS was installed to replace the initial system. In 2000, a PC 104 system was installed in conjunction with a Hyperlabs TDR pulser but has only answered sporadically.

Readings and conclusion

Readings

Readings have been taken with the two remote data acquisition system from the site and the polling computer at ITI's lab at Northwestern University. The data have never been downloaded continuously because of all the failures of the phone line and the system. In the end, the little data collected has been lost.

Conclusion

The installation of TDR cables at this site was challenging. The efficiency of the system was reduced by problems with the DAS. A new data acquisition system, based on the reliable Campbell Scientific datalogger CR10X and TDR pulser TDR100 could be installed in order to create a reliable fully autonomous remote data acquisition system to monitor the pier movements.

Chapter conclusion

This chapter demonstrates the success of the combination of autonomous remote monitoring TDR cables and tiltmeters and autonomous internet display of data. It highlighted the efficiency of the Campbell scientific based system and its reliability in comparison to other PC based systems. The combination of TDR cables and tiltmeters allows multiple failure modes as well as water level to be monitored with a single data acquisition system. Finally, autonomous display of data over the internet allows simultaneous , real time surveillance as well as shearing of data among multiple users.

Chapter 3

Landfill and Embankment Stability Monitoring Using TDR

This chapter describes the details of the installation of and equipment for TDR cables and Slope Inclinometers to monitor the movement of a landfill and a bridge embankment. In these two cases instability arises from the same possible mechanism: slope failure. Both cases involve the installation of both TDR cables and Slope Inclinometers to detect two types of movement. Slope Inclinometers detect general movement of the slope whereas TDR cables measure local deformation. The information contained in this Chapter come from GeoTDR Inc. installation reports (O’Connor, 2002).

3.1 Clark landfill, Indiana-Landfill stability

Project presentation

Introduction

Slope movement occurred in the southwestern corner of the Clark Landfill shown by Figure 3-1 and Figure 3-2. The slide mass is essentially 640 m (2100 ft) long by 213 m (700 ft) wide, with a height of some 24.3 m (80 ft). As shown by Figure 3-3, the original slope angle is estimated to have been 3H:1V.

Figure 3-1: View looking at the Clark Landfill, IN.

Figure 3-2: View of the failure of the Clark landfill, Indiana.

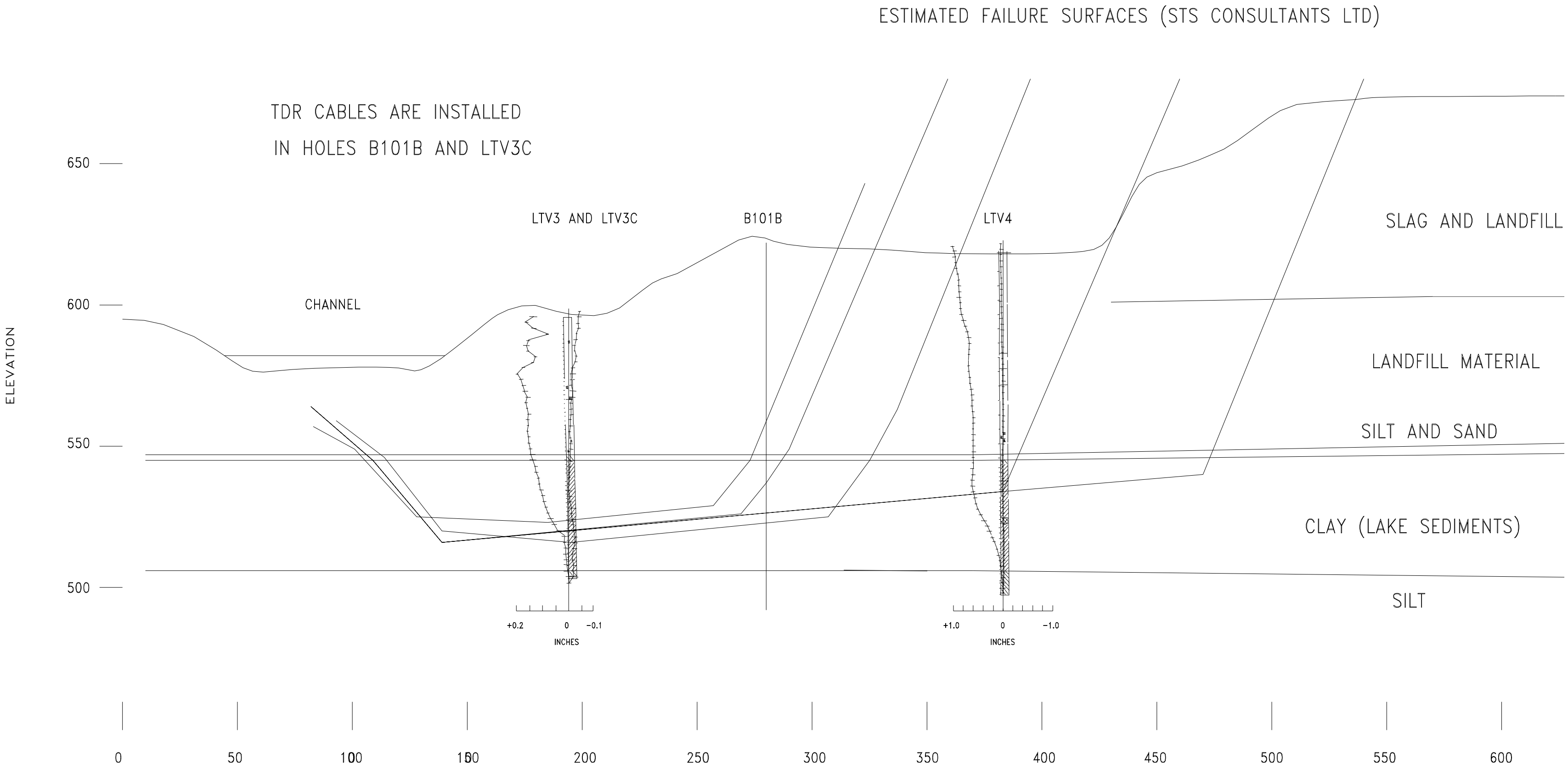


Figure 3-3: Cross section of the Clark Landfill, IN, showing the failure surface and the position of the TDR cables.

Site conditions

The landfill is located next to the Lake Michigan and the stratigraphy consists of landfill over soft clay. The landfill and slag pile rests as shown by Figure 3-3 on 1 m (3 ft) of silt and sand which is underlain by 9.0 to 12 m (30 to 40 feet) of soft to medium clay. Those layers are underlain by stiffer clay. The softer clay layer has a shear strength between 9.6 to 23.9 Kpa (0.2 and 0.5 Ksf) whereas the deep stiffer clay has a shear strength of 47.9 Kpa (1.0 Ksf).

Issues of monitoring

In April 1998 it was decided to install TDR cables to demonstrate their feasibility in landslide monitoring. Based on Slope Inclinometer data it is known that subsurface deformation is occurring within a shear zone at a depth of approximately 30 m (100 ft) within the soft clay layer as shown by Figure 3-3. It was also decided to compare the performances of a small diameter but more compliant braided cable versus a larger diameter solid aluminum cable.

Site installation

Installation of grouted cables for monitoring deformation using TDR

Two TDR cables were installed in separate existing piezometer holes for possible correlation with adjacent Slope Inclinometer response. Hole B101B near Slope Inclinometer LTV4, hosts a solid aluminum coaxial cable and hole LTV3c near Slope Inclinometer LTV3 hosts a more compliant braided cable. The location of Slope Inclinometers and the TDR cables is shown in Figure 3.3 and Figure 3.4.

As shown in Table 3-1, the major design consideration was the stiffness and shear strength of the grouted cable compared to that of the soft clay. A 2 cm (0.8 in) diameter CommScope coaxial P3-75-875-CA cable with a solid aluminum outer conductor was selected as the stiffer cable and an Alpha 1/2 –in. foam dielectric braided copper coaxial cable (#9847) was chosen as the more compliant cable. The cement bentonite grout mix was designed to match the soil stiffness of soft clay in which deformation may occur.

Material	**Description**	Strength **(Mpa)**	Stiffness **(Mpa)**
Cable B101B	solid aluminum outer conductor	1.6	88.0
Cable LTV3c	braided foam polyethylene cable	0.4	8.0
Grout B101B	cement-bentonite mix	0.5	?
Grout LTV3c	cement-bentonite mix	3.9	?
Soft soil	soft clay	0.009-0.024	?
stiff soil	“hard” clay	0.047	?

Table 3-1: Summary of cable, grout and soil properties for Clark Landfill, IN.

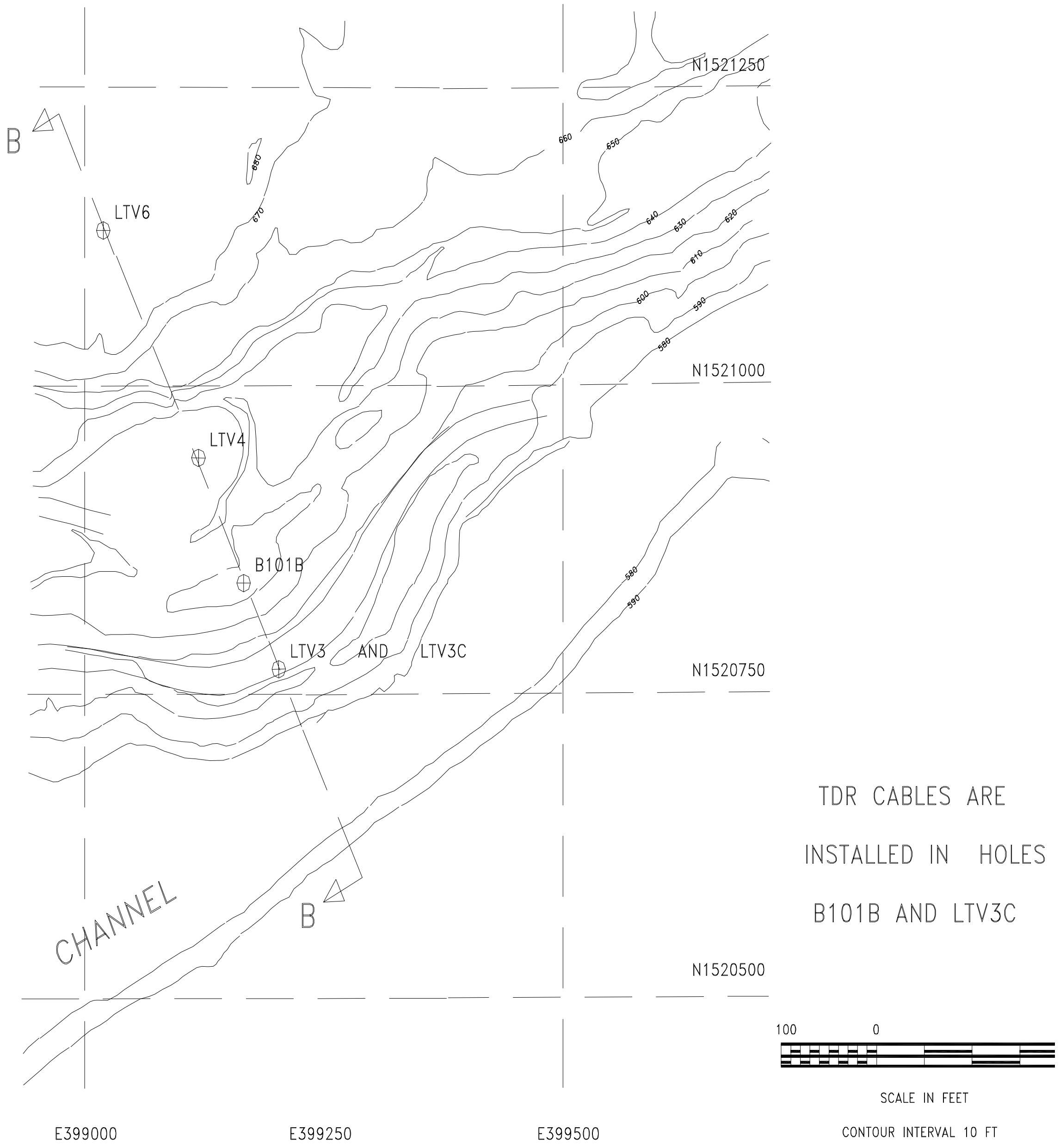


Figure 3-4: TDR and Slope Inclinometer hole location at the Clark Landfill, IN.

Hole B101B

Hole B101B near Slope Inclinometer LTV4 was cased with an inside diameter of 9.8 cm (3-7/8 in). The hole was rotary drilled under bentonite slurry with an outer 12.7 cm (5 in.) PVC casing set in the slag and a 10.1 cm (4 in.) steel casing set through the soft clay. A coating of plastic clay formed on the outside of the steel casing and jammed into the PVC casing when 3 m (10 ft) had been extracted. In order to remove the steel casing, the PVC casing had to be removed whereas it was planned to leave it in place. The open annulus between the top of the grout and the ground surface was filled with sand and landfill material and a protective steel casing was placed over the top. The as built conditions are summarized in the Table 3-2 below.

Prior to installation, the CommScope cable was spray painted with metal primer to minimize the possibility of bubbles forming due to a reaction with the hydrating cement grout. The cable was also crimped at 21 m (70 ft) from the bottom in order to produce a reference TDR reflection as shown in Figure 3-5.

The cement-bentonite grout was mixed in a 208 L (55 gal) barrel and tremie pumped into the hole. Two batches of grout were prepared for this hole and their composition is described in Table 3-3. The grout was pumped to the bottom through rods within the cased hole. While pumping the second batch, grout return occurred at the surface as computed in Table 3-4 below. The solid aluminum coaxial cable was then lowered into the hole filled hole with grout.

Cable & Structure		Elevation
top of cable		elev 195.6 m
ground surface		elev 188.9 m
top of grout		elev 180.1 m
reference crimp		elev 171.3 m
top of shear zone		elev 161.5 m
bottom of shear zone		elev 157.2 m
bottom of cable		elev 149.9 m

Table 3-2: As-built conditions for B101B hole at Clark Landfill, IN.

Grout Mix Component	Quantity (in lbs) Batch 1	Quantity (in lbs) Batch 2
Water	361	361
Portland cement	188	282
Bentonite	10	10
Specrete-IP Intrusion Aid type R	5	7.5
Water:Cement ratio	**1.92**	**1.28**

Table 3-3: Grout mix composition for B101B hole at Clark Landfill, IN.

	B101B	
		Volume
PVC casing	5 in. dia., 77 ft long (removed)	10.50 ft^3
Steel casing	4 in. dia., 27 ft (removed)	2.36 ft^3
Uncased hole	3-7/8 in. dia., 25 ft	2.05 ft^3
Hypothetical hole volume		14.91 ft^3
Grouted Volume pumped		13.1 ft^3
	Difference	-1.81 ft^3
Depth to top of grout after casing removal	29 ft	
Volume of open annulus	5 in. dia.	3.95 ft3
	Discrepancy	**0.16 m^3 (-5.76 ft^3)**

Table 3-4: Hole volumes and grout loss for B101B hole at Clark Landfill, IN.

Hole LTV3c

The hole LTV3C adjacent to Slope Inclinometer hole LTV3 was also cased and has an inside diameter of 7.4 cm (2-15/16 in). The hole was rotary drilled under bentonite slurry with an outer 10.1 cm (4 in.) PVC casing set in the slag. A 8.9 cm (3-1/2 in.) steel casing was set through the soft clay. The as built conditions are summarized in Table 3-5 below.

Prior to installation, the outer polyethylene jacket was stripped from the bottommost 15.2 m (50 ft) of the cable to minimize stiffness. The bottom of the cable was connected to a cone in which the 1.9 cm (¾ in.) ID flush-coupled PVC pipe could easily fit. Before grout pumping, the cable was pulled down the hole with the PVC pipe pushing in the cone and grout was tremie placed to anchor the coaxial cable. This procedure is also described in more detail in Chapter 6.

The cement-bentonite grout was mixed in a 208 L (55 gal) barrel and pumped into the hole. The day before installation, bentonite was added to water in a 208 L (55 gal) barrels and allowed to hydrate for 12 hours. Cement and additives were added the next day in the proportions described in Table 3-6 below. Then, once the cable in place, the grout mix was pumped by tremie placement and grout loss occurred at the surface.

Although grout return occurred at the surface, the grout settled after pulling the steel casing and grout pipe, as shown in Table 3-7. After 12 hours, the annulus between the top of the grout and ground surface was filled with sand and landfill material. (Sandy silt and slag) A protective PVC casing was placed on top of the 10.1 cm (4 in.) PVC casing.

Cable & Structure		**Elevation**
top of cable		elev 183.4 m
ground surface		elev 182.5 m
top of grout		elev 176.7 m
top of bare cable		elev 168.8 m
bottom of PVC casing		elev 167 m
top of shear zone		elev 167 m
bottom of shear zone		elev 157.8 m
bottom of cable		elev 153.6 m

Table 3-5: As built conditions for LTV3C hole at Clark Landfill, IN.

Grout Mix Component	**Quantity (in lbs)**
Water	319
Portland cement	329
Bentonite (hydrated for 20 hours)	12.5
Specrete-IP Intrusion Aid type R	2
Water:Cement ratio	**0.97**

Table 3-6: Grout mix composition for LTV3C hole at Clark Landfill, IN.

	LTV3C	
		Volume
PVC casing	4 in. dia., 51 ft (in place)	4.45 ft^3
Steel casing	3-1/2 in. dia., 27 ft (removed)	1.80 ft^3
Uncased hole	2-15/16 in. dia., 22 ft	1.04 ft^3
Hypothetical hole volume		7.29 ft^3
Grouted Volume pumped		7.09 ft^3
	Difference	-0.20 ft^3
Depth to top of grout after casing removal	19 ft	
Volume of open annulus	4 in. dia.	1.65 ft3
	Discrepancy	**-0.052 m^3 (-1.85 ft^3)**

Table 3-7: Hole volumes and grout loss for LTV3C hole at Clark Landfill, IN.

Other instruments

Four Slope Inclinometers LTV 1 to 4, were installed by STS Consultants Ltd. in the landslide. The Slope Inclinometer readings allowed location of the shear zones within 30 m (100 ft) of the soft clay and a determination of its thickness; 1.5 to 9 m (5 to 30 ft). A comparison was further possible between the TDR cable readings and the Slope Inclinometer data. Piezometers have also been installed to monitor pore water pressure. A detailed list of hardware and tools and manufacturers is displayed in Appendix 1.

Readings and conclusion

Readings

No automated data acquisition system was installed on this project. The cables were periodically interrogated by graduate students from Northwestern University. A Textronix 1502 Cable tester connected to a laptop computer equipped with SP232 was used to pulse the cables. The baseline waveforms shown in Figure 3-5 and Figure 3-6 were obtained in April 1998.

Readings were taken on a regular basis and a first reflection was observed in the stiffer cable B101B in July 1998 at the interface between the landfill material and the thin silt and sand layer, as shown in Figure 3-5. In August 1999, a much larger reflection was observed in the shear zone predicted by the Slope Inclinometers. The grown reflection at the bottom of cable LTV 3C in Figure 3-6 is thought to result from water infiltration between the inner and outer conductor.

Conclusion

The solid aluminum cable B101B responded well to the observed shearing. The reflection was caused by a total displacement measured by Slope Inclinometer LTV4 of 21.0 mm (0.83 in) or by an incremental displacement of 1.5 mm (0.07 in) between August 98 and August 99. Further analysis can be found in Cole, 1999.

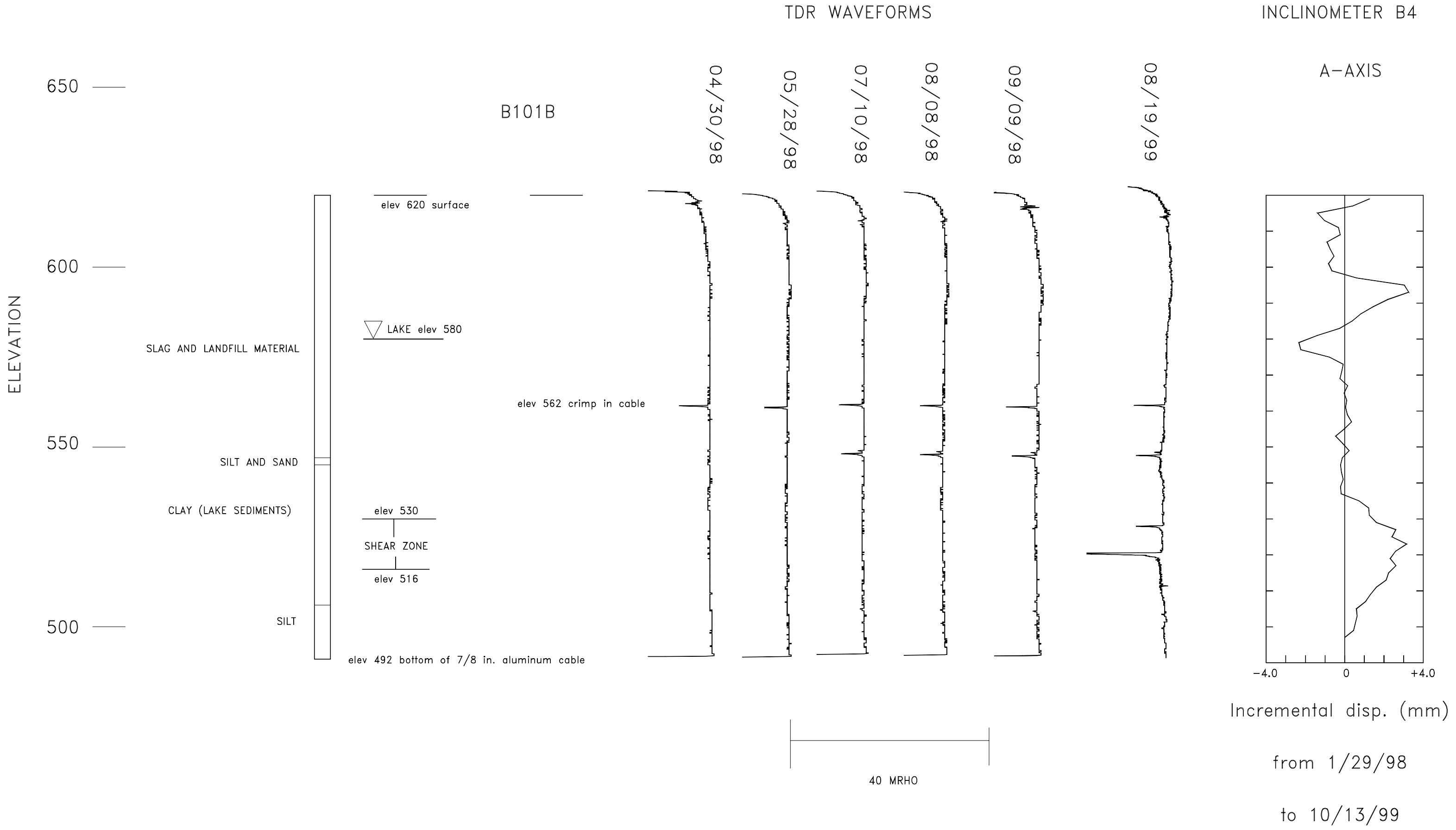


Figure 3-5: B101B TDR waveform compared to Slope Inclinometer 4 incremental reading, Clark Landfill, IN.

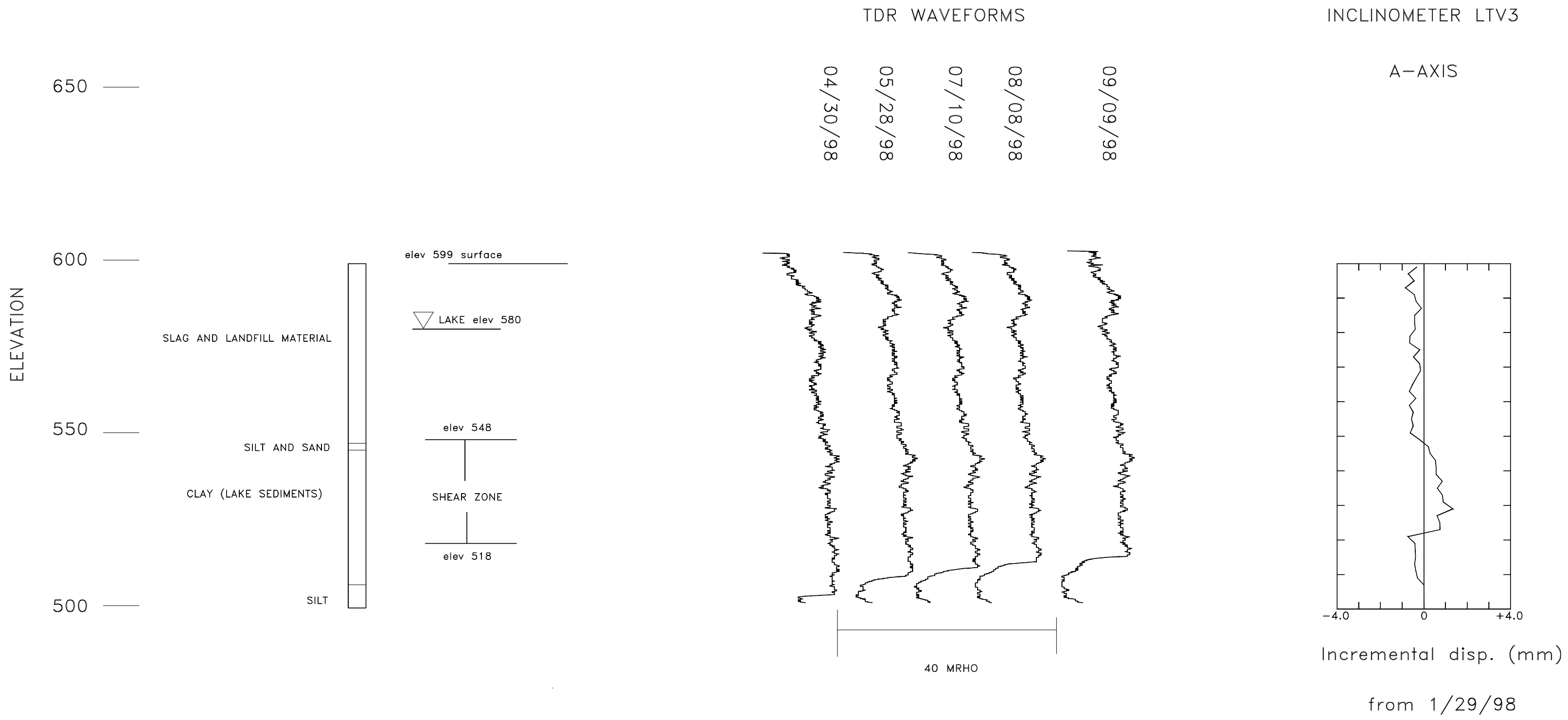


Figure 3-6: LTV3C TDR waveform compared to Slope Inclinometer 3 incremental reading, Clark Landfill, IN.

3.2.I-64, Indiana-Bridge embankment stability

Project presentation

Introduction

The two bridges on I-64 over the Little Blue river, Crawford County, Indiana, are continuous steel girder structures supported by bents and piers. As shown in Figure 3-7 and Figure 3-8, the westbound and eastbound bridges are supported by Bents No 1 and 4. on the west and east abutments and Piers No2. and 3. adjacent to the river. Approaches of the bridge were constructed by building embankments over the existing soil and bedrock. The three bridge spans are 39.5 m (129.5 ft), 49 m (161 ft) and 39.5 m (129.5 ft) respectively.

Figure 3-7: Bridges on I-64 over the Little Blue river, Crawford County, Indiana.

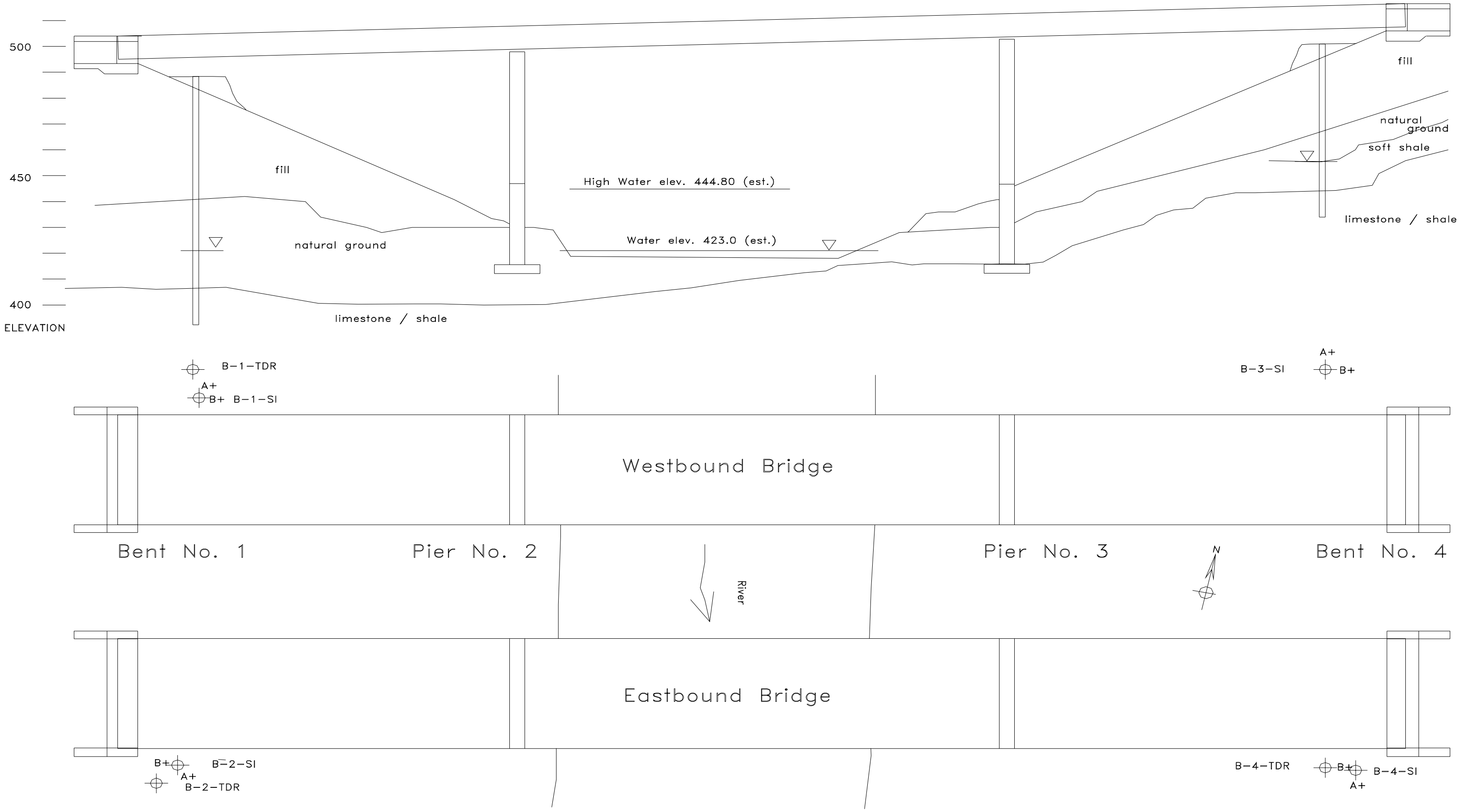


Figure 3-8: Plan view and elevation of the bridges on I-64 over the Little Blue river, Crawford County, Indiana.

In 1997, the bridge inspector noted displacement of the abutments to significantly rotate the rocker bearings as shown by Figure 3-9 and Figure 3-10. Measurements of the rocker rotations were made at that time and new measurements in 1999 indicated little change. On both ends of the bridges, the top of the rocker has rotated towards the embankment.

The bridges are allowed to move at each end but no movement is tolerated at the connection between the piers and the deck and several scenarios have been developed to explain the movement. First, the bridges are fixed and there has been movement of slopes of both abutments towards the river. Cracks in the mud wall of all abutments support this theory. Second scenario, only one abutment slope is moving towards the river and this is causing displacement of the bridge deck and bending of the piers. Spalling of the concrete at the base of the piers may substantiate this scenario.

Figure 3-9: Rotated rockers bearings of the bridges on I-64 over the Little Blue river, Crawford County, Indiana.

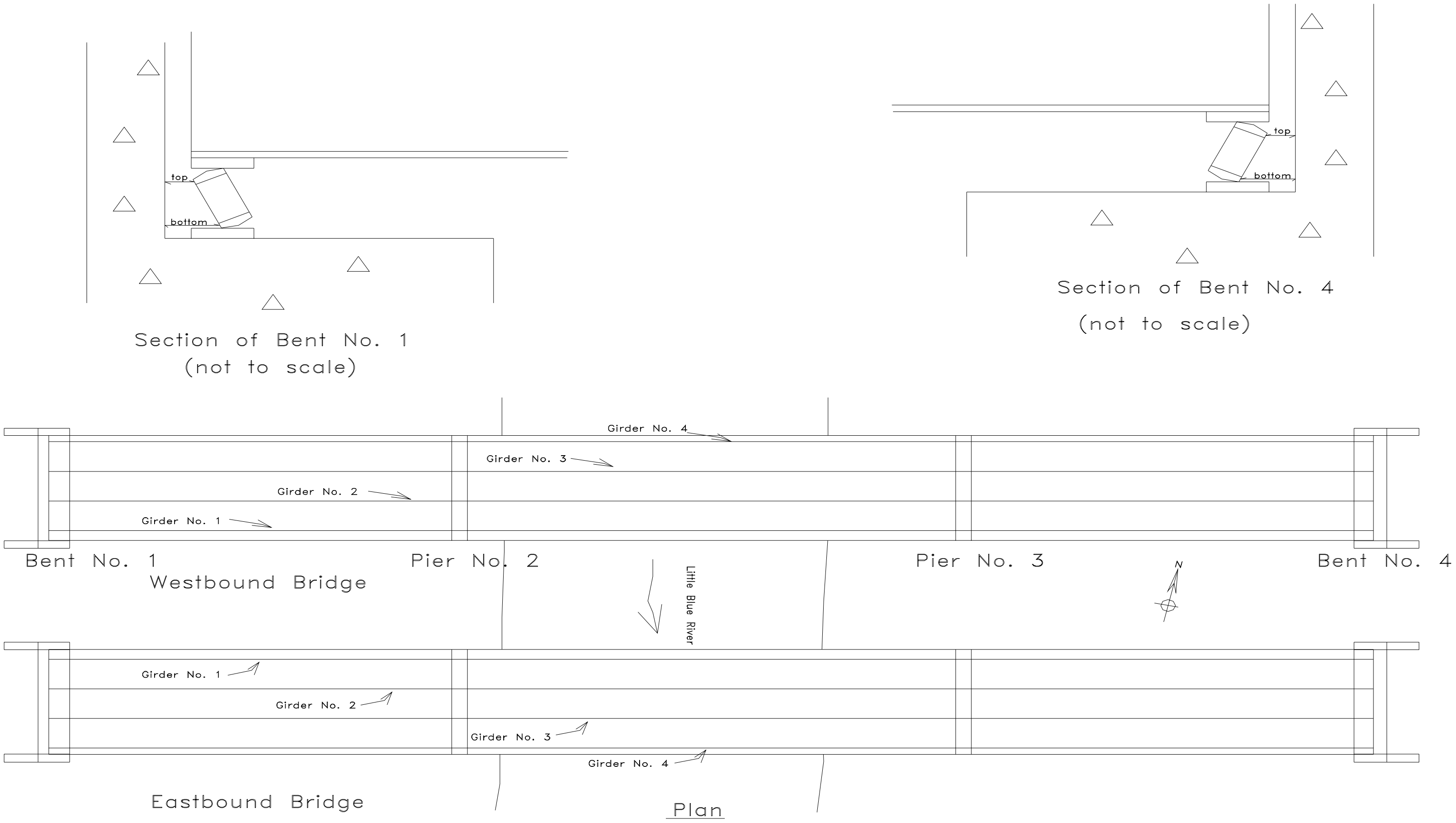


Figure 3-10: Plan view and elevation of the rockers of the bridges on I-64 over the Little Blue river, Crawford County, Indiana.

Site conditions

As shown by Figure 3-8, the embankment fill consists of stiff silty clay and rock fragment overlying existing soft clay and loose sand. The underlying bedrock is Upper Mississippian shale and limestone. The shale is soft and erodible and the limestone is conspicuous as ledges in exposures along I-64. One hazard in this region is also sinkhole development since this is a well known kharst area. The potential of slope erosion and movement are evident by the soft soils and shales which are commonly associated with landslides in this area.

The embankments were constructed with slopes of 2H:1V and previous problems with slope instability required that they be rehabilitated in 1986. As shown in Figure 3-7, erosion is more apparent on the east abutment and in an attempt to control it, rip rap was placed on the slope in 1986.

Issues of monitoring

The causes of movement are still unknown. In order to monitor movement and investigate the usefulness of TDR cables, the Indiana Department of Transportation decided to install 4 Slope Inclinometers, 2 in each embankment as shown by Figure 3-8. In addition to the Slope Inclinometers (SI), three experimental TDR coaxial cables were installed.

Site installation

Installation of grouted cables for monitoring deformation using TDR

The major design consideration is the stiffness and shear strength of the grouted cable. Experience from the Clark Landfill monitoring guided this project and two CommScope solid aluminum coaxial cables (P3-75-875-CA) were chosen for hole B-1 TDR and B-2 TDR in order that their properties match as well as possible the soil properties displayed in Table 3-8. A more compliant cable built by Northwestern University was installed in hole B-4-TDR. The more compliant cable is built from a solid aluminum cable, which outer conductor was removed and replaced by silver paint and later wrapped with vinyl electrical tape.

Material	**Description**	**Strength (Mpa)**	**Stiffness (Mpa)**
Grouted cable	solid aluminum outer conductor	1.6	88.0
Grouted cable	Compliant cable	0.4	8.0
Hole B-1-TDR and B-2-TDR	sand and clay below water table	0.1	0.1
Hole B-4-TDR	soft shale below water table	2.0	2.0

Table 3-8: summary of TDR cable and soil properties for the bridges on I-64 over the Little Blue river, Crawford County, Indiana.

As shown by Figure 3-11, grading was necessary for the accessibility of the drilling equipment. The holes were drilled through the embankment and a pad for the drilling rig was built with a bulldozer by simply pushing the soil out over the rip rap that had been placed in 1986. The same drilling technique was used for the three TDR holes: first the holes were open in the soft soil with a hollow stem auger, then rotary drilling was used in rock. Advancing the augers through the boulders located in the soil was a major obstacle.

Figure 3-11: View of the pad built for the drilling rig on the west bank of the Little Blue River, Indiana and the drilling of hole B-1-TDR with a hollow stem auger.

Hole B-1-TDR

The hole B-1-TDR is located near hole B-1-SI as shown by Figure 3-8, Figure 3-10 and Figure 3-11 and the objective here was to install a solid aluminum cable. Hole B-1-TDR was drilled with a 11.4 cm (4-1/2 in.) ID hollow stem auger down to rock at a depth of 25.9 ft and then rotary drilled in rock to a depth of 28.9 m (95 ft). The boulders encountered at depths varying from 2.4 to 5.5 m (8 to 18 feet) caused deviation as the auger was advanced.

Prior to installation, the bare aluminum 2.2 cm (7/8 in) CommScope coaxial cable was crimped at a spacing of 6 m (20 feet) in order to produce the reference TDR reflections shown in Figure 3.13. It was then spray painted with metal primer to minimize any reaction with the hydrating cement grout. On April 22, 1999, the cable was lowered down through the hollow stem auger as shown by Figure 3-12 and worked down through sand in the bottom of the rotary hole to a depth of 28.9 m (95 feet). Then a 2.5 cm (1in) flush-coupled PVC pipe was lowered into the hole for tremie placement of grout.

Figure 3-12: Lowering of the solid aluminum cable in open hole B-1-TDR through the hollow stem auger, bridges on I-64 over the Little Blue river, Crawford County, Indiana.

The cement-bentonite grout mix was made in a 11.7 L (31 gallon) tub and pumped to the bottom of the hole through the PVC pipe. The initial grout mix was intended to produce a less stiff grout based on experience from the Clark Landfill, IN project. After pumping 441.7 L (15.6 ft^3) of this mix into the hole (batches 1-4 in Table 3-11), sounding measurements indicated that it was flowing out through either fractures in the rock or through the sand and boulder layer immediately overlying it. To overcome this problem, the grout mix was switched to the stiff mix used for installation of the Slope Inclinometer (batch 5-6, in Table 3-11). The hollow stem auger was pulled in stages always keeping the top of the grout above the bottom of the auger. After pumping 453 L (16 ft^3), of the new grout mix, sounding measurements indicated that the hole was filling successfully. For batches 7, 8 and 9, the mix was then changed back to a less stiff mix. Finally, the stiffer mix was used again for batches 10 and 11 near the top of the hole because of the risks of losses between the shallow boulders. No grout return at the surface was observed and the grout was sounded at a depth of 6.1 m (20 ft) after all the augers were pulled. Table 3-12, displays the grout losses in the different layers. The next day, the top of the grout was sounded at 8.2 m (27 feet) of the surface, the annular area was filled with sand and a protective PVC cover was set over the top of the hole.

Cable		**Elevation**
top of cable		elev 149 m
ground surface		elev 148.7 m
top of grout		elev 140.5 m
reference crimp		elev 147.2 m
reference crimp		elev 141 m
reference crimp		elev 135 m
reference crimp		elev 128.9 m
reference crimp		elev 122.8 m
bottom of cable		elev 119.8 m

Table 3-9: As built conditions for hole B-1-TDR, bridges on I-64 over the Little Blue river, Crawford County, Indiana.

Hole B-4-TDR

In order to have a TDR cable in place on the east abutment, one was installed in a hole adjacent to Slope Inclinometer B-4-SI as shown by Figure 3-8 and Figure 3-10.The hole was drilled as indicated above with hard boulders encountered at 12.5 m (41 ft) and soft shale encountered below the water table from 14.3 to 17.3 m (47 to 57 ft). The deformability of the embankment silty clay is evident by the tension cracks that developed in the drill pad.

The solid aluminum outer conductor cable was crimped on April 21, 1999 at 10 feet from the bottom and at a spacing of 20 feet as shown by Table 3.10 and then spray painted. The installation was completed using the same procedure as for hole B-1-TDR. The stiffer grout mix displayed in Table 3.11 was used in order to minimize any problems with grout placement. Grout returned at the top of cable as shown by Table 3.13. A protective PVC casing was set over the top of the hole.

Cable		**Elevation**
top of cable		elev 152.7 m
ground surface		elev 152.7 m
top of grout		elev 152.5 m
reference crimp		elev 147.0 m
reference crimp		elev 140.9 m
reference crimp		elev 134.8 m
bottom of cable		elev 131.8 m

Table 3-10: As built conditions for hole B-4-TDR, bridges on I-64 over the Little Blue river, Crawford County, Indiana.

Hole B-2-TDR

The objective at location B-2-TDR shown in Figure 3-8 and Figure 3-10, was to install a compliant grouted cable for comparison with the cable and grout installed at B-1-TDR and B-4-TDR. The hole was drilled as indicated above with hard boulders encountered at 1.2-6.1 m (4-20 feet), 10-11.6m (33-38 feet), 14.9-16.8m (49-55 feet) and 17.1-21.0 m (56-69 feet). Soft shale boulders were encountered at 5.5-7.3 m (18-24 feet). The silty clay was also very moist.

The cable used for this hole was designed and prepared by Northwestern University by only stripping the bottom 10.6 m (35 feet) of outer solid aluminum conductor from a CommScope 2.2 cm (7/8 in) coaxial cable. The exposed polyethylene foam dielectric was coated with silver paint then wrapped with vinyl electrical tape. The top 18.6 m (61 feet) section of the solid a aluminum cable was crimped at two locations and spray painted with primer to minimize reaction with grout whereas the bottommost flexible section was spray painted with rubberized undercoat for waterproofing. This allowed the more flexible stripped part of the cable to be installed in the soft soils overlying the rock but underlying the embankment fill.

In order to install this flexible cable, a 5.0 cm (2 in.) OD flush-coupled PVC pipe was placed inside the hollow stem auger down to the bottom of the rotary hole. The coaxial cable was lowered down through this pipe and then the tremie pipe was pulled out as the grout was tremied into place. A 2.5 cm (1 in) polyethylene gout tube was then lowered into the hole down to the top of rock.

With the cable and grout pipe in place, the stiffer grout mix was tremied into the hole. Sounding measurements indicated that grout was not being lost and the auger was removed in stages. When 4.6 m (15 ft) of auger had been pulled, the flexible cable slumped into the larger diameter hole so that the top of cable dropped 4.6 m (15 ft) below the ground surface. It was necessary to “fish” it out by placing 5.0 cm (2 in) PVC pipe over the cable. When the top of cable was again above the ground surface, the 5.0 cm (2 in) PVC pipe was placed back in the hole down to the top of rock and the top of cable was attached to the top of pipe. The pipe was later removed.

The installation was completed by pumping grout and pulling augers in stages. Grout returned to the surface while pumping batch 3, indication that grout was not being lost. As the augers were pulled, the grout would settle as it filled the larger diameter annulus. When all augers had been removed, grout was pumped until it was within 1.0 m (3 feet) of the ground surface. The hole volume and grout take are summarized in Table 3-12.

Cable		**Elevation**
top of cable		elev 148.9 m
ground surface		elev 148.7 m
top of grout		elev 147.8 m
crimp in solid aluminum		elev 146.1 m
crimp in solid aluminum		elev 140.0 m
interface silver paint/solid aluminum		elev 130.3 m
bottom of cable		elev 119.6 m

Table 3-11: As built conditions for hole B-2-TDR, bridges on I-64 over the Little Blue river, Crawford County, Indiana.

	Grout Mix					
Hole	Batch	Water (lbs)	Bentonite (lbs)	Cement (lbs)	Additives (lbs)	Water:cement ratio
B-1-TDR (solid alu.)	2, 3, 4	240	15	141	2.5	**1.70**
	5,6	240	15	329	0	**0.73**
	7, 8, 9	240	15	141	2.5	**1.70**
	10, 11	240	15	235	0	**1.02**
B-2-TDR (compliant)	1 to 11	168	15	329	0	**0.51**
B-3-TDR (solid alu.)	1 to 8	168	15	329	0	**0.51**

Table 3-12: Summary of grout mix composition for TDR holes, I-64 over the Little Blue river, Crawford County, Indiana.

	B-1-TDR		**B-2-TDR**		**B-4-TDR**	
		Volume		Volume		Volume
Rotary hole in rock	3-7/8 in. dia., 10 ft	0.82 ft^3	3-7/8 in. dia., 10 ft	0.82 ft^3	3-7/8 in. dia., 10 ft	0.82 ft^3
Hollow stem auger hole in soils	6 in. dia., 85 ft*	16.69 ft^3	6 in. dia., 83 ft*	16.30 ft^3	6 in. dia., 58 ft	11.39 ft^3
Hypothetical hole volume		17.51 ft^3		17.12 ft^3		12.21 ft^3
Grouted Volume pumped	batches 1-4	15.6 ft^3*				
	batches 5-11	26.4 ft^3	batches 1-11	26.4 ft^3	batches 1-8	19.2 ft^3
Volume of open annulus	6 in. dia., 27 ft**	5.30 ft3	6 in. dia., 3 ft**	0.59 ft3	6 in. dia., 0 ft**	0 ft3
Grout Loss		**-0.84 m^3** **(- 29.79 ft^3)***		**-0.27 m^3** **(-9.57 ft^3)***		**-0.19 m^3** **(- 6.99 ft^3)***

Notes: **: hole volume is greater and loss overestimated. *: all batches were lost

Table 3-13: Hole volume and grout loss for TDR cable holes, I-64 over the Little Blue river, Crawford County, Indiana.

Other instruments

As shown by Figure 3-8, Indiana DOT decided to install four Slope Inclinometers; one in each embankment for the bridges. The readings given by the Slope Inclinometers were later compared with the TDR data. The comparison provided information concerning the magnitude of movement needed to deform the different type of cables. A list of hardware, tools and manufacturers is presented in Appendix 1.

Readings and conclusions

Readings

The cables were periodically interrogated by Indiana DOT personnel. A Textronix 1502 Cable tester connected to a laptop computer equipped with SP232 was used to interrogate the cables. The baseline waveforms shown in Figure 3-13, Figure 3-14 and Figure 3-15 were obtained in April 1999. No automated data acquisition system was installed on this project.

Readings taken periodically showed many reflections in the cables. As shown by Figure 3-13 , a first reflection was observed in Cable B-1-TDR, in October 1999 due to a local shearing at the interface between the silty clay with rock fragments and the soft silty clay layer. Another reflection appeared at the level of the interface between the limestone and the deep sand layer. These reflections increased in width and amplitude till August 2001and are possibly due to local deformation in the layers located below the water table.

As shown by Figure 3-14, TDR reflection appeared also in cable B-4-TDR in October 1999. The first reflections were located in the medium to stiff clay layer, at the interface between this layer and the overlying silty clay layer and at the interface between the limestone and the soft shale. The spikes increased in both amplitude and width as time progressed until the cable was severed. As for B-1-TDR, most of the reflections are due to movement in regions below the water table but the upper most spikes are possibly due to local shearing of the cable by rock fragments.

The signal shown by B-2-TDR cable is divided into two distinctive portions as shown in Figure 3-14. The first 18 m (60 ft) correspond to the solid aluminum outer conductor cable while the last 9.1 m (30 ft) correspond to the silver painted cable. The signal is heavily distorted in this silver painted portion due to the high level of signal attenuation, noise and line resistance.

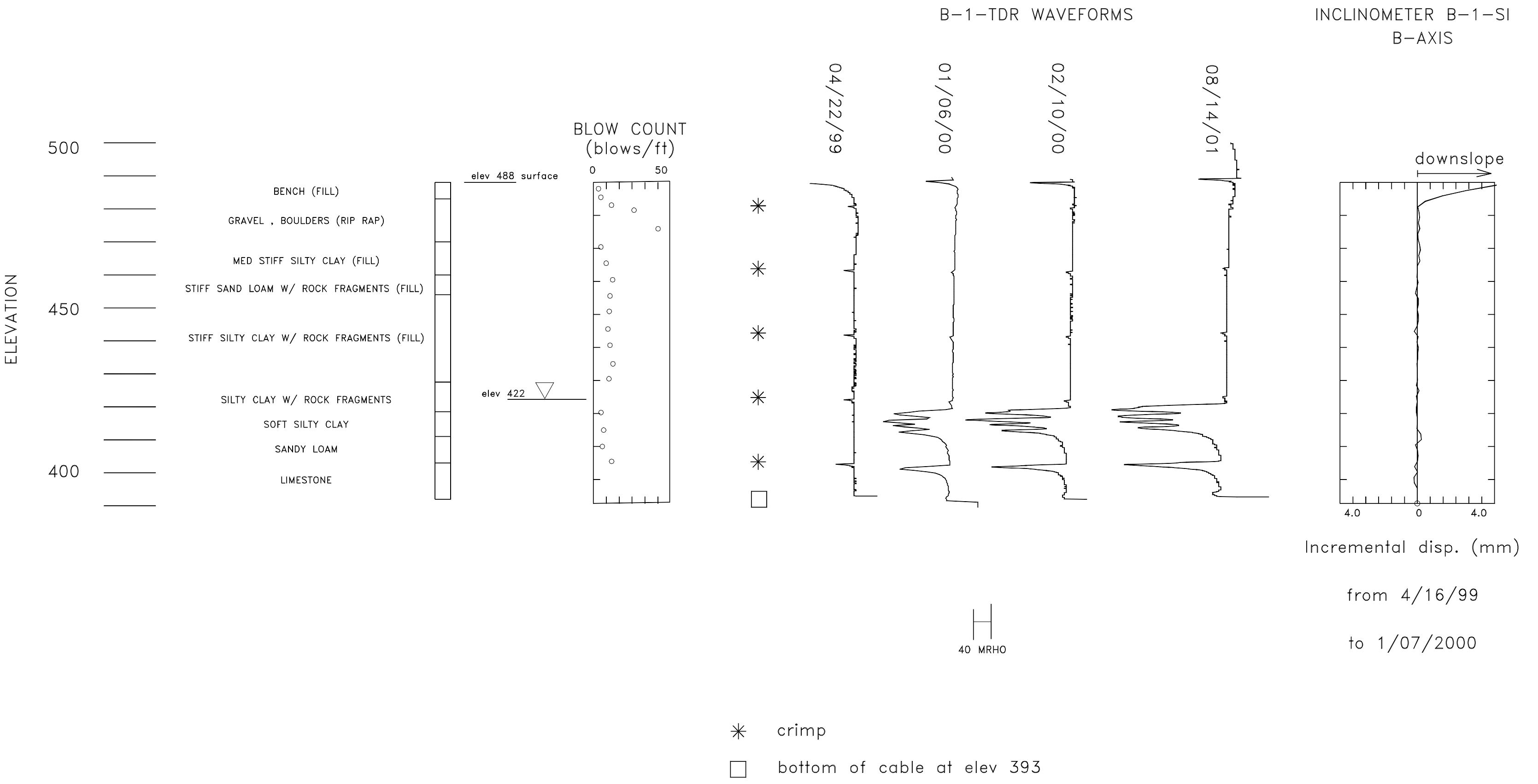


Figure 3-13: B-1-TDR (Solid aluminum) waveforms compared to Slope Inclinometer data for bridges over I-64 on Little Blue River, Indiana

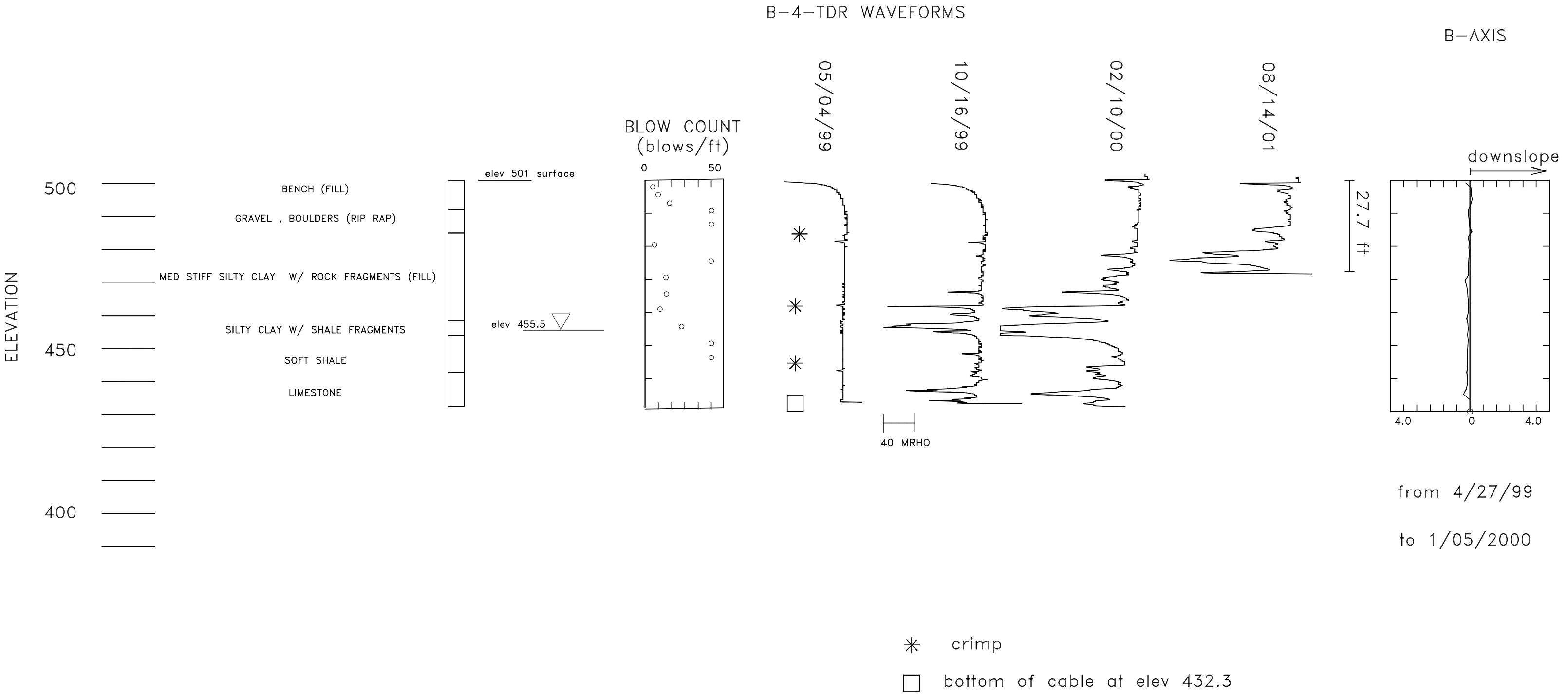


Figure 3-14: B-4-TDR (Solid aluminum) waveforms compared to Slope Inclinometer data for bridges over I-64 on Little Blue River, Indiana

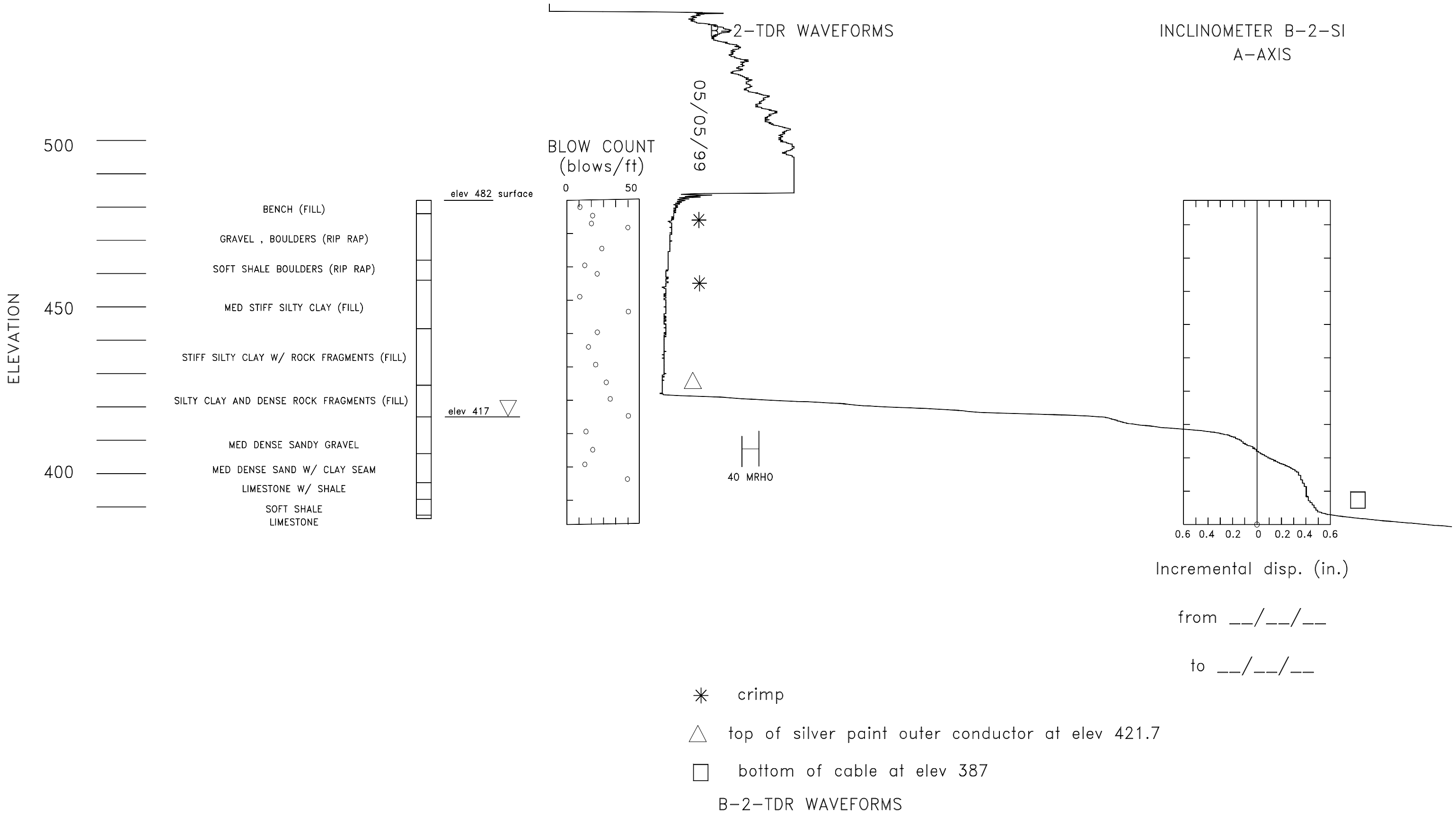


Figure 3-15: B-2-TDR (Silver painted) waveforms compared to Slope Inclinometer data for bridges over I-64 on Little Blue River, Indiana

Chapter conclusion

In conclusion, it appears that TDR technology is suitable for landslide monitoring in soft soils because it allows early detection of localized shearing within a shear band. In addition, it confirms failure surfaces determinated from Slope Inclinometer readings. The painted TDR cable does not perform well and was replaced in further projects with a braided cable.

In addition, it appears that hole drilling represents a major effort and expense that overshadows cable installation. Installation is made more difficult by subsurface conditions, especially in miscellaneous fill. Of course, the drilling conditions are the same as encountered during placement ofSlope Inclinometer.

Chapter 4

Monitoring of Subsidence for Sinkholes and Mining Using TDR

This chapter describes the details of the installation of and equipment for TDR cables and tiltmeters to detect and monitor the subsidence produced by sinkholes and mining. The three cases presented below involve: 1) potential deformation of a landbridge due to an expanding sinkhole and 2) actual deformation of roadways from longwall mining. Monitoring of sinkhole expansion involves the most unique instrumentation to date. Tiltmeters detect soil and structure tilt. TDR cables were placed both vertically to detect shearing deformation and horizontally. In addition, hollow TDR cables were installed to measure changes in the water table. This approach reflects a strategy to measure the tilt of the ground and structure and correlate them to deep and surface sinkhole induced shearing. Monitoring of mining induced subsidence, focuses on detecting shearing in deep strata before deformation reaches the surface. The information contained in this Chapter come from GeoTDR Inc. installation reports (O’Connor, 2002).

4.1 State Route 66, Florida – Sinkhole induced subsidence

Project Presentation

Introduction

Sinkhole activity occurred unexpectedly in April 2001 along State Route 66 in Highlands County, FL. Details of the topography at S.R. 66 are shown in Figure 4-1 . These events were unusual since this is an area of the “sand ridge” where the depth to rock is 60 m (200 feet) or more. It is more common for sinkholes to develop in areas where the depth of rock is 15 m (50 feet) or less. When a sinkhole opens, the most cost-effective approach is to let it develop until it stops. Typically, this process occurs in several days. Then the sinkhole is backfilled and repairs are made to pavement or utilities. The sinkhole at S.R. 66 was unusual because it continued to move over a period of one week. After an investigation which involved PSI, LaMoreaux and Associates and Technos Inc., no definitive conclusion about the cause of the sinkholes was reached. The road was repaired and the emergency solution proposed by the Florida Department of Transportation was to build a land bridge over the sinkhole.

Site conditions

The subsurface at S.R. 66 site generally consist of 2 m (6 feet) of poorly graded sand with silt (SP-SM), 4.5 m (14 feet) of medium dense silty sand (SM) and 5.8 m (19 feet) of stiff clayey sand (SC) all overlying very loose poorly graded sand with silt (SP-SM), which extends to depths greater than 46 m (150 feet). The significance of these strata changes for monitoring deformation with TDR is that localized shearing is anticipated at the top and bottom of the relatively stiff clay layer. It is hypothesized that the sinkhole at this site is of raveling chimney type as shown in Figure 4-2. The land bridge is built of six 28.6 m (94 feet) AASHTO Type 4 precast concrete beams, supported on spread footings at each end. A one foot thick slab is cast on top of those beams.

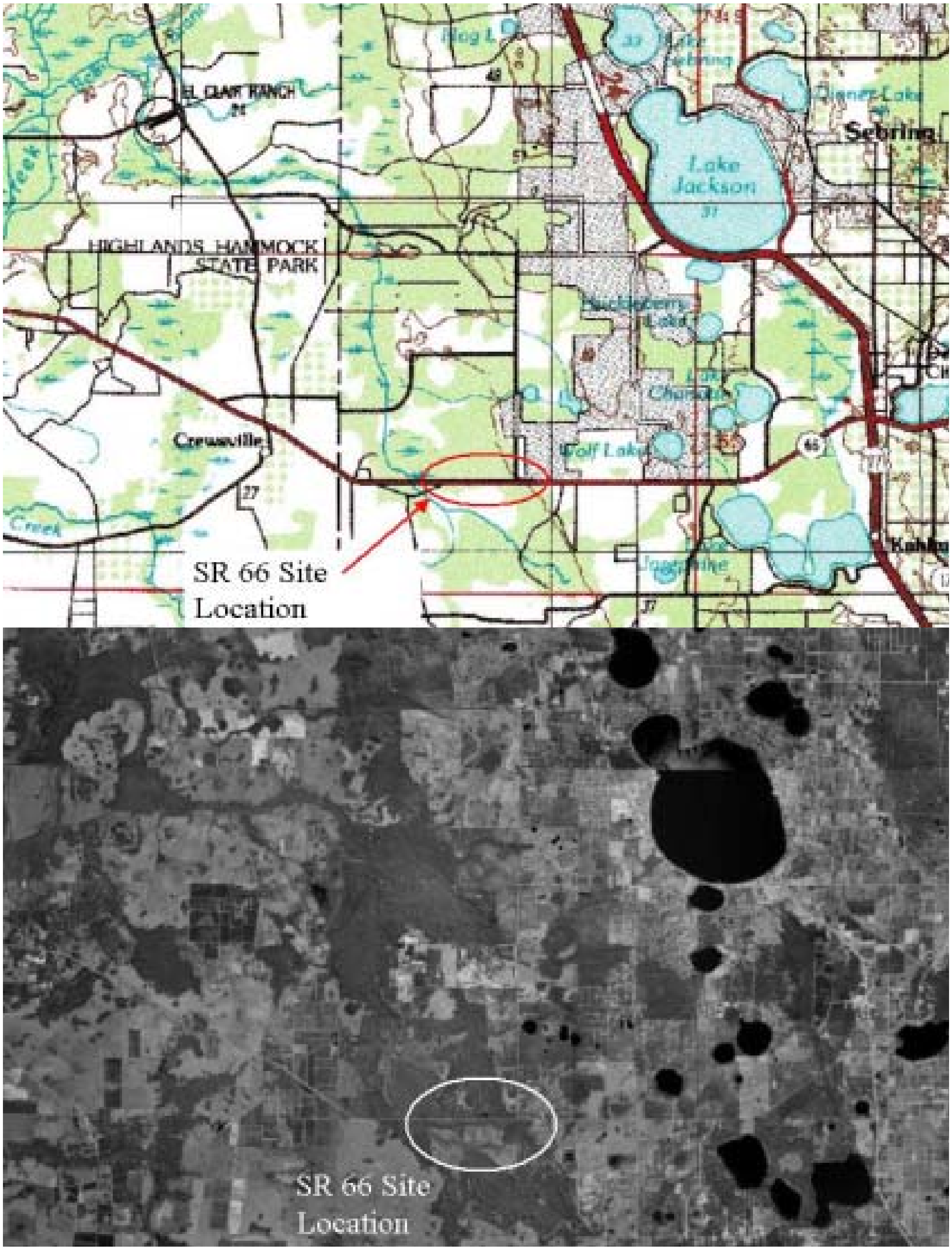


Figure 4-1: Topo map and airphoto showing the location of the S.R.66 site, Highlands county, FL.

Issues of monitoring

For sinkholes to develop, soil must ravel or “pipe” into and through a joint or cavity. Raveling is usually enhanced by water flow during precipitation events or during periods of increased groundwater withdrawal. The issues addressed by monitoring at this site are: the deformation of the bridge’s spread footings and the correlation of such between water level changes and subsurface movement. Two vertical deformation-TDR cables (TDR-1 and TDR-2) have been installed in order to detect subsurface deformation under two scenarios: the cable is located within the sinkhole as it migrates to the surface, or the cable is located besides the sinkhole as it expands laterally.

In addition, a coaxial cable (TDR-5) has been installed horizontally in a trench which extends the entire length of the bridge. Horizontal cables have an advantage over vertical cables in that they can monitor a larger surface area. Each vertical cable can only detect upwards migration or expansion at one map location. On the other hand, a single horizontal cable can detect surface deformation over a wide area. If deformation occurs, response of cable TDR-5 can be compared with that of cables TDR-1 and TDR-2. To monitor changes in ground water, monitoring wells on each side of the bridge were fitted with air dielectric cables (TDR-3 and TDR-4). Through the use of dataloggers and multiplexers, it is possible to acquire both types of data: deformation and water level with a single data acquisition system.

As shown in Figure 4-2, Tiltmeters have also been installed in the soil on each side of the bridge to detect expansion of the sinkhole. Tiltmeters have also been attached on the bridge beams near the footings to monitor the movements of the structure. They were polled by the same data logger than polls the TDR system.

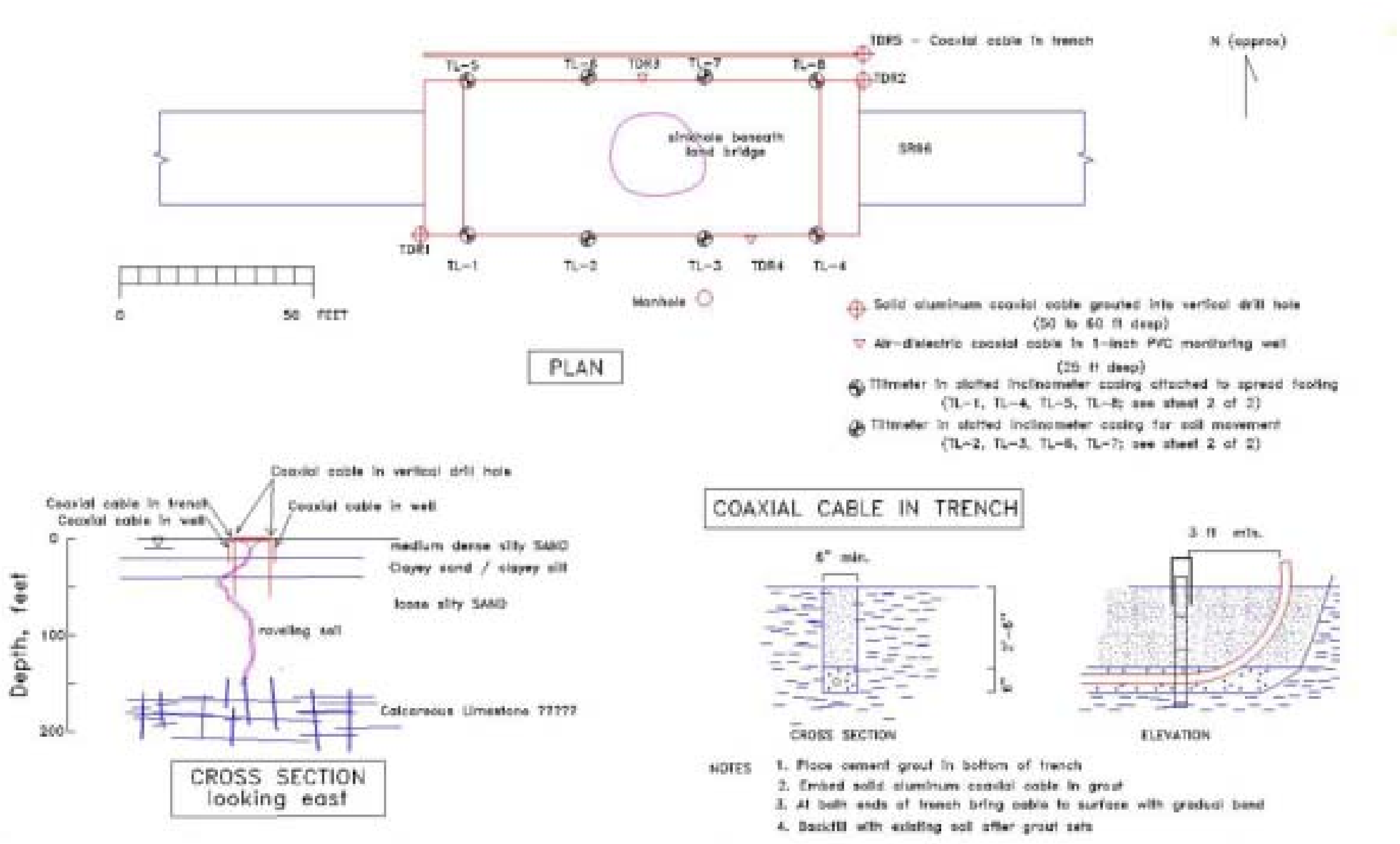


Figure 4-2: Plan view of the instrumentation and cross section of the sinkhole at S.R. 66, Highland county, Florida.

Site installation

Installation of grouted cables for monitoring deformation with TDR

As shown in Figure 4-3, classical drilling and grouting techniques were used to drill the holes for the installation of the two solid aluminum TDR cables. The deformation-TDR cables used on this site are Commscope 2.2 cm (7/8-in) P3-75-875 foam dielectric solid aluminum coaxial cables and are equipped with a Gilbert Engineering F-type connector. Holes for cables TDR 1 and TDR 2 were rotary drilled with water and cased with 10.1 cm (4-in) steel casing. The cable and the 2.5 cm (1 in) OD flush couple grout tremie pipe were installed through the casing, and grout was pumped from the bottom until return occurred at the surface. The grout mix composition and the grout losses that occurred during installation are summarized in Table 4.1 and Table 4.2. The casing was removed and sand was placed in the hole to backfill the ungrouted portion generated by the grout losses.

As shown in Figure 4.4, the horizontal cable TDR-5 was placed in the bottom of a trench covered with concrete and excavated along the bridge. The first trench encountered concrete like material and a new trench was excavated further away from the bridge. The bottom of the trench was covered with 2 to 7 cm (1 to 3 in) of concrete, then the cable was placed on the top of this layer and finally covered with 2 to 7 cm (1 to 3 in) of concrete. After the concrete had cured, the trench was backfilled with excavated material. Table 4.3 summarizes the as-built condition for TDR cables 1, 2 3, 4 and 5.

Figure 4-3: Drilling TDR 1 hole at SR.66 site, Florida.

Figure 4-4: Placement of TDR cable 5 in an horizontal trench, SR. 66, Florida.

Grout Mix						
Hole	**Water content (lbs)**	**Cement content (lbs)**	**Additives (lbs)**	**Gravel and sand (lbs)**	**Water: cement ratio**	**Estimated Unconfined compressive strength (Will, 1996)**
TDR-1	800	460	10		**1.74**	1.17 MPa
TDR-2	800	460	10		**1.74**	1.17 MPa
TDR-5	40	48		253	**0.83**	

Table 4-1: Grout Mix and grout test summary for the TDR holes, S.R. 66 Highlands county, FL.

	TDR-1		**TDR-2**	
		Volume		**Volume**
Steel casing	4-1/2 in. ID 60 ft (removed) 4 in. diameter hole	6.6 ft^3	4-1/2 in. ID 60 ft (removed) 4 in. diameter hole	6.6 ft^3
Hypothetical hole volume		5.2 ft^3		5.2 ft^3
Grouted volume pumped		8.7 ft^3		6.5 ft^3
Open hole above grout	4-in diameter 10 ft	0.9 ft^3	4-in diameter 20 ft	1.75 ft^3
	Grout loss	8.7-(6.6-0.9) ft^3		6.5-(6.6-1.75) ft^3
	Total grout loss	**0.084 m^3** **(3.0 ft^3)**	**Total grout loss**	**0.045 m^3** **(1.6 ft^3)**

Table 4-2: Calculation of the grout mix losses for the TDR holes, S.R. 66 Highlands county, FL

elevation, in meter	**TDR-1**	**TDR-2**	**TDR-3**	**TDR-4**	**TDR-5**
Ground surface	26.5	26.5	26.5	26.5	26.5
Top of cable	26.3	26.3	26.3	26.3	26.3
Top of grout	23.4	20.4			
Crimps (Elevation)	22 16	22 16	25	25	
Crimps (Distance from connector) in meter					8.2, 17.3, 26.5, 35.8
Bottom of cable	9.8	9.8	20	20.1	36 m (120 ft) long cable
Bottom of hole	9.5	9.5	20.2	20.3	
Bottom of trench	-	-	-	-	25.4
Top of well casing	-	-	26.3	26.3	-
Top of bentonite seal	-	-	26.1	26.1	-
Top of bentonite seal			86	86	
Top of sand			74	73	

Table 4-3: As built conditions for TDR 1 to 5 around the landbridge at S.R.66, Highlands county, FL

Installation of tiltmeters

Figure 4.5 shows the eight Applied Geomechanics tiltmeters installed both in the ground as well as attached to the structure. They are “Little Dippers” units, 20 cm (8 in) long and have a resolution of 0.006 arc-degrees and a range of 10 arc-degrees.

Four tiltmeters that monitor soil deformation (TL-2, 3, 6 and 7) are placed in SI casings cemented in the ground as shown in Figure 4.5. The 3 m (10 ft) long sections of SI casing were cemented into holes dug with a posthole digger to a depth of 1.5 m (5 ft). The casing grooves were aligned perpendicular and parallel to the edge of the land bridge. After the cement had cured, the casing was cut off at 15.2 cm (6 in) below the ground surface. Each tiltmeter will be set in the casing at a depth of 1.3 m (4.25 ft) so that it is at the elevation of the bottom of the bridge beam. In the case of structure-monitoring tiltmeters (TL-1, TL-4, TL-5 and TL-8), two foot long sections of SI casing were attached to the bridge beams with brackets.

Installation of water-level monitoring cables

Two air-dielectric coaxial cables (Cablewave HCC12-50) equipped with a HCC N-type connector were installed in wells to monitor changes in ground water levels. Holes TDR-3 and TDR-4 were augered to a depth of 7.6 m (25 feet), 5cm (2 in) PVC well screen was installed and sand backfill was placed. Then bentonite pellets were placed to within 1 foot of the surface. The installation was completed on April 25, 2001.

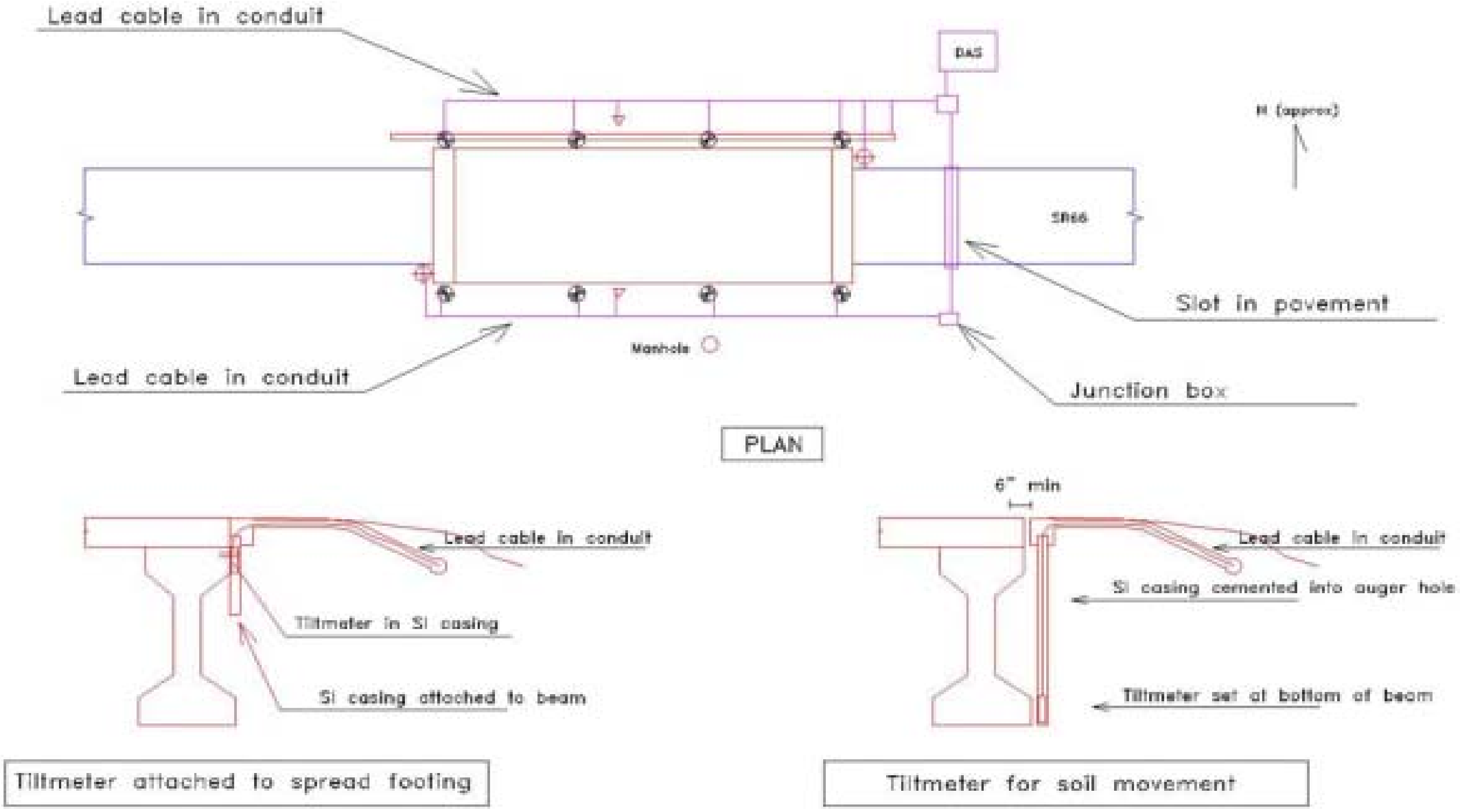


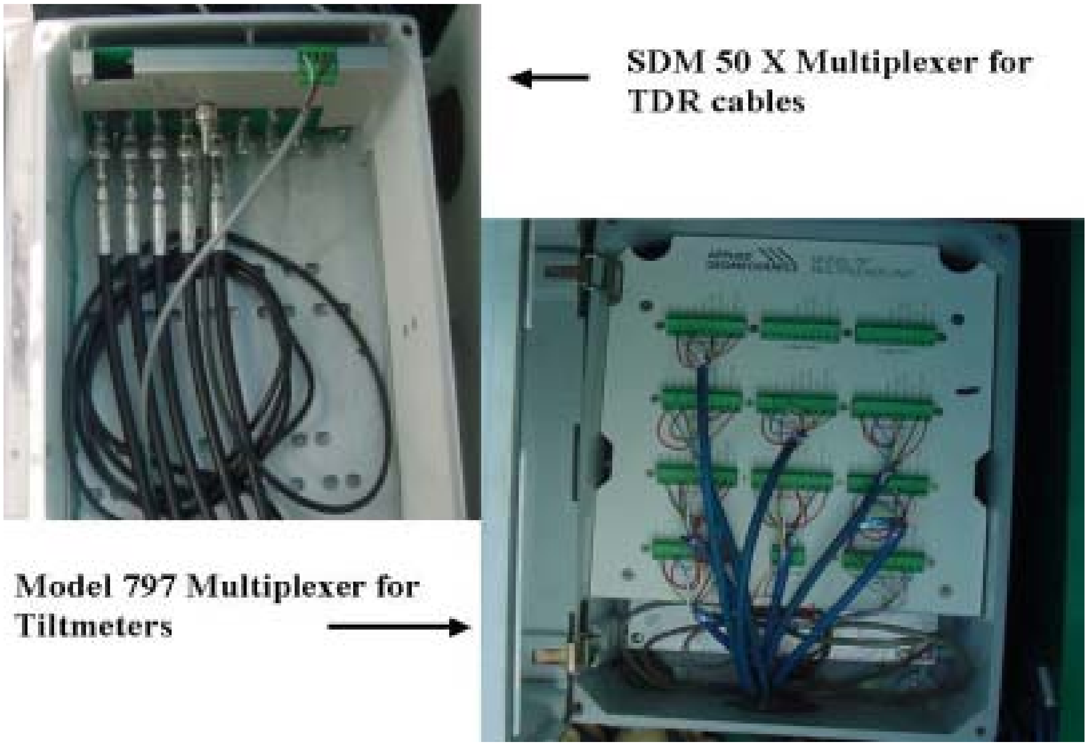
Figure 4-5: Plan view of the lead cable system and cross section of the tiltmeters at S.R. 66, Highland county, Florida.

Remote communication

Initial installation

The data acquisition system was installed, with the aim of remotely interrogating of the TDR cables and tiltmeters. As shown in Figure 4.6, all 8 tiltmeters were connected to an Applied Geomechanics Model 797 multiplexer and the 5 TDR cables to a Campbell Scientific SDMX 50. A Tektronix 1502 TDR pulser was first connected to the Campbell multiplexer. The TDR pulser and the Applied Geomechanics multiplexer connect to a Campbell scientific datalogger CR10X. The datalogger is in turn connected to a Campbell Scientific CM100 modem and cell phone. All these instruments are placed in a shock proof box and powered by a deep cycle battery recharged with solar panels. A desktop PC equipped with the PC 208 software could call the cell phone and retrieve the data stored into the datalogger.

This system was initially afonctionnal because both the cell phone and 1502 pulser require more power than could be supplied by the battery. To overcome the inefficiency, a new battery was brought on site and as shown in Figure 4.7, the old TXT 1502 TDR pulser was replaced by the low power consuming Campbell Scientific TDR 100 pulser. The datalogger was also reprogrammed to accept the new pulser. This change now allows remote, cell phone based data acquisition.



SDM 50 X Multiplexer for TDR cables

Model 797 Multiplexer for Tiltmeters

Figure 4-6: Comparison between the two multiplexers installed at SR 66, FL.

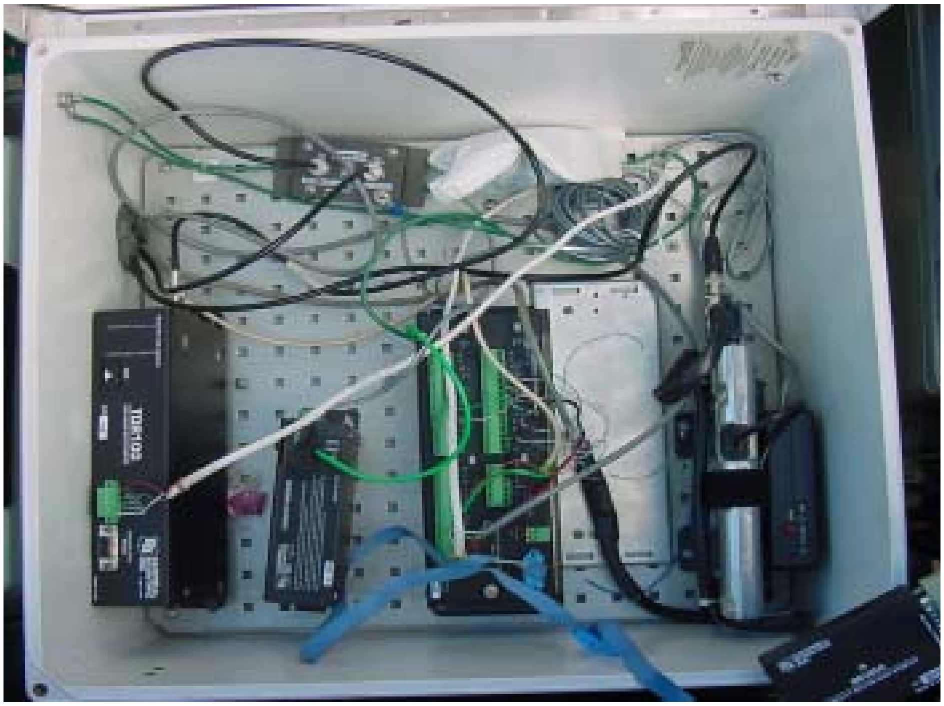


Figure 4-7: View of the remote data acquisition system installed at SR. 66, Fl. based on a TXT 1502 TDR pulser (Left) and a CSI CR10X datalogger (right).

Readings and conclusion

Readings and data display

No valid TDR data were acquired with the initial system because the TDR pulser could not communicate with the datalogger. However, the system yield valid tiltmeter data which allowed FL DOT to monitor structure and ground surface movement. The first valid TDR data were obtained in September 2002. The data were collected by FL DOT and Kevin O'Connor from GeoTDR Inc. and sent to Northwestern's ITI. As shown in Figure 4.8, raw data are now downloaded from a polling computer at ITI and displayed in realtime on ITI's website at the following address: http://www.iti.northwestern.edu/tdr/operational/florida. Even through interpretation of the measurements remains the responsibility of FLDOT, it is informative to remark that TDR-1 signal is flat. This is certainly due to a loose connector. All tiltmeter waveforms acquired since the initial reading are displayed while the TDR readings are archived and accessible so that it is possible to monitor changes in the reflection signals.

Partial conclusion

Instrumentation at this site was innovative in both the number of instruments and the installation of an horizontal cable. But the remote data acquisition system caused some problems. Reliability of the Campbell Scientific pair, CR10X Datalogger and TDR 100 pulser, is excellent. The next step in this project is to setup a fully autonomous remote data acquisition system similar to that of in Sulfur or Cambridge. To achieve this goal, the reliability of the power source and the cell phone has to be increased.

As discussed in Chapter 6, one option to improve the reliability of the communication is to replace the cell phone by a point to point communication device and a hard line.

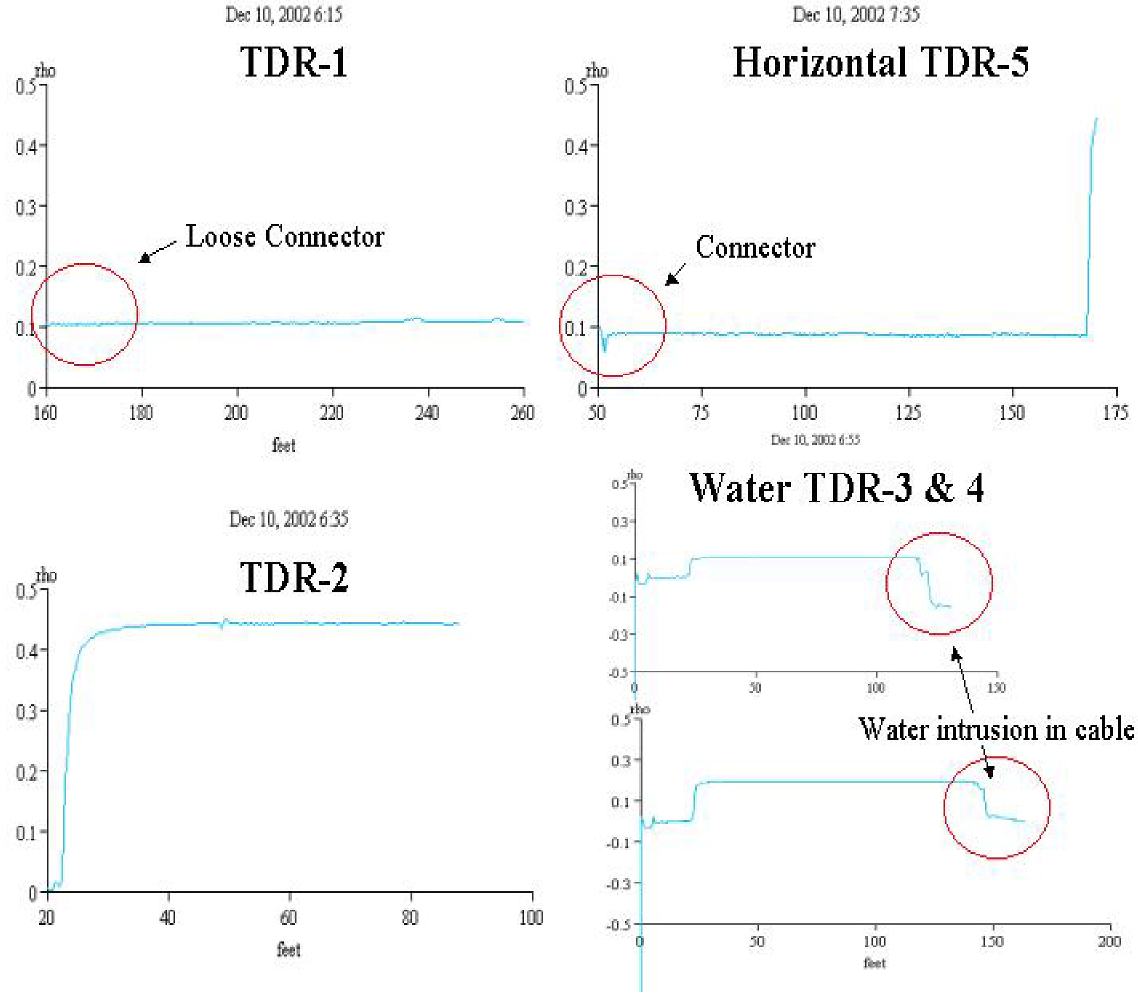


Figure 4-8: TDR waveforms for TDR 1 to 5, S.R. 66, Highlands County, Florida.

4.2 I-70 Pennsylvania – Mining induced subsidence

Project presentation

Introduction

Two longwall coalmine panels were mined using high extraction techniques at a depth of approximately 156m (510ft) beneath I-70, east of Washington, Pennsylvania. The highway, shown in Figure 4.9, crossed the width of one panel at two locations. The Pennsylvania Department of Transportation (PennDOT) assumed responsibility for real time monitoring of both ground deformation and changes in highway conditions.

The 1.8m (6ft) thick Pittsburgh coal seam was being mined by the longwall method, involving a moveable roof supporting the excavation of an entire block of coal 332m (1090 ft) wide and 2650m (8700 ft) long. A shearer moves across the full width of a panel making a cut about 1m (3 ft) deep and loads the coal onto a conveyor that transports it to another loading point. Hydraulic roof supports are advanced behind the shearer and the mine roof and overlying rock collapse into the void behind the supports. With this loss of support, subsidence of the overlying rock mass is a certainty and the ground surface deforms into a trough with a maximum subsidence of 1.0 to 1.5m (3 to 5 ft). The induced strains cause both general and occasionally abrupt deformation of pavement and structures as shown in Figure 4.9.

Figure 4-9: View of mining induced subsidence on I-70, east of Washington, Pennsylvania.

Issues of monitoring

The plan of action developed by PennDOT had a primary objective of protecting the driving public from settlement bumps such as shown in Figure 4.9. One of the component of the action plan was the installation of an alarm system and visual monitoring. The alarm system relied on an extensive array of tiltmeters along the highway connected to a central data acquisition system for automated monitoring as well as one hundred of survey points. In addition, an array of TDR monitoring cables were grouted into deep holes to sense shearing that occurs within the rock mass overlying the mine and preceding surface settlement. In addition to the alarm, the instruments provided quantitative information about ground response to supplement PennDOT experience.

Site installation

Installation of grouted cables for monitoring rock deformation using TDR

Precursor subsurface deformation was monitored by grouting solid aluminum outer conductor coaxial cables into 100 m (300 ft) deep holes. The holes were drilled from the surface to within 46 m (150ft) of the coal seam as shown in Figure 4.10. It was originally planned to install cables at seven locations where the highway intersects the edges of the mine panels, but four holes (TDR-1, TDR-3, TDR-4 and TDR-5) were moved closer to the centerlines of the panels to increase sensitivity to precursor movement ahead of the advancing mine face. TDR waveforms were acquired by hand with a laptop computer equipped with SP 232 and a Tektronix 1502 TDR pulser.

Tiltmeter installation

Thirty two biaxial tiltmeters were installed along the roadway shoulder at a spacing of 60 m (200 ft) beginning at the location where it intersects Panel 4 south. The tiltmeters are Little Dippers manufactured by Applied Geomechanics and have a resolution of 0.006 arc degree and a range of +/- 10 arc-degrees. Detachable fins allow the tiltmeters to be installed in slotted Slope Inclinometer casing that is grouted into a 150 mm diameter auger hole. The x-axis was oriented perpendicular to the longwall centerline (N30E) and the y-axis was oriented parallel to the centerline (N60W).

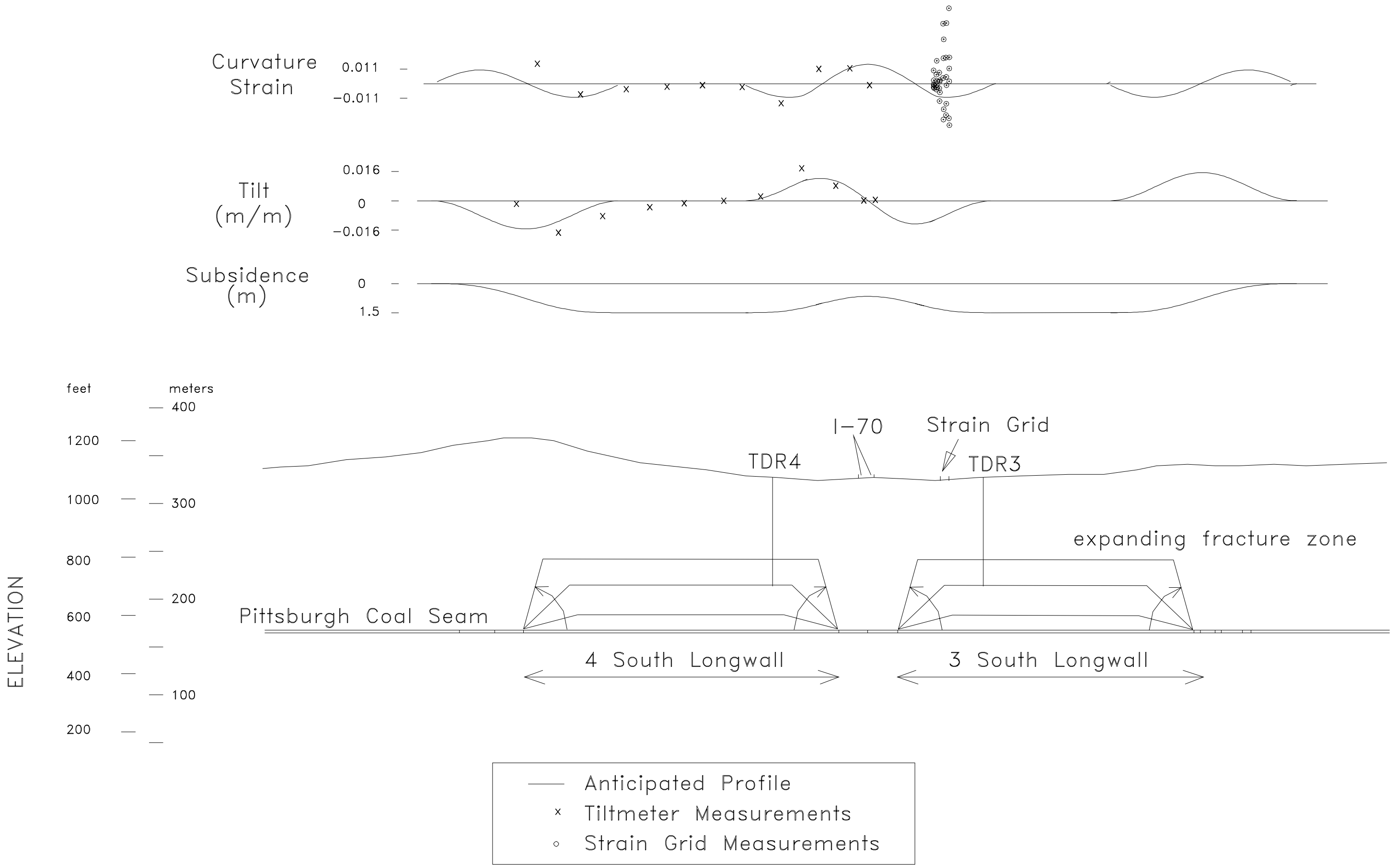


Figure 4-10: Elevation of Longwall 3 and 4 and subsidence, tilt and curvature strain profiles for I-70, Pennsylvania.

Remote communication

A critical requirement for the monitoring system was an automatic, datalogger-initiated capability to alert PennDOT personnel in the event that anticipated movement was exceeded. Automation was accomplished by connecting the tiltmeters to a central data acquisition system controlled by a Campbell Scientific CR10X datalogger. This data acquisition system could be connected to eight tiltmeters at one time then moved as mining progressed so the greatest distance from any tiltmeter to the system would be no greater than 300m (1000ft). four locations for the monitoring system were selected and utility poles were installed to have power and a phone line available at each location. All the electronics were placed in the steel enclosure shown in Figure 4.11, that could be carried by two people and loaded into a pickup truck for a better mobility.

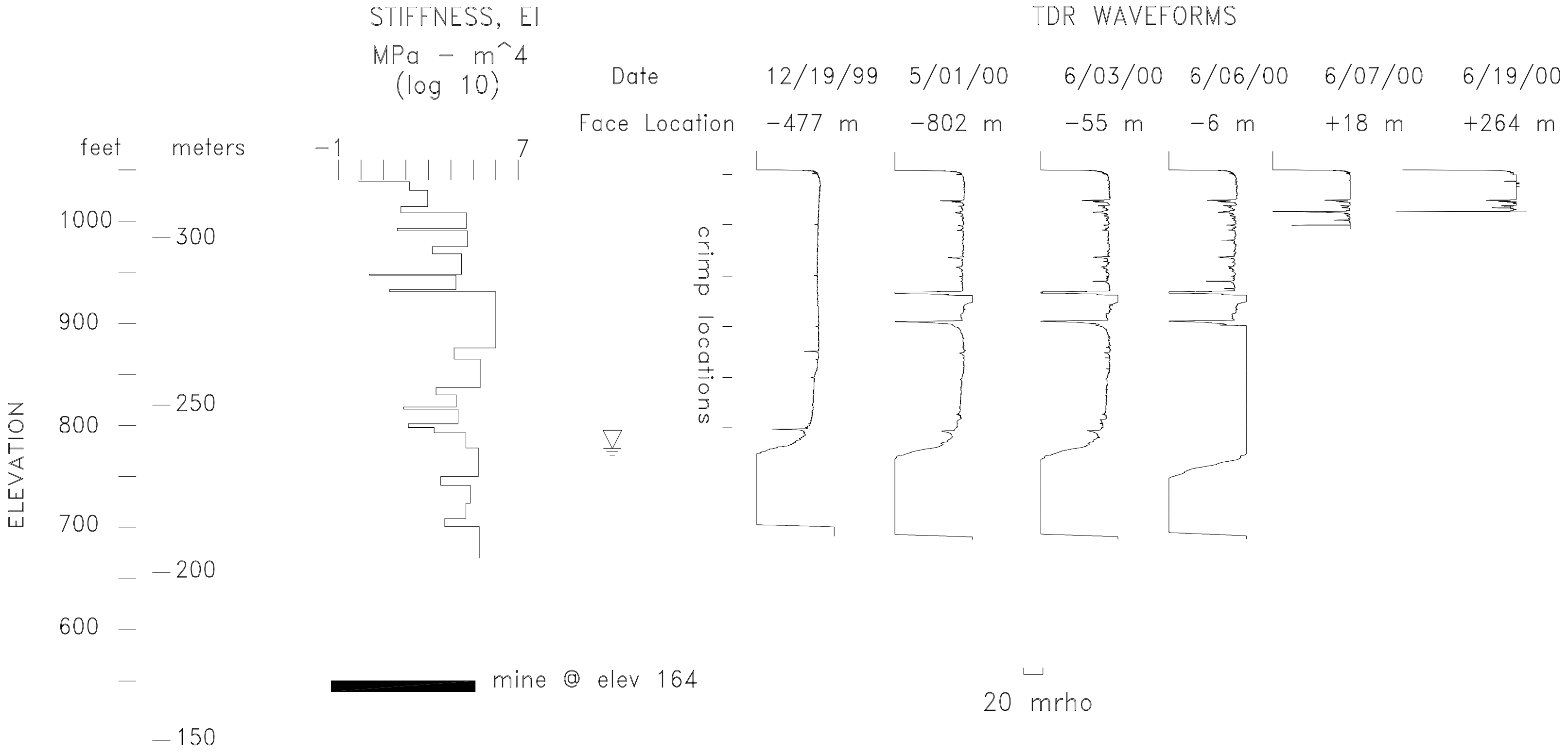
The datalogger would cycle over the eight tiltmeters being actively monitored once every fifteen minutes and store the measurements. Whenever the tilt value exceeds the maximum allowed value, the datalogger would initiate a phone call to PennDOT personnel on duty 24 hours a day.

Figure 4-11: View of the portable steel enclosure hosting the datalogger and multiplexer, I-70, Pennsylvania.

Readings and conclusions

The spikes in TDR signature shown in Figure 4.12 developed at each location where the cables were being deformed. This deformation was concentrated at depths where the largest changes in strata lateral stiffness occurred. Strata stiffness is graphed in the histogram on the left side of Figure 4.12. This behavior was evident in all the TDR cables but only the signature of TDR cable 4 was displayed as an example in Figure 4.12. Precursor movement occurred ahead of the mine face and outside the edges of the panel being mined. For example, the TDR signature for 6/3/00 in Figure 4.12 shows that precursor movement had occurred even earlier due to mining of the previous mine panel (Panel 3 South) that was over 135 m north of the cable location. Typically, cables detected precursor movement 200m from active mining but one cable detected movement as far as 365m from active mining.

In conclusion, TDR coaxial cables provided good sensitivity to precursor movement whereas tiltmeter measurements proved to be reliable and sufficiently cost effective for automated monitoring and purposes of early warning.



NOTES

1. Stratum were identified from boring for hole TDR1A
2. Modulus, E, was estimated from rock mass rating (RMR) for each stratum
3. Moment of inertia, I, was computed for each stratum assuming it to be a beam of unit width

Figure 4-12: TDR waveforms acquired at location TDR4, I-70, Pennsylvania.

4.3 I-70, Cambridge, Ohio – Mining induced subsidence

Project presentation

The sinkhole like opening which developed in I-70 at the location shown in Figure 4.13, lead to the installation of two TDR cables to monitor further deformation. the sinkhole was caused by collapse of shallow abandoned coal mine. An automated remote data acquisition system was setup at this site to allow a real-time deformation monitoring. The stratigraphy of the site consists of 2 m (6 feet) of soft shale, overlying 1.2 m (4 feet) of gray shale with hard streaks, overlying 13 m (43 feet) of brown shale with a stiffness between 3.10^5 and 6.10^4 $MPA.m^3$. The top layers of the deep coal mine can be found between 17 and 18 m (56 and 60 feet) depth.

Figure 4-13: View of the Eastbound side of I-70, at point Mile 183.11 showing the trench for installation of transmission cable, Cambridge, Ohio

Site installation

Installation of grouted cables for monitoring rock deformation using TDR

Two Commscope Inc., P3-75-875 CA solid aluminum outer conductor cables were installed at location Mile 183.26 (TDR-2) and Mile 183.11 (TDR-1), on the eastbound side of I-70. Cable TDR-1 is 45 m (150 feet) long with crimps were made at 15 m (50 ft), 30 m (100 ft) and 45.7 m (150 ft). Cable TDR-2 is 15 m (50 feet) long.

The same water-cement grout mixes were prepared for both holes. The grout mix had a water to cement ratio of 0.96 and had been prepared with 14 bags of cement, 160 gal of water and 6 bags of fluidizing agent Intrusion Aid Type R. Grout losses occurred in both cases in the mine.

Remote communication

P3-75-875 solid aluminum outer conductor coaxial cables extend from the top of the sensor TDR holes as shown in Figure 4.14 to the enclosures shown in Figure 4.15 where the data acquisition system is installed. The cable extending from TDR-1 (Mile 183.11) to the enclosure is approximately 820 feet long whereas the one between TDR-2 (Mile 183.26) is only 160 feet long. The first data acquisition system installed, was based on a Tektronix 1502 TDR pulser and a Campbell Scientific CR10X datalogger. This system was replaced by a Campbell Scientific TDR 100 unit. The new system also incorporate a callback capability with a 9600 phone modem/voice synthetiser. A list of hardware used is given in Appendix 1. The new system is similar to the one installed at SR 62, Indiana.

A fully autonomous remote monitoring system is now operational at this site. A polling computer at Northwestern ITI calls every morning the datalogger and downloads the waveforms from the previous day. The waveform is then automatically displayed on ITI website at the following address:

http://www.iti.northwestern.edu/ tdr/operational/Cambridge.

Figure 4-14: View of the horizontal lead cable, linking the TDR cable to the data acquisition system, I-70 Cambridge, Ohio.

Figure 4-15: View of the enclosures hosting the first data acquisition system based on Tektronix 1502 pulser, I-70, Cambridge, Ohio.

Readings and conclusions

Potential losses from the significant length of the connecting cables were overcome by employing the low loss P3-75-875 cable also used as TDR sensor. Note from Figure 4.16 how the longest system (TDR-1) still shows details in reflection after the connector whereas it appears that the shorter system (TDR-2) is shortening out after a certainly deficient connector. These automatic observations provide OhioDOT the necessary information to repair the system.

The monitoring of subsidence for mining at Cambridge, is the perfect example of the use of a remote monitoring system. Through the data acquisition system and the real time display of the waveforms on the internet, Ohio Dot is able to monitor this site remotely and eventually take preventive action if either maintenmance is necessary or movement occurs.

Chapter conclusion

It appears that TDR technology is perfectly suitable for monitoring mining induced subsidence. It allows an early detection of any movement below the roads and through an autonomous remote operation, it provides an early warning system. Remote sites represent a real challenge for communicating with a polling computer. One can either use a point to point communication device to connect the remote site to a hard line or use long low losses P3 coaxial cables to connect the sensor cables to a data acquisition system closer to reliable communication infrastructure. As suggested by the performance of the Florida installation, data transmission via a cellular network is unreliable and represents a major effort to improve.

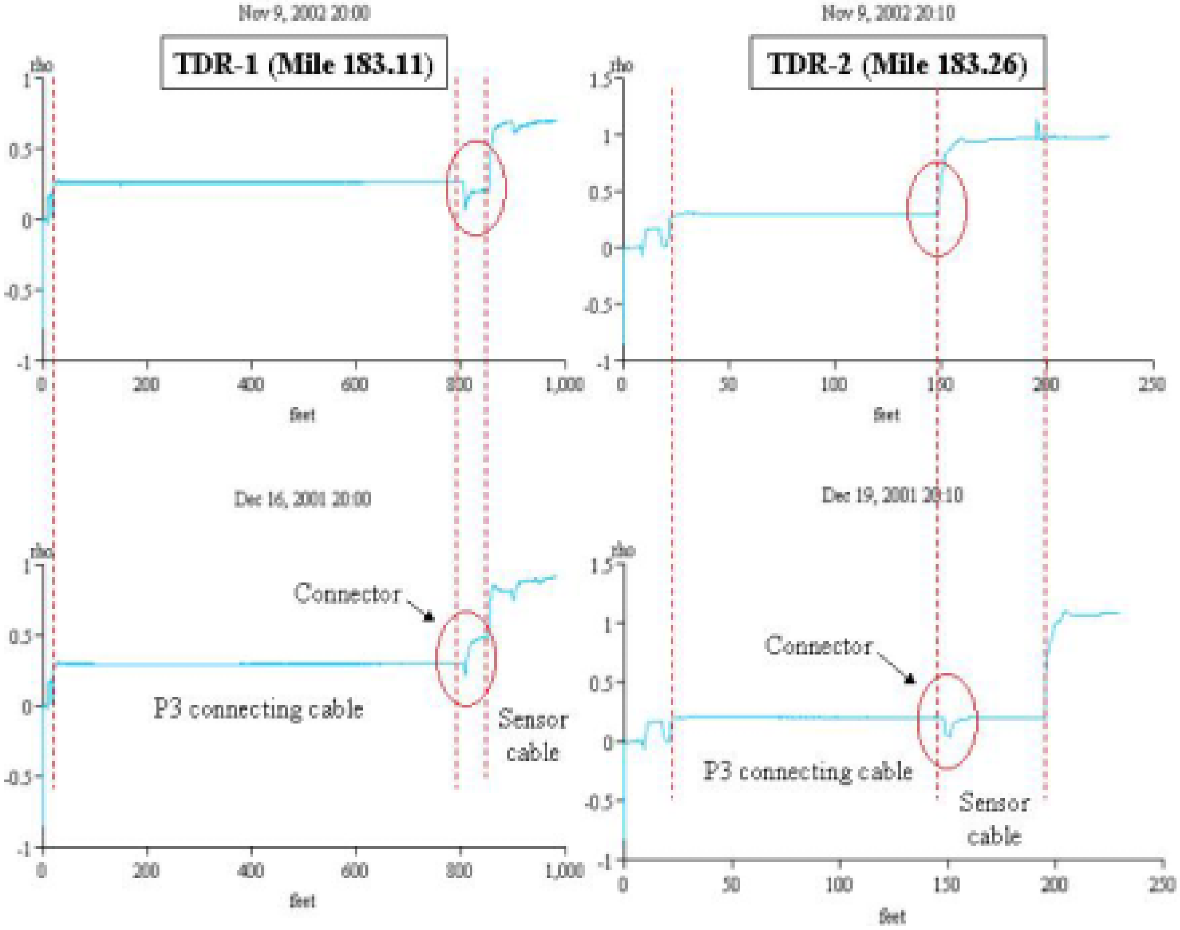


Figure 4-16: Comparison of current and reference waveforms for TDR1 and 2 for I-70, Cambridge, Ohio.

Chapter 5

Stability Monitoring for Excavation in Soft Soils Using TDR

This chapter describes the details of the installation of and equipment for TDR cables to monitor ground movement produced by deep excavation in soft soil. In these two similar cases, ground instability arises from stress relief due to a deep excavation in soft to medium strength clays. Both cases involve installation of deep vertical TDR cables in a dense urban environment, together with extensive other instrumentation.

5.1 Chicago and State subway excavation, Chicago, Illinois

Project presentation

Introduction

The subway stations along the CTA red line in Chicago, IL were lengthened to allow two more cars per train. Extension required a deep excavation at certain underground stations as shown in Figure 5.1 and Figure 5.2. The station in this case is located at Chicago and State Streets adjacent to Holy Name cathedral and the Frances Xavier Warde School. As shown in Figure 5.1 and Figure 5.3, the deep cut is supported with struts at the upper level and secant piles anchored with tiebacks for the lower levels. Performance of this support system was monitored with extensive instrumentation comprising Slope Inclinometers, piezometers and load cells (Bryson, 2002).

Site conditions

As shown in Figure 5.6 and Figure 5.7, the excavated soils are typical for the Chicago area. They consist of 4.5 m (15 feet) of fill and rubble overlying glacial till and Chicago Blue clay. As shown in Figure 5.1, the excavation is being made to a depth of 12 m (39 ft-elev. –25.0 ft) and is braced with as ecant pile wall. The secant piles are cast in-place in 1 m (3 feet) diameter auger holes spaced 70 cm (2.5 feet) on center extending to a depth of 18 m (60 feet-elev. –46.0 ft) which are filled with cement slurry. A steel H-pile is placed in alternate holes. In addition, to pipe struts installed at a depth of 1 m (3 feet-elev. +11.0) for lateral support, tiebacks anchors were installed by drilling through the unreinforced secant piles. As shown in Figure 5.2, the tiebacks were installed at a depth of 5 and 9 m (17 feet and 29 feet, elev. –3.0 and elev. –15.0) at an angle of 45 degrees. The upper tiebacks were 18 m (60 feet) long and the lower tiebacks were 13.5 m (44 feet) long. The grouted anchors length was 5.5 m (18 feet) in both levels.

Issues of monitoring

Two main issues governed the installation of TDR cables near the Chicago and State excavation. First, this excavation provided an opportunity to test the sensitivity of TDR coaxial cables to localized shearing in soft Chicago clays if it occured. It also provided an opportunity to compare the response of two types of flexible cable manufactured at Northwestern University (by stripping the outer conductor), with a commercially available solid aluminum outer conductor cable.

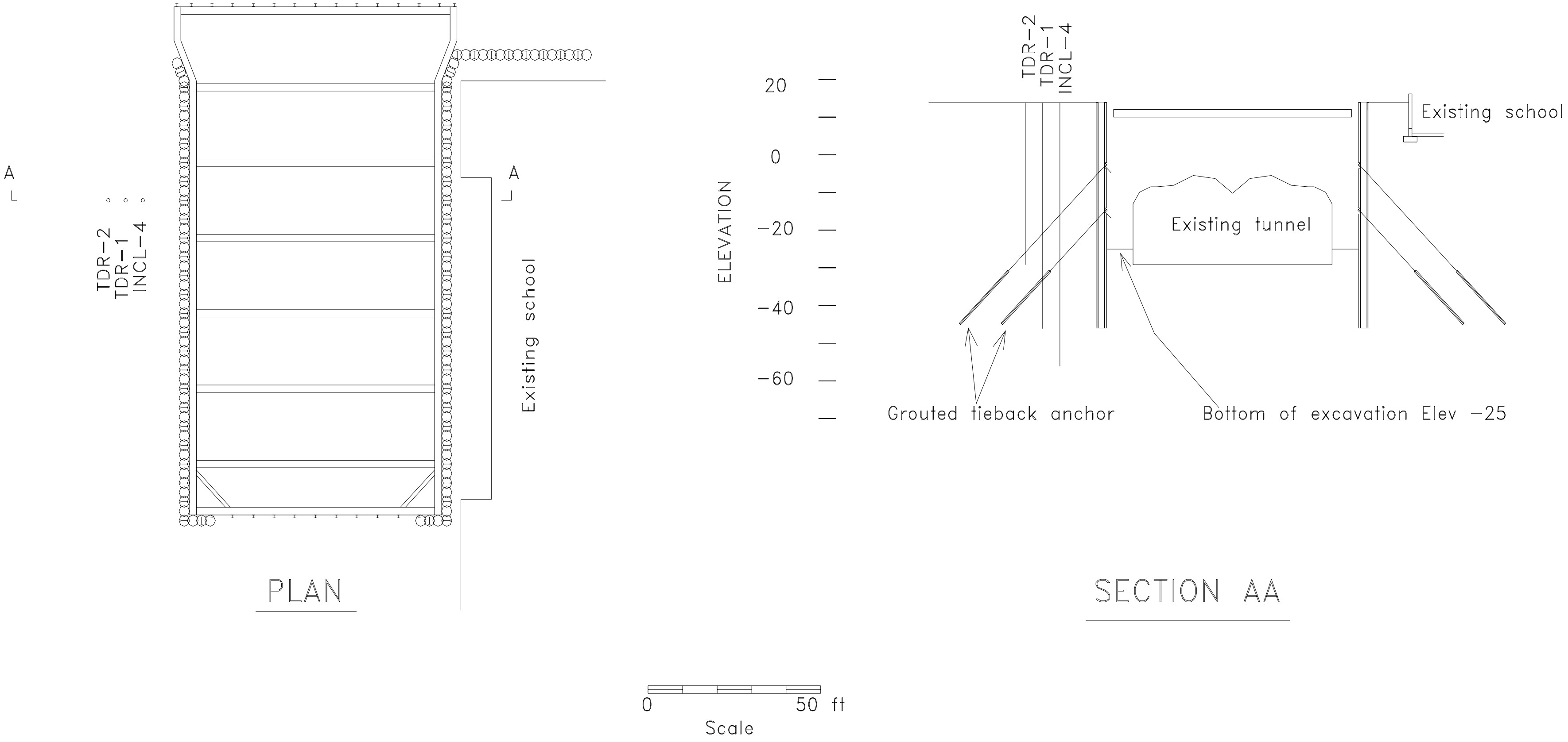


Figure 5-1: Plan view and cross section of the Chicago and State subway excavation, Chicago, Illinois.

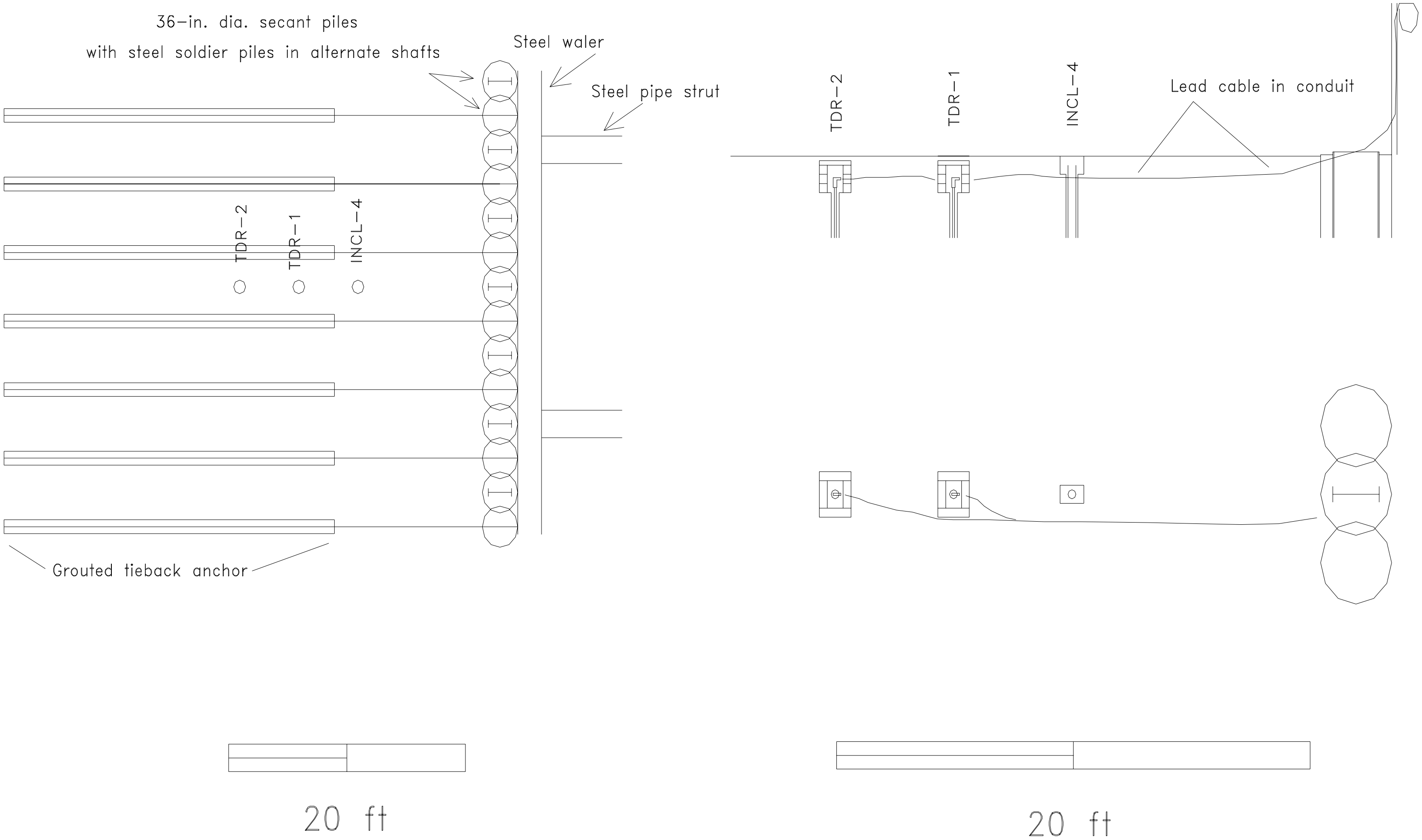


Figure 5-2: Plan view of the supporting system and location of the TDR cables, Chicago and State subway excavation, Chicago, Illinois.

Figure 5-3: Aerial view of the Chicago and State subway excavation, Chicago, Illinois

Site installation

Installation of grouted cables for monitoring deformation using TDR

A major design consideration is the stiffness and shear strength of the grouted cables. A 2.2 cm (7/8 in) CommScope coaxial cable with a solid aluminum outer conductor (P3-75-875-CA) with the properties displayed in Table 5-1, was selected after study of previous field experience. A more flexible cable, manufactured by Northwestern (Cole, 1999) was also installed. This cable, with the properties also displayed in Table 5-1 was manufactured by stripping the solid aluminum outer conductor from the

CommScope cable. The exposed polyethylene foam was then covered with tinned copper braid outer conductor and polyethylene shrink tubing.

Another flexible cable was also tested at this site. It was a larger diameter cable, with a hollow copper tube as inner conductor, foam rubber as the dielectric and tinned copper braid as outer conductor. This cable was also covered with polyethylene heat shrink tubing to made it robust and water resistant. The cable inserted into a grout filled hole was so locally compressible that the fluid pressure of the unsolidified grout deformed the cable into an elliptical shape. As a result, this third cable was abandoned in favor of the braided cable made from the CommScope P3 solid aluminum cable (Cole, 1999).

Material	**Description**	**Shear Strength MPa**	**Shear Stiffness MPa**
grouted cable	solid aluminum outer conductor	1.6	88.0
grouted cable	silver braid outer conductor	0.4	8.0
soil	soft clay below water table	0.024	12.0

Table 5-1: Summary of Cable and soil properties for Chicago & State subway excavation, Chicago, Illinois.

The cables were installed on September 27, 1999. Figure 5.4 shows TDR hole drilling. Each hole was rotary drilled with a diameter of 12.7 cm (5 in.) through the fill and rubble to a depth of 4.5 m (15 ft) then a 10 cm (4-in.) ID surface casing was set in the hole. The hole was then rotary drilled uncased with a diameter of 10 cm (3-7/8 in.) to the required depth. Grout was tremmie pumped into the hole through a 2.5 cm (1 in) OD flush coupled PVC pipe and then the cable was placed, and the surface casing removed.

Figure 5-4: View of the drilling of TDR-1, Chicago & State subway excavation, Chicago, Illinois (the Frances Xavier Warde school is seen in the background).

Hole TDR-1

A solid aluminum outer conductor coaxial cable was installed at location TDR-1. As shown in Figure 5.1 and Figure 5.2, hole TDR-1 is located 1.5 m (5 ft) west of Slope Inclinometer-4 and was drilled to a depth of 18.2 m (60 ft) in order to extend to the same depth as the secant piles. The cement grout whose composition is given in Table 5-2 was mixed in a 189 L (50 gallon) barrel. The grout mix was designed to produce a grout with a strength less than 0.5 MPa based on experience from previous projects and lab tests.

As explained in Table 5-3, it is estimated that the grout volume required to fill the hole to the surface is 0.16 m^3 (5.74 ft^3). There was grout return after pumping a volume of 0.19 m^3 (6.72 ft^3), which implies a grout loss of 0.025 m^3 (0.9 ft^3) . As noted in Table 5-5, the top of the grout was sounded at 1.8 m (6 ft) after the surface casing was pulled out so the grout loss was restricted to the zone of fill and rubble within the top 4.5 m (15 ft).

Prior to installation, the bare aluminum 2.2 cm (7/8 in). CommScope coaxial cable was spray painted with metal primer to minimize the possibility of bubble forming due to a reaction with the hydrating cement grout. It was then crimped at 6.1 m (20 ft) and 12.1 m (40 ft) from the bottom, in order to produce reference TDR reflections. The total length of cable installed was 18 m (59 ft) after trimming to install a connector. A protective enclosure was constructed around the top of cable and connector using 10 cm (4-in) by 10 cm (4-in.) pretreated wooden blocks of variable lengths. The as-built conditions are summarized in Table 5-4.

Hole TDR-2

The objective at location TDR-2 was to install a compliant grouted cable for comparison with the cable and grout installed at TDR-1. The hole is located 1.5 m (5 ft) west of TDR-1. As shown in Table 5-3, the estimated grout volume to fill the hole, was 0.12 m^3 (4.34 ft^3). Grout return occurred after pumping 0.14 m^3 (4.93 ft^3) implying that there was a loss of 0.017 m^3 (0.59 ft^3). As shown in Table 5-3, the top of grout was sounded at a depth of 1.2 m (4 ft) after pulling the surface casing so the grout loss was restricted to the zone of fill and rubble within the top 4.5 m (15 feet).

	Grout Mix						
Hole	Batch	Water (lbs)	Bentonite (lbs)	Cement (lbs)	Additives (lbs)	Water:cement ratio	Sample Cylinders
TDR-1	1	360	12	188	5	**1.91**	9/27/99 four cylinders
TDR-2	1	360	12	188	5	**1.91**	9/27/99 four cylinders

Table 5-2: Grout mix and test summary, Chicago & State subway excavation, Chicago, Illinois.

	TDR-1		TDR-2	
		Volume		**Volume**
Steel casing removed	5 in. dia. 15 ft	2.05 ft^3	5 in. dia. 15 ft	2.05 ft^3
rotary drilling in clay	3-7/8 in. dia. 45 ft	3.69 ft^3	3-7/8 in. dia. 45 ft	3.69 ft^3
Hypothetical Hole volume		5.74 ft^3		5.74 ft^3
Grouted Volume Pumped	batch 1	6.72 ft^3	batch 1	6.72 ft^3
Grout Loss		**-0.027 m^3** **(- 0.98 ft^3)**		**-0.027 m^3** **(- 0.98 ft^3)**

Table 5-3: Summary of hole volumes and grout take, Chicago & State subway excavation, Chicago, Illinois.

Cable and structure	Elevation in feet (CCD)	
	TDR-1	**TDR-2**
ground surface	+13.85	+13.85
top of cable	+13.18	+13.18
top of grout	+7.85	+9.85
crimps in cable	-5.82 & -25.82	
bottom of cable	-45.82	-29.07

Table 5-4: As built conditions for the TDR cables installed next to the Chicago & State subway excavation, Chicago, Illinois.

Other instruments

Extensive instrumentation was installed both to measure the performance of the support system and measure the response of the adjacent structure (Bryson, 2002). To that end, 5 Slope Inclinometers and two piezometers were installed in deep holes around the excavation. Load cells and strain gages were also installed on the supporting structure while the adjacent building was fitted with survey points and tiltmeters. The readings given by the Slope Inclinometers were later compared with TDR data.

Readings and conclusion

Readings

As shown in Figure 5.5, baseline digital records were obtained on both cables by connecting an 24 m (80 ft) long RG11 coaxial lead cable to a Tektronix 1502 TDR pulser and a laptop computer equipped with DP 232. These baseline readings are given in Figure 5-6 and Figure 5.7 below. Very few readings were taken because the cables were destroyed by subsequent installation of the tieback anchors. No shear reflection was observed as the cables were damaged before the second level was excavated.

Conclusion

This project showed that a hollow copper tube inner conductor cable with foam rubber dielectric was not stiff enough to resist the gout pressure deep in the hole. More research is also needed to assess both the performance of coaxial cable in monitoring soft soil deformations induced by excavation and the sensitivity of a braided compliant cable.

Figure 5-5: Kevin O'Connor (GeoTDR Inc.) is taking a manual reading on TDR-1 with a Tektronix 1502 pulser and a laptop computer, Chicago & State subway excavation, Chicago, Illinois.

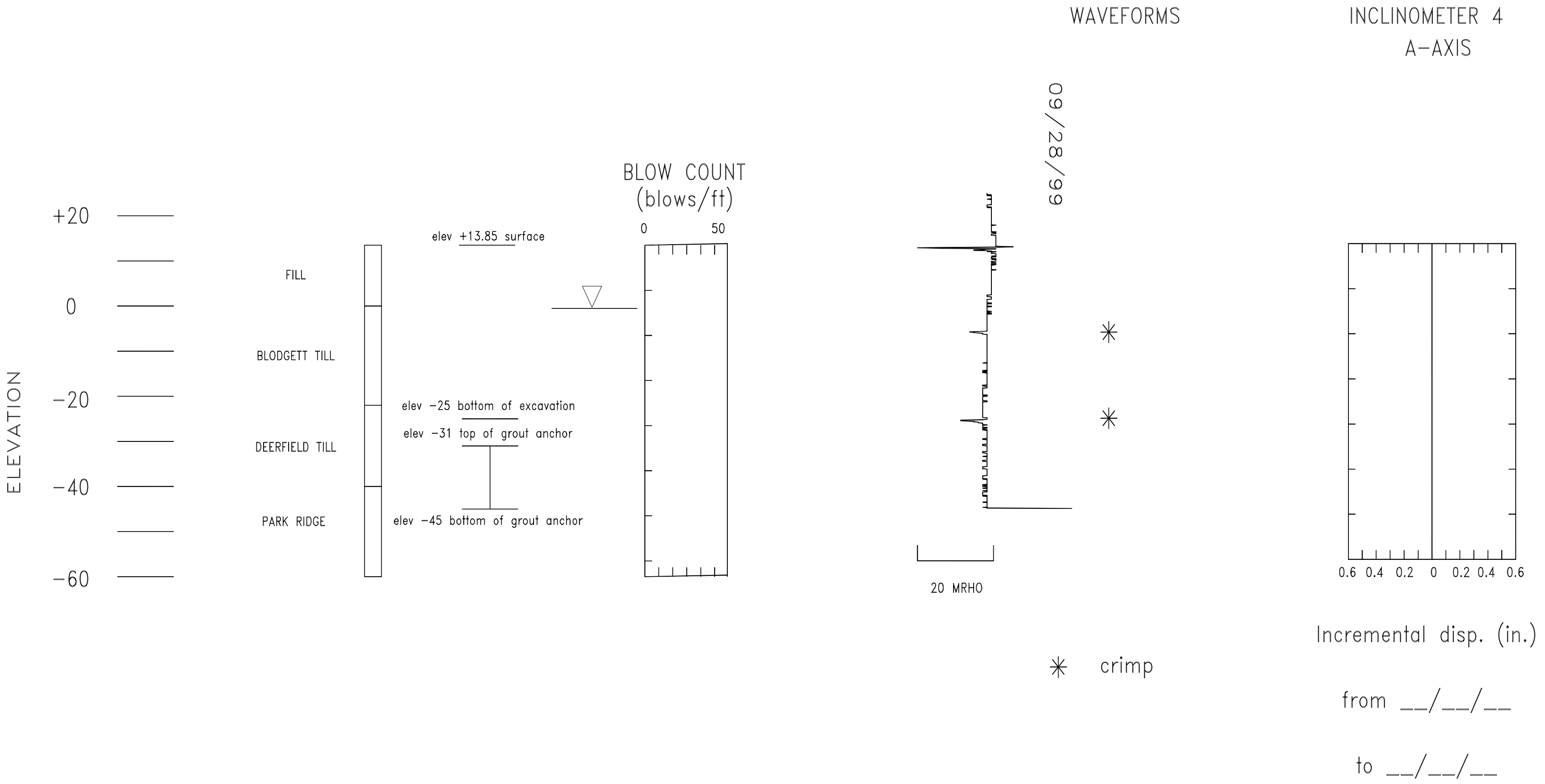


Figure 5-6: Baseline reading and stratigraphy for TDR-1, Chicago and State subway excavation, Chicago, Illinois.

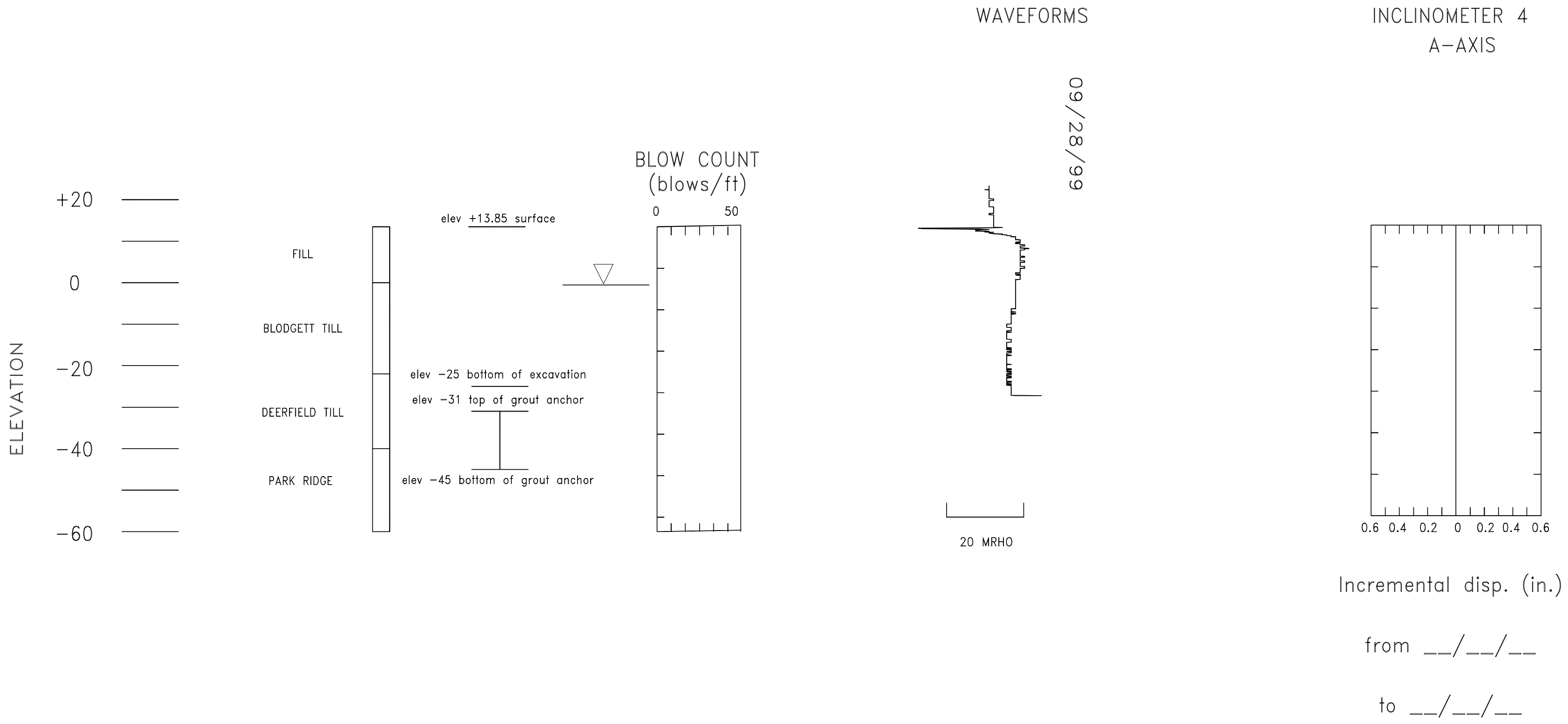


Figure 5-7: Baseline and stratigraphy for TDR-2, Chicago & State subway excavation, Chicago, Illinois.

5.2 Northwestern University Lurie Research Center excavation, Chicago, IL.

Project presentation

Introduction

Northwestern University is building the Lurie research center for its medical school on the Chicago campus at the intersection of Superior St. and Fairbanks Ct. The structure, shown in Figure 5.8 and located as shown in Figure 5.10, will be 12 stories high with two basement levels requiring a 12 m (40 feet) deep excavation. As shown in Figure 5.9, the retaining system designed by Case Foundation consists of a sheet pile wall (PZ 27) supported by three rows of tiebacks.

Figure 5-8: View of the Lurie Research center, Northwestern University campus, Chicago, Illinois.

Site conditions

The stratigraphy of the site is typical from the Chicago area. This is a flat surface covering the area of old sand beach and fill. As shown in Figure 5.13, the existing stratigraphy consists of 3 to 5 m (10 to 17 feet) of sandy fill containing bricks and former utility structure, overlying 5.5 m (18 feet) of fine to coarse beach sand (SM) overlying 4.5 m (15 feet) of soft to medium silty glacial clay (CL), overlying 13.7 m (45 feet) of stiff to very stiff clay (CL). Limestone is found 30 m (100 feet) below the surface. The ground water table is located around 4.5 m (15 feet) from the ground surface, at the interface between the fill and the fine to coarse sand. Concrete and masonry obstructions were found 4.5 m (15 feet) below surface and may be remains of an old building footing or rubble.

Issues of monitoring

Significant movements are expected in the soft clay (>3 in.) and redundant instrumentation was installed to monitor the vertical and horizontal settlement. Instrumentation includes 8 Slope Inclinometers (80 feet deep) to monitor horizontal movements, 30 utility settlements indicators and 149 ground surface survey points. The redundant instrumentation installed provided an opportunity to compare the sensitivity of compliant and stiff TDR cables in soft soils with Slope Inclinometers and survey data.

Figure 5-9: View of the south wall (Huron St.) of the Lurie Research Center excavation showing the first and second level of tiebacks, Chicago, Illinois.

Site installation

Installation of grouted cables for monitoring deformation using TDR

Two major design considerations were the stiffness and shear strength of the grouted cable and grout mix. A CommScope coaxial cable with a solid aluminum outer conductor (P3-75-875-CA) and a tinned copper outer conductor cable manufactured at Northwestern University (Cole, 1999) with the properties displayed in Table 5-5 were selected from previous field experience. The cement bentonite grout mix was also designed from experience on previous projects to produce a strength that would match the relatively weak soil properties.

Material	**Description**	**Strength (MPa)**	**Stiffness (MPa)**
Grouted Cable	Solid Aluminum outer conductor	1.6	88.0
Grouted Cable	Braided outer conductor	0.4	8.0
Soil	Soft to medium clay	0.0306	

Table 5-5: Summary of cable and soil properties for Lurie Research Center excavation, Chicago, Illinois.

Hole TDR-1 (B8-A)

As shown in Figure 5.10, Hole TDR-1 (B8-A), is located 3 m (10 ft) west of Slope Inclinometer B8, on Huron Street. The cable used for this hole was designed and prepared by Northwestern University (Cole, 1999) by stripping out the outer solid aluminum conductor along a 19.2 m (63 ft) section of a 20 m (65 ft.) long piece of CommScope cable coaxial cable (P3-75-875 CA). The exposed polyethylene foam dielectric was covered with a tinned copper braid outer conductor and heat shrink tubing.

As shown by Figure 5.11, the hole was rotary drilled with a diameter of 10 cm (4-1/4 in.) through the fill to a depth of 4.6 m (15 feet), then a 10 cm (4 in.) ID casing was set. It was then rotary drilled under bentonite slurry with a diameter of 9.8 cm (3-7/8 in.) to the required depth of 20 m (65 feet). The hole was drilled to a depth of 20 m (65 feet) in order to anchor the cable in the stiffer clay.

The cement bentonite grout mix whose composition is given in Table 5-6, was mixed in a 208 L (55 gal) barrel and pumped into the hole. The bentonite was prehydrated for 24 hours before being mixed with cement. Only one bag of cement was introduced in the mix and it produced a very weak grout with a measured unconfined compressive strength, q_u=0.109 MPa at 28 days. This measured strength is based upon laboratory tests. The estimated hole volume is 0.16 m^3 (5.87 ft^3) and the grout volume pumped in the hole is 0.18 m^3 (6.30 ft^3). After the casing was extracted (the last length of which was first lost at 10 m (33 feet) and then recovered), the grout level dropped 2 m 6 feet below the surface. The losses occurred in the fill layer, above 5.2 m (17 feet) below the surface.

As shown in Figure 5.12 the cable was guided down employing a plastic cone attached with wire and electrical tape. A PVC tremie pipe is placed in the attached cone and pushed down the hole. No crimp was made on the cable. A protective enclosure was put around the above ground part of the connector using a 10 cm (4 in. PVC) tube. The tube was sealed in the ground and a locker put on it.

Hole TDR-2 (B8-B)

As shown in Figure 5.10, cable TDR-2 (B8-B) is located 1.5 m (5 ft) west of Slope Inclinometer B8 on Huron St. The objective at this location, is to install a stiff cable to compare its behavior with the more compliant cable installed in hole TDR-1 (B8-A). The cable installed is a 2.2 cm (7/8 in.) diameter, 20 m (63 feet) long CommScope solid outer conductor aluminum cable.

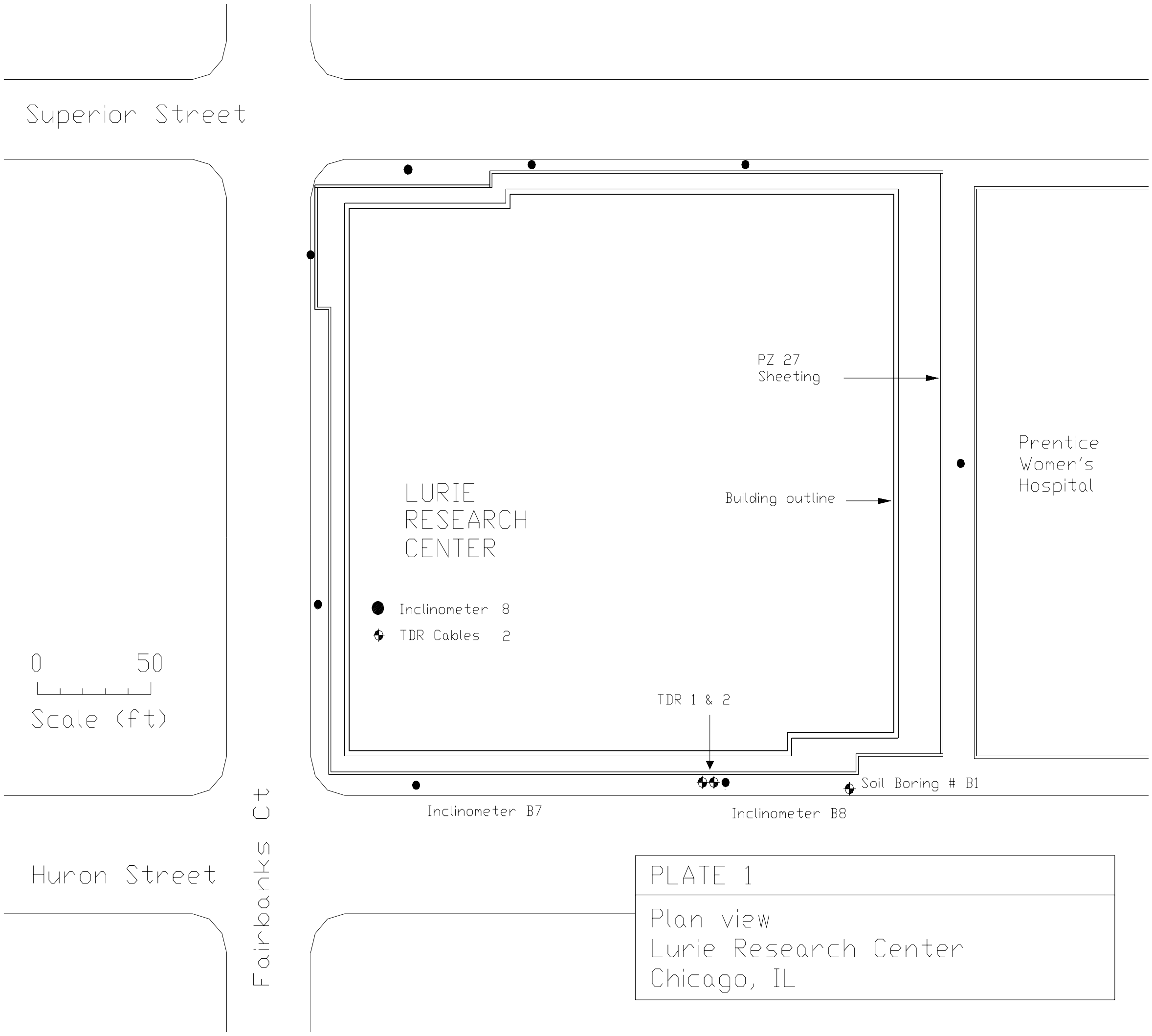


Figure 5-10: Plan view of the Lurie Research Center's excavation, Chicago, Illinois.

Figure 5-11: Drilling of hole TDR-1 (B8-A), Lurie Research Center excavation, Chicago, Illinois.

Figure 5-12: Construction of the plastic guide at the tip of cable TDR-1, Lurie Research Center, Chicago, Illinois.

Hole TDR-2 (B8-B) was drilled using a different technique than for hole TDR-1 (B8-A) to gain time. The initial 9.1 m (30 feet) was drilled using a 15.8 cm (6-1/4) in. ID hollow stem auger which remained in the hole during coaxial cable installation. Then a 9.8 cm (3-7/8 in.) solid stem auger was employed to drill the final 10 m (34 ft) with bentonite slurry. A masonry obstruction was encountered 4.5 m (15 ft) below the surface.

The cement bentonite grout mix which composition is given in Table 5-6, was mixed in a 208 L (55 gallon) barrel and pumped into the hole. The bentonite was prehydrated for less than 10 hours before being mixed with cement. This resulted into a mix with a low viscosity and lower strength. Only one bag of cement was also introduced and produced a very weak grout with a measured unconfined compressive strength, q_u=0.015 MPa at 28 days. Measured grout strength is based upon laboratory tests. The estimated hole volume is 0.37 m^3 (13.2 ft^3) and the grout volume pumped in the hole is 0.18 m^3 (6.37 ft^3). After removing the hollow stem auger, the grout level dropped 6 m (20 ft) below the ground surface. The losses occurred in the fill and sand and the drop is also due to the significant larger diameter of the hollow stem auger.

Solid aluminum cables are usually easy to install but the tip of TDR-2 jammed during insertion. A 1 m (3 ft) long PVC pipe was tapped at the bottom of the cable to stiffen and strengthen the end. No crimp was made on the cable and the above ground part was placed in a protective enclosure. This enclosure is a 10 cm (4 in.) locked PVC tube, sealed in the sidewalk. Table 5-7 summarizes the as-built conditions for both coaxial TDR cables.

	Grout Mix						
Hole	**Water (lbs-%)**	**Bentonite (lbs-%)**	**Cement (lbs-%)**	**Additive (lbs-%)**	**Water-Cement ratio**	**Sample Cylinders**	**Measured q_u (MPa)**
TDR-1 (B8-A)	397 lbs 82.6%	12 lbs 2.5 %	70.5 lbs 14.6%	1 lbs 0.3 %	**5.6**	Yes 02/04/02	0.109
TDR-2 (B8-B)	397 lbs 78.7%	12 lbs 2.4 %	94 lbs 18.7%	1 lbs 0.2 %	**4.2**	Yes 02/04/02	0.015

Table 5-6: Grout mix and test summary for holes TDR-1 and TDR-2, Lurie research center, Chicago, Illinois.

Cable & Structure	**Elevation in ft.**	
	TDR-1 (B8-A)	**TDR-2 (B8-B)**
Ground Surface	+ 13.6 CCD	+ 13.6 CCD
Top of cable	+ 17.0 CCD	+ 15.6 CCD
Top of grout	+ 7.6 CCD	- 6.4 CCD
Bottom of cable	- 48.0 CCD	-46.4 CCD

Table 5-7: As built conditions for deformation TDR of Lurie Research Center excavation, Chicago, Illinois.

Other instruments

Extensive instrumentation was installed both to measure the performance of the support system and measure the response of the adjacent steel pipelines. To that end, 8 Slope Inclinometers were installed in deep 80 feet holes around the excavation. Some 30 utility settlements indicators as well as 149 ground surface survey points reinforce the monitoring of excavation induced movements. Readings given by the Slope Inclinometers were later compared with TDR data.

Readings and conclusions

Baseline and later digital records displayed in Figure 5.13 and Figure 5.14 were obtained on both cables by connecting an 1.5 m (5 ft) long RG11 coaxial lead cable to a Tektronix 1502 TDR pulser and a laptop computer equipped with SP 232. Simultaneous manual interrogation of both cables with a CR10X datalogger, a TDR 100 pulser and a multiplexer was tried but readings were then taken weekly with the Tektronix 1502. No reflection spike has been observed in the cables certainly because the cement bentonite mix was too weak. The grout was not able to shear the cable even after 6.5 cm (2.5 in.) of lateral movement measured by Slope Inclinometer 8 at the beginning of December 2002.

Later investigation showed that the grout level dropped deeper than expected for Hole B8-a. The top sand layer certainly absorbed all of the grout. As the grout was mostly water and bentonite, It formed a column of cemented sand around the hole and kept it open, empty of any grout until the clay layer.

Chapter conclusion

Cable installation must be supervised by personnel with experience in TDR technology. These projects highlighted the importance of drilling and grout mixing. Grout mixing is critical for the development of a stiff grout. Sufficient cement has to be added, at least two bags for a 200 L mix. A too weak mix like in Lurie, would either be totally absorbed by a granular material layer or harden into powder. As a consequence, a potential local deformation of the soil. won’t shear the cable A good hydrating of the bentonite is also necessary for strength to develop. Note that the grout strength for TDR-1 is 10 times higher than for TDR-2 whereas more cement was inserted in TDR-2 grout mix. Bentonite for TDR-2 grout mix was not prehydrated enough and significantly weakened the grout. Grout mixing procedures are developed in more detail in Chapter 6.

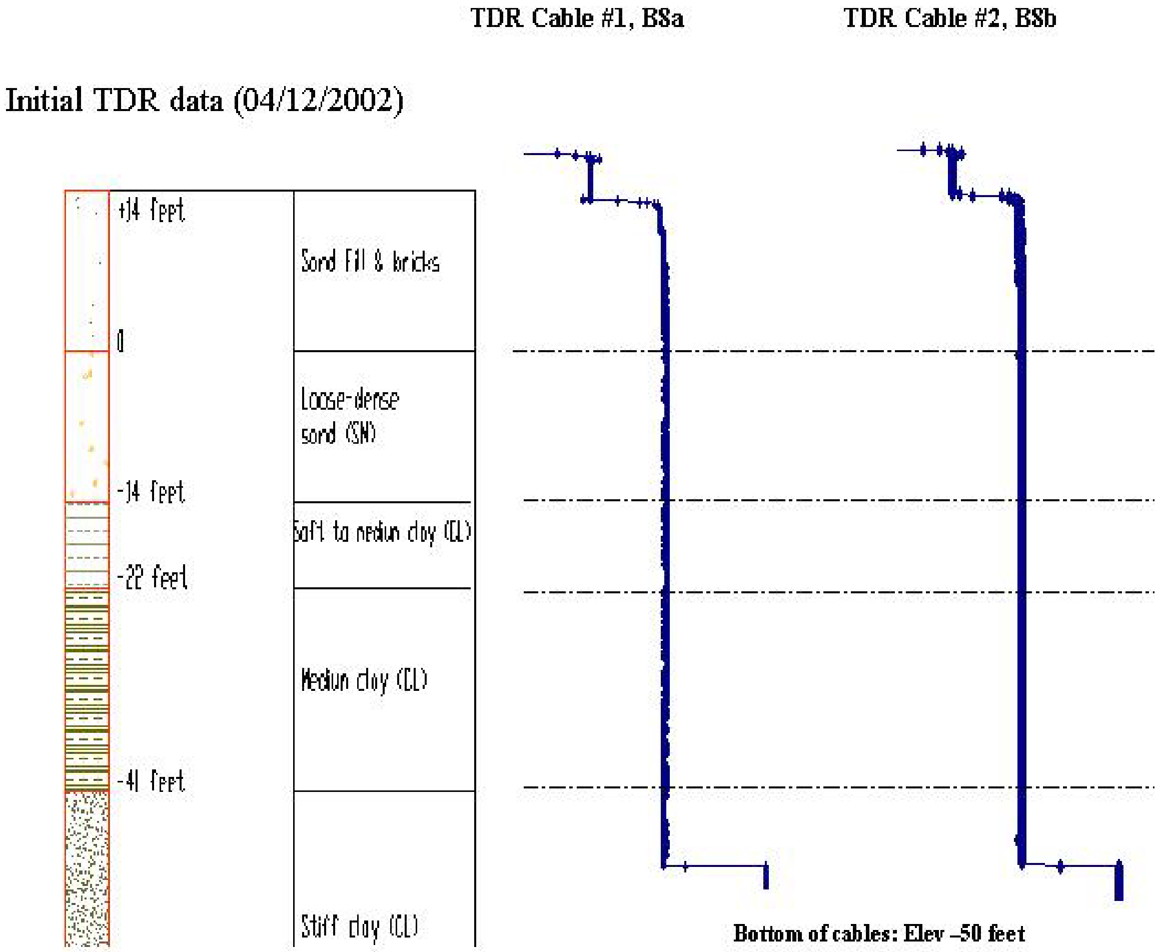


Figure 5-13: Baseline readings for TDR-1 and TDR-2, Lurie Research Center, Chicago, Illinois.

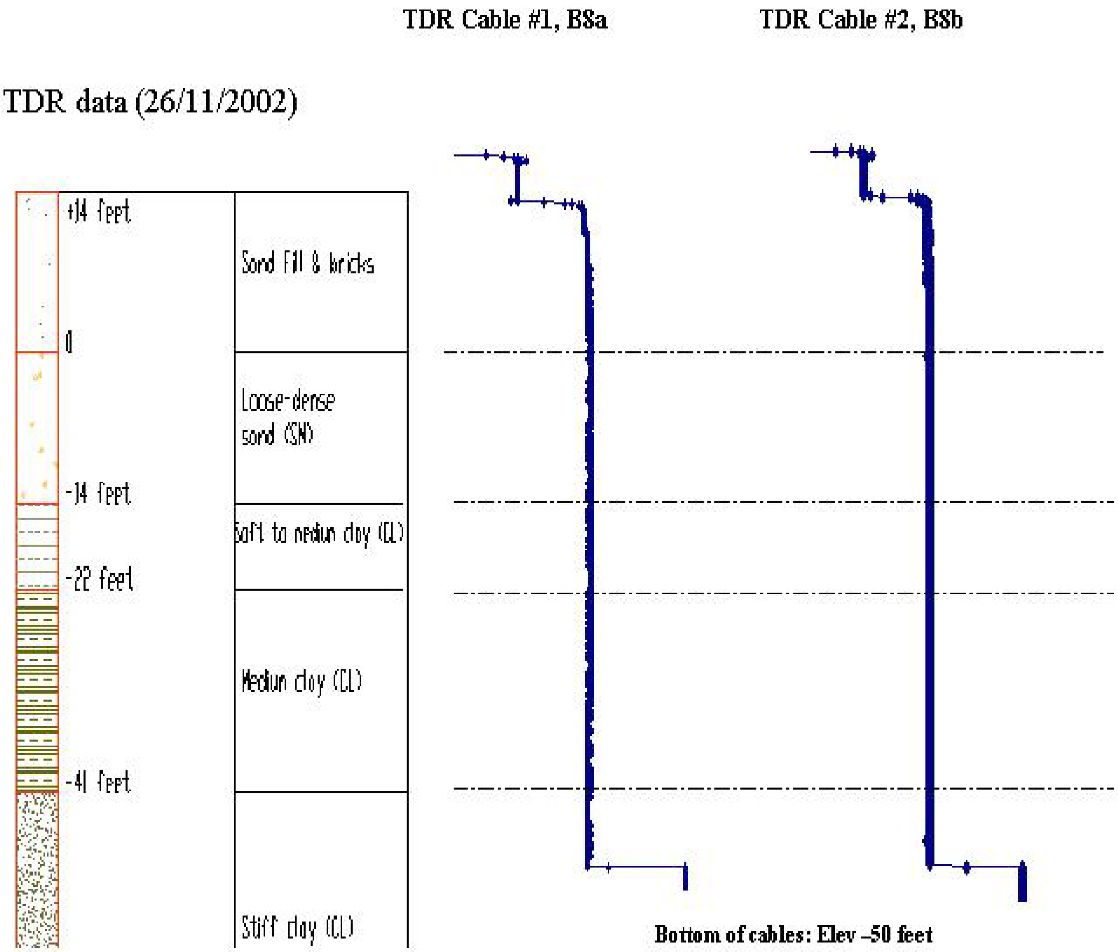


Figure 5-14: Readings for TDR-1 and TDR-2, Lurie Research Center, Chicago, Illinois.

Chapter 6

TDR Cable Installation for Soil Deformation Monitoring

This Chapter summarizes some of the techniques of cable construction and installation to monitor soil deformation. Previous work by former graduate students and the work conducted for the instrumentation of the Lurie Research center project serve as a basis for this Chapter.

Cable preparation

Cable manufacture

Aside from commercially available TDR cables, more compliant TDR cables have been built following a specific design (Pierce, 1998) in order to monitor more efficiently soft soil deformation. Three issues to be addressed when considering the design of coaxial cables for TDR measurements of localized deformations in soil were identified (Pierce, 1998). First, a low cable stiffness is needed to match the surrounding soil stiffness, second, a large diameter cable is required to track the largest shear displacements and third a low characteristic impedance, will reduce attenuation.

Different TDR cables were built and tested using these recommendations (Cole, 1999). Table 6-1, summarizes the TDR cables built and tested at Northwestern University. Two braided foam cables were built and compared with a painted polyethylene cable and two stiff solid aluminum cables. These tests showed that the braided foam polyethylene had the best electromagnetic properties.

The braided foam polyethylene cable showed the most promising properties of the three compliant cables built and tested at Northwestern University. This cable shown in Figure 6.1 was constructed from a Parameter III 875 Commscope Cable, with the aluminum outer conductor stripped and replaced with military specification grade wire braid. At one end of the cable, the aluminum was not removed to allow a standard Commscope cable connection detail. The wire braid was placed over the dielectric for the outer conductor. At the connection end, the braid was placed over the remaining aluminum, and secured using a hose clamp. Shrink-wrap PVC was placed over the outer conductor and shrunk onto the cable. This cable, compared to solid aluminum cable in Figure 6-1, has high electromagnetic reflection properties generated per unit of shear displacement and is recommended for soft soil deformation monitoring.

For stiffer soil, a solid aluminum foam polyethylene cable is more suitable because it is commercially available. This stiff cable, compared in Figure 6.1 to a braided compliant cable, is available from CommScope Inc. or Cablewave Inc. It has been intensively used for rock movement and slope failure monitoring.

Cable Description	**Cable Model Number**	**Inner Conductor**		**Dielectric**		**Outer Conductor**		**Jacket**		**Calculated Bending Stiffness, EI (kN.m^2)**	**Measured Shear Stiffness (kN/m)***
		Material	**Dia (mm)**	**Material**	**Dia (mm)**	**Material**	**Dia (mm)**	**Material**	**Dia (mm)**		
Braided Foam	N/a	Copper refrigeration tubing	15.88	Cellular foam	27.4	Tin/copper braid	28.2	PVC Shrink-wrap	29	47	n/a
Painted Foam Polyethylene	N/a	Solid copper	4.93	Micro cellular polyethylene foam	20.24	Colloidal Silver Paint	20.24	Vinyl Electrical Tape	21.5	5.4	400
Braided Foam Polyethylene	N/a	Solid copper	4.93	Micro cellular polyethylene foam	20.24	Tin/copper braid	21.02	PVC Shrink-wrap	21.85	6.2	480
Braided Polyethylene	Pasternack Enterprises RG218/U	Bare copper	4.95	Solid Polyethylene	17.27	Bare copper braid	18.48	PVC	22.1	13	650
Solid Aluminum Foam Polyethylene	Commscope Parameter III 875 Cable	Copper clad aluminum	4.93	Micro cellular polyethylene foam	20.24	Aluminum	22.23	n/a	n/a	275	1760
Solid Aluminum Foam Polyethylene	Cablewave FXA 12-50	Copper clad aluminum	2.77	Micro cellular polyethylene foam	11.43	Aluminum	12.7	n/a	n/a	38	980

Table 6-1: Compliant TDR cables built and tested at Northwestern University. (Cole, 1999)

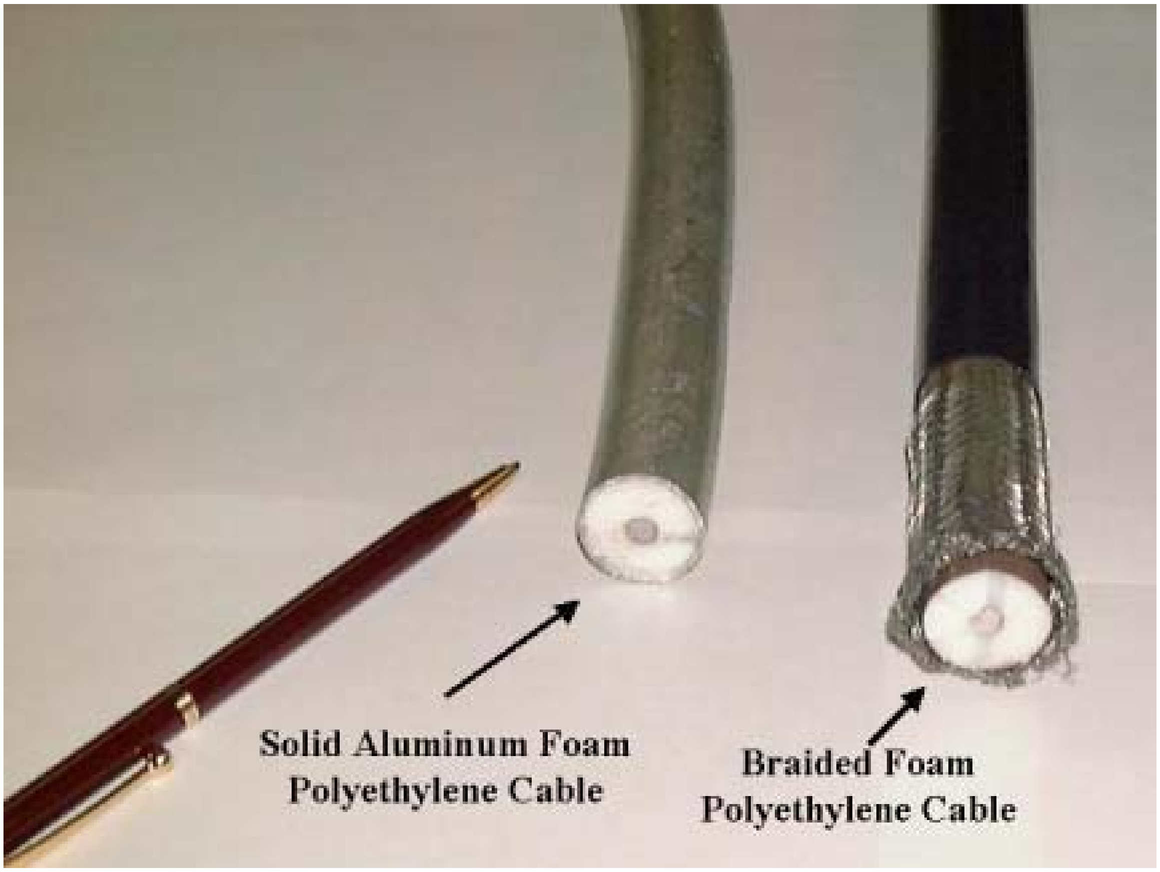


Figure 6-1: Comparison between a Solid Aluminum cable and a Braided cable.

Connectors and final preparation

Connectors must be attached to cables following strict procedure and be water proofed in order to properly transmit the voltage signal from the pulser. Once the cable's built or cut from the roll, the bottom end is sealed against moisture penetration with a PVC cap and urethane sealant. Then usually, a type F, N or UHF connector is placed at the top end as displayed by Figure 6.2 and Figure 6.3. A type N is usually preferred.

A procedure to place a Gilbert Engineering GRS type connector on a Commscope PIII cable is as follows. First, expose the inner conductor by removing the outer conductor and the dielectric. Connectors, as shown in Figure 6.3, have a trim gauge on the main nut to assist in removal the proper amount of outer conductor and dielectric. Then, double check the length, scrape any glue the inner conductor with a cutter and carefully give the tip a pyramidal shape to facilitate the penetration into the body. The third operation is to core the dielectric, install the back nut and the main nut on the cable. The different parts of the connector should be firmly tightened using wrenches before shrink-wrap PVC is placed over and shrunk.

Connectors are the weak link in a TDR monitoring system and require the greatest attention. Connectors should be installed with care and well maintained. They should be protected with electrical tape and shrink-wrap PVC and placed in a waterproof casing. A loose or wet connector will induce lots of losses in the cable and eventually will not transmit any signal.

Figure 6-2: Components of a GRS Gilbert Eng. Connector and tools for its installation on a PIII Commscope solid aluminum Cable.

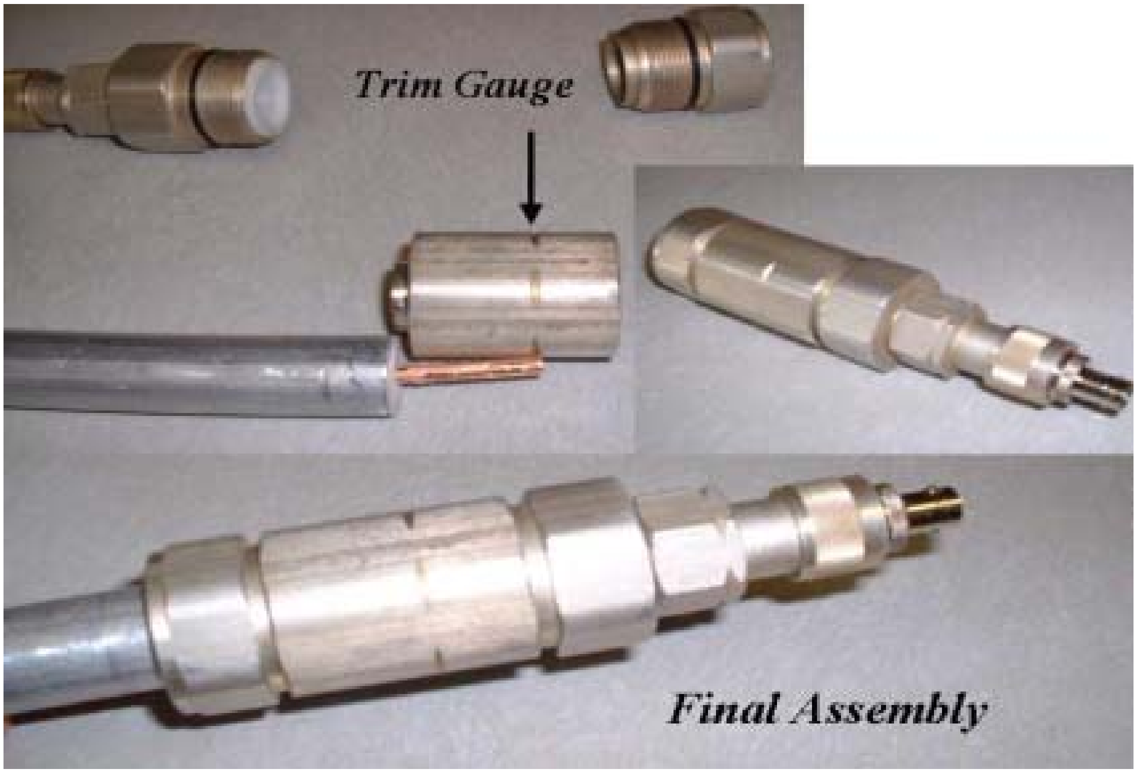


Figure 6-3: Final assembly of Gilbert Eng. GRS type N connector on a PIII Commscope cable.

Site installation

TDR cables in their own holes

TDR cables have been installed both in their own holes and together with Slope Inclinometer casings. Yes, grouting together a TDR cable and an Slope Inclinometer casing in the same borehole might save money. However the presence of the casing will prevent the TDR cable from being sheared sharply by a localized shear band. Furthermore cables tapped to SI casings are small diameter lossy cables which have inherently less sensitivity. For proper operation, TDR cables must be grouted in their own holes in order to detect localized shearing.

TDR hole drilling

TDR holes can be drilled with all drilling techniques but are usually drilled using casing with a drilling fluid or with a hollow stem auger depending on the nature of the soil and the schedule of the work as shown by the pictures displayed in Appendix 2. When the stratigraphy consists of sandy materials below the water table, the use of casing and drilling fluid like bentonite slurry is recommended. This technique, selected for TDR-1 at the Lurie Research Center (Chicago, IL) where a 10 cm (4 in.) ID casing was used, will stabilize the hole and prevent sand from running into the hole.

In order to drill the hole more quickly and without drilling fluid, a hollow stem auger can be used, but this technique involves a large disturbed zone around the hole. The smaller auger commercially available has a 5.7 cm (2-1/4 in.) ID but creates a hole 17.1 cm (6-3/4 in.) in diameter and a large 26 cm (10-1/4 in.) ID auger creates a hole of 35 cm (14 in) in diameter. This method was also chosen for TDR-2 at the Lurie Research Center (Chicago, IL) and for the S.R. 62 site (Crawford county, IN).

Another consideration for the choice of the drilling technique is the grout losses upon removal of the casing. The hollow stem auger can remove a large annulus of soil during extraction, which requires significantly more grout than a cased wash boring. A large drop in the grout level, reduces the length of possible shear band detection near the top of the cable. If hollow stem auger is chosen because of practically, the important grout losses have to be overcome by preparing larger amounts of grout that are tremied upon removal of the auger.

Grout mix preparation

A cement-bentonite grout mix design based on a ratio of grout strength to soft soil strength of five and possibly ten in soils (Blackburn, 2002), is necessary to create optimum conditions for a TDR reflection. To detect soft soil deformations via kinking of the TDR cables, the grout surrounding the cable must be stiff enough to shear the cable but not so stiff as to shear soil on either side of the slip plane. A finite element analysis of TDR cable-grout-soil mass interaction, showed that a ratio of grout strength to soil strength of five or less would provide optimal conditions for shearing both cables and avoid smearing the slip surface in soft to medium soils. At this ratio, as shown in Figure 6.4, the shear stress in the cable is maximized since the cable must be locally deformed to cause reflection. Other estimates and field experience indicated that in certain conditions, this ratio could be as high as 10 for sufficient kinking of the cable.

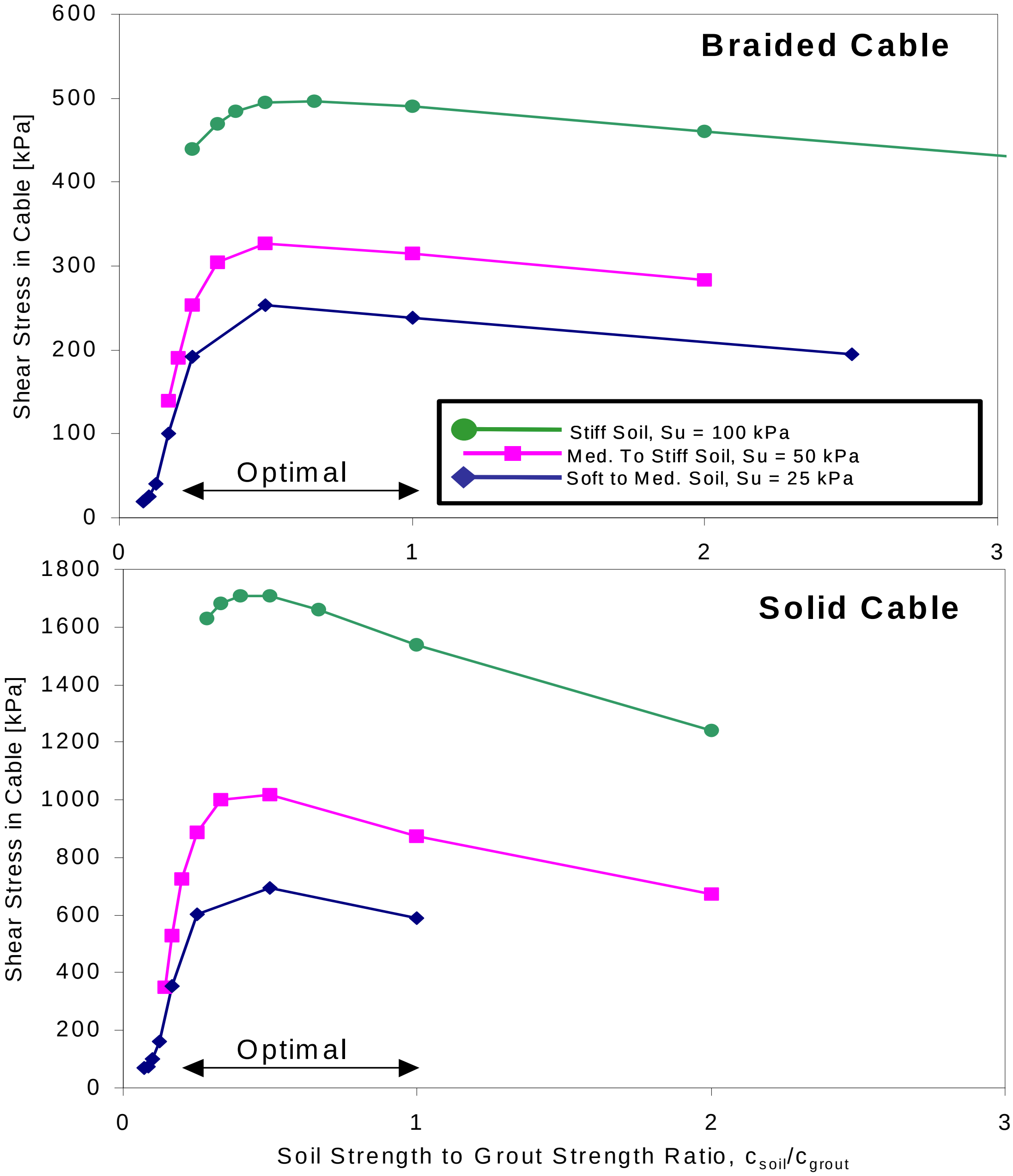


Figure 6-4: Comparison of calculated shear stress in cable to ratio of soil to grout strength showing that stress is maximized at soil to grout strength of 1/5 total, (Blackburn, 2002)

Manually prepared grout mixes should have an adequate water-to-cement ratio in order to create the proper grout strength and should employ additives to fluidize the grout and avoid blocking the drilling rig water pumps. A typical grout mix generally consists of cement, bentonite, water and additive. The unconfined compressive strength of a cement-bentonite grout depends on the materials and the composition of the mix specially on the water to cement ratio. Figure 6.5 displays the compressive strength versus the water to cement ratio at 3, 7 and 28 days for weak grout mixes (Will, 1996) and should be used to design the grout according to Blackburn’s recommendations discussed above. The grout mixture must be placed with a typical drilling rig water pump and should have as low a viscosity as possible to avoid pump overstress. Fluidizing agent (typically Intrusion Aid type R) is employed to make the grout flow easily and limit shrinkage (Manufacturers are given in Appendix 1).

Bentonite prehydration and grout mixing are essential to the strength and fluidity quality of the grout. Water-to-bentonite ratio (w/b) controls bleeding. It is suggested to use a w/b ratio of 30 or less (Will, 1996) to avoid excessive bleeding. But with such low levels of bentonite (around 2%) it is critical that the bentonite is fully prehydrated.

When powdered bentonite is added to water, it immediately expands and forms small clumps. Prehydratation is the process of breaking those bentonite clumps into a homogeneous, very viscous, water-bentonite suspension. The weight of the bentonite has first to be controlled rigorously with an portable scale and full prehydration of the water-bentonite mix during 24 hours must be achieved by the drilling team before going on site. Bentonite is fully hydrated after standing 24 hours in water, but the process can be accelerated by 30 minutes of agitation (Will, 1996). A visual and manual inspection is necessary to check the bentonite slurry and confirm its high viscosity. The addition of

Fluidizing agents such as Intrusion Aid Type R will reduce later the viscosity of the mix and facilitate its pumping. This response must be demonstrated to the drillers who will not wish to pump a viscous grout for fear of blocking their water pump.

When full hydration is reached, cement, additives and water can be added in the proper proportions to the water-bentonite slurry and mixed for at least 30 minutes (Will, 1996). Prepared that way in the field, the grout mix is fluid, homogeneous and will have hardened properties consistent with properties of laboratory grouts.

Comparison between grout mix for Lurie Research Center and Chicago and State illustrate the importance of grout preparation. In both cases, the issue of monitoring was to detect local shearing in soft to medium glacial clays with two different TDR cables. Table 6.2 show the similarities in the quantity of grout produced for Lurie and Chicago and State. Note that for Lurie, for the same amount of bentonite and water but half cement, the mix produced measured unconfined compressive strength less than 1/10th that for Chicago and State. For similar water-cement content there is a significant difference in strength between TDR-1 and TDR-2 grout mixes for Lurie. Bentonite for TDR-2 grout mix was not prehydrated which may have contributed to a weaker grout than TDR-1 despite a higher cement content.

Hole *	Water	Bentonite	Cement	water/cement	Qu in MPa
1	360 lbs	12 lbs	188 lbs	1.91	1.4 (Measured)
2	360 lbs	12 lbs	188 lbs	1.91	1.4 (Measured)
3	397 lbs	12 lbs**	70 lbs	5.6	0.11 (Measured)
4	397 lbs	12 lbs**	94 lbs	4.2	0.015 (Measured)

Note: ***Holes 1 and 2 are for Chicago and State, hole 3 and 4 are for the Lurie Center, ** estimated by drillers.

Table 6-2: Comparison between grout mix composition and measured unconfined compression strength for Chicago and State and Lurie research Center.

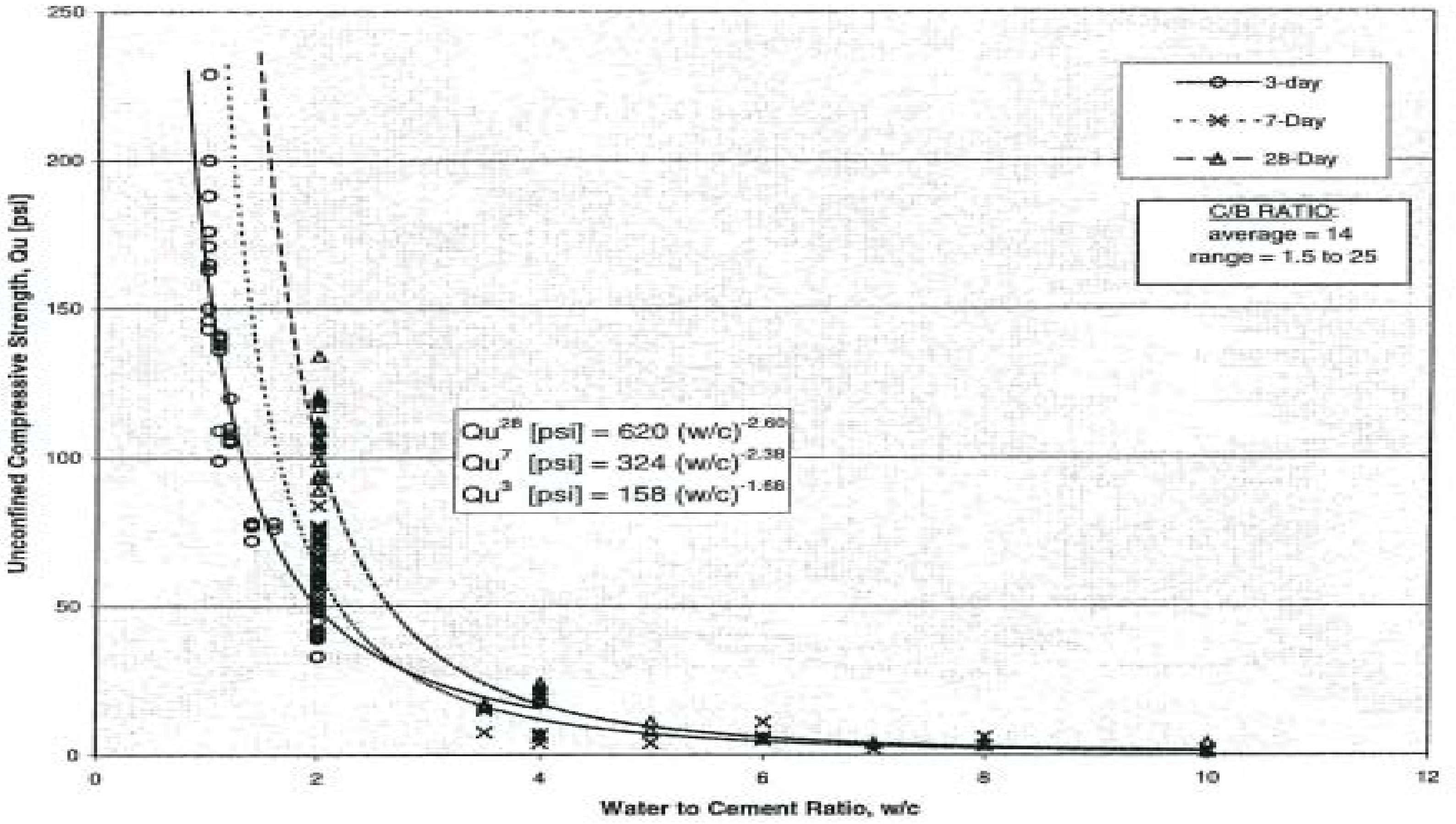


Figure 6-5: Compressive strength of grout mix versus its water to cement ratio (Will, 1996)

Grout pumping

Upon completion of drilling and before inserting the cable, grout is tremie pumped to displace the drilling mud. Grout is pumped through either a tremie PVC pipe or a standard drilling rod. The PVC pipe or the rod is lowered down to the bottom of the hole. Grout is then pumped in, which pushes up the drilling mud because of its lower density. The drilling mud is received at the surface and kept to be recycled. While grout is pumped, the operator has to keep a constant distance of 1 meter (3 to 4 ft) between the grout head and the bottom of the drilling rod or PVC pipe to prevent any air intrusion into the grout.

Usual tremie flush PVC pipes are 5 cm (2 in) in diameter. Drilling rods range from 4.4 to 8.8 cm (1.75 to 3.5 in) in OD. These pumping pipes shouldn’t not be used with mixes containing concrete type aggregates or too viscous grouts. Cement bentonite grouts used in TDR applications are usually very viscous. Drilling crew may not wish to pump such grouts, so fluidizing agents will need to be added to the mix.

Cable insertion

A flexible braided cable can be pushed into the hole with a cone attached to its end tip as shown in Figure 6.6. Whereas a stiffer solid aluminum cable can be pushed in directly. Before inserting the cable, the end tip has been sealed and made perfectly waterproof. Stiffer solid aluminum cable is the simplest to insert but if the tip of the cable becomes jammed, it may be difficult to reach the bottom. A good solution is to tape a 3 ft long PVC pipe to the bottom end of the cable to stiffen and strengthen it or create an extra weight at the end tip by taping a piece of steel casing. The flexible braided cable will need to be equipped with a small plastic cone at its tip as shown in Figure 6.6, and pushed into the grouted hole with the flush coupled PVC pipe employed to tremie the grout into position. The crimps can also be made at predetermined positions marked with electrical tape just when the cable is about to be lowered in. This delay avoids accidental bending at the weaker crimps during placement.

Safety tips

Apart from the normal precautions on a drilling site, two additional safety issues are important when installing TDR cables. First, eye and hand injuries are possible during grout mixing and cable insertion, so gloves and safety glasses are compulsory. A second hazard concerns the cables themselves. The connector ends have to be protected from outside activity and placed in locked casings. If the connector is above ground, it must be placed into a sealed PVC casing as shown in Figure 6.7 and warnings be placed around it. If the connector is below ground, it must be placed in an solid underground structure with a removable top cover and correctly marked at the surface.

Figure 6-6: Installation of the penetration plastic cone at the end tip of a flexible braided cable at the Lurie Research Center, April 2002.

Figure 6-7: Comparison of an underground TDR connector casing (Left) and an above ground TDR connector casing (Right).

Verification of grout strength

Sampling, casting and curing the grout

Three test samples should be taken in coated 3x6"cylinder molds for each slurry batch, cured in the curing room then removed carefully from the mold and trimmed before testing. Once a batch of slurry mix is ready to be pumped in the TDR hole, three ASTM 3x6" cylinder molds are filled to the top with grout mix. The cylinders have before been coated with a layer of spray lubricant type WD-40 (Will, 1996) to aid in removal the cured specimen and labeled. In the lab, the plastic cap is removed from the cylinders and a "sandwich" plastic film is placed on top of the sample which is then left in the curing room for three days at 100% humidity and constant temperature. The removal of the mold before the compression test is a delicate process (some low strength specimens can be damaged) and the best method is to cut the mold with a knife down opposite sides and across the bottom. Trimming of the sample with a wire or hand saw and a hand level is necessary to make the sample right cylinders with parallel ends and perpendicular sides.

Compressive strength testing

The 3x6" cylindrical specimens are tested at seven and twenty eight days with a Soiltest rotary hand-cranked unconfined compression machine following the ASTM D 4832-88 standards (Will, 1996). The model U560 Soiltest rotary hand-cranked unconfined compression machine displayed by Figure 6.8 has a bottom plate moving upwards which compresses the specimen against the top plate. The load is measured indirectly by a compressed proving ring. Its displacement, measured by a dial gage, is multiplied by a constant to determine the actual load applied to the specimen. The constant is found by loading the ring placed upside down and measure its displacement for given loads.

Figure 6-8: Soiltest unconfined compression machine used to test grout mix samples.

Chapter conclusion

Great care in TDR field installation is necessary to create optimum conditions to observe a reflection waveform; this is the most critical part of every TDR project. A loose or wet connector will not transmit the signal for example. Grout mixing and pumping requires close attention. Grout has to be stiff enough but not too stiff to be pumped. Enough cement, prehydration of the bentonite and fluidizing agents are necessary. A good communication with and understanding of the drilling subcontractor and the crew on site is also vital in order to be sure they understand the reasons for the steps detailed in this chapter.

Chapter 7

Acquisition, Real-Time Monitoring and Web Display for TDR Data.

This Chapter summarizes the different modes of data acquisition and concentrates on the procedures for real time monitoring of soil deformation using TDR and on the advantages of web display of TDR waveforms. Data acquisition can be either accomplished manually or automatically. Real-time monitoring requires the proper choice of data acquisition and communication equipment to allows display of TDR waveforms over the internet.

7.1 Waveform acquisition

This section explains two modes of waveform acquisition in the field. The first part concentrates on manual data acquisition and analysis with a TDR pulser and a laptop computer and the second part on automated data acquisition and analysis with a datalogger and a multiplexer.

Manual Waveform acquisition

Data acquisition

Manual data acquisition in the field is accomplished by directly connecting the sensor cable to a digital TDR cable tester. Commonly used TDR pulser like the Tektronix 1502 cable tester, are directly linked to the sensor cable through a low loss lead cable equipped with BNC connectors. If the lead connecting cable is shorter than 50 m (160 ft), standard 50 Ohm cable can be used. If a long connecting cable is required as for Cambridge Ohio, 75 Ohm lead cable should be employed to minimize losses and signal attenuation.

The Tektronix 1502 cable tester is the standard portable TDR tester. It has a maximum range of 500 meters with a distance resolution of 0.30 cm, and a Dist/Div ranging from 0.025 to 50 m/div. The operator has to choose and keep the same propagation velocity (Vp) for all readings in order to match the distance given on the screen by the cursor at specific locations (end of the cable or crimps) with their known location in the field. The operator can modify the scale, the position of the cursor or zoom to view an area of interest. Waveforms can be recorded digitally if the TXT 1502 TDR pulser is equipped with an SP 232 module.

The Tektronix SP232 host application program, controls the 1502 TDR tester through a laptop computer. SP232 is a DOS application which allows a waveform to be acquired in data windows through software settings written in an ASCI file. Each waveform is divided into N windows of 251 data points. Obtaining greater accuracy with the longer cable requires a larger N. N can be as small as 1 but for a 65 feet long cable typically 5 windows are usually sufficient.

Figure 7.1 below shows the SP232 interface and the different functions offered by SP 232: Get a waveform, Set, Read, Info, Alt, Diff, Erase, Quit and More. However, a settings file has to be created before acquiring the waveform. This .SET file, includes the following information for each window of data: number of waveforms to be averaged, vertical sensitivity, horizontal sensitivity, propagation velocity (Vp), distance at which interrogation should begin, vertical position of waveform on screen and location of cursor on screen.

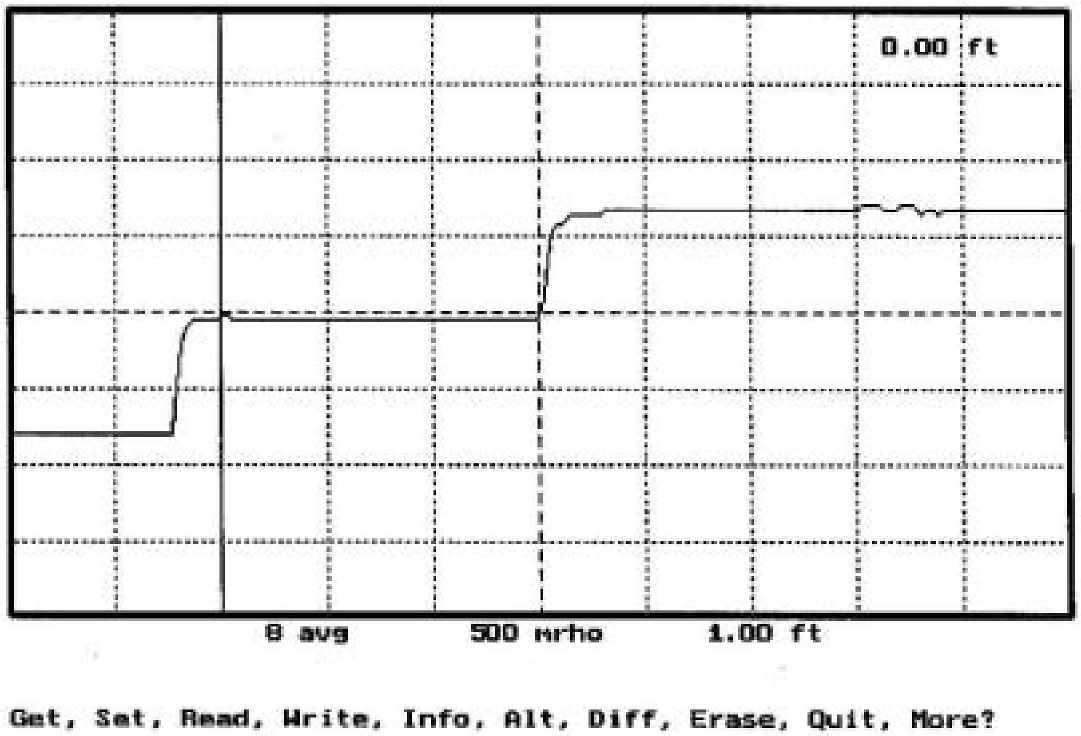
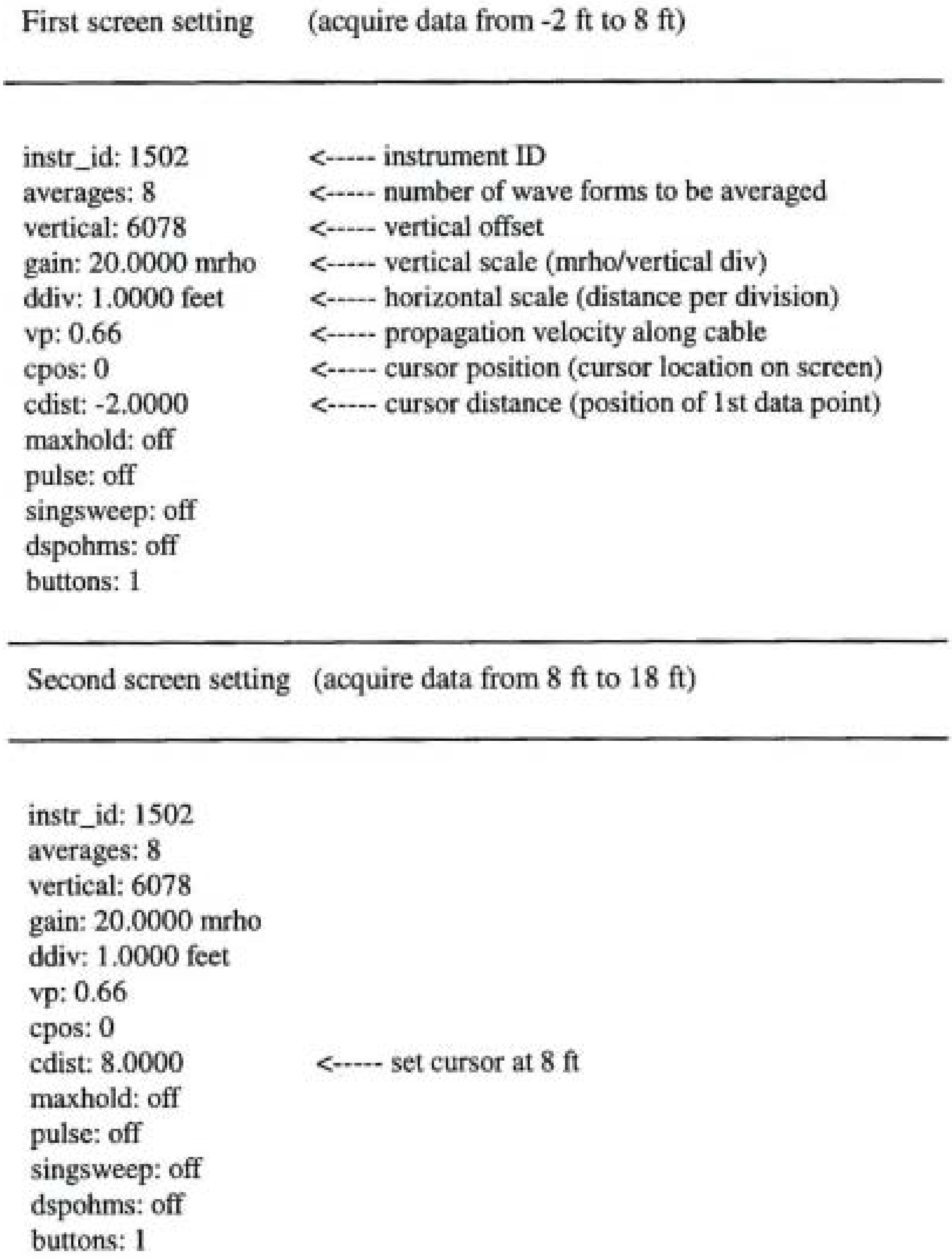


Figure 7-1: SP232 Host application Program screen displaying a waveform (Tektronix, 1989).

The settings file may be saved and modified for several different applications. Figure 7.2 below is an example of settings for the acquisition of the waveform from a 6 m (20 ft) coaxial cable divided into two windows of data: -60 cm (-2ft) to 2.4 m (8ft) and 2.4 m (8ft) to 5.5 m (18ft) (Dowding and O'Connor, 1999). Figure 7.3 displays the first block of data obtained from this cable and those settings. The data block contains 3 parts: a title, the settings, and waveform data under the format of 251values of the reflection coefficient. Use of SP232 allows capture of raw waveform data for any TDR measurement: soil moisture, deformation, water level, etc.

Data interpretation

NUTSA (or TRAP) are software programs for analysis of TDR data, display and comparison of TDR waveforms to identify changes in reflections. NUTSA, which tutorial is also given in Appendix 3 (or TRAP) allows the comparison of up to three TDR waveforms as well as the conversion of raw digital waveform into ASCII files for easy import to Microsoft Excel. The menu window in Figure 7-4 allows the loading of the waveforms displayed in the window shown in Figure 7-5. Many options are available such as the zooming or selection of an area of interest, difference between two waveforms to detect reflection peaks, value of the reflectance at a specific point with the cursor. Figure 7-6 is a list of all the parameters and functions used by NUTSA (or TRAP) and should be very helpful for any user of the software.

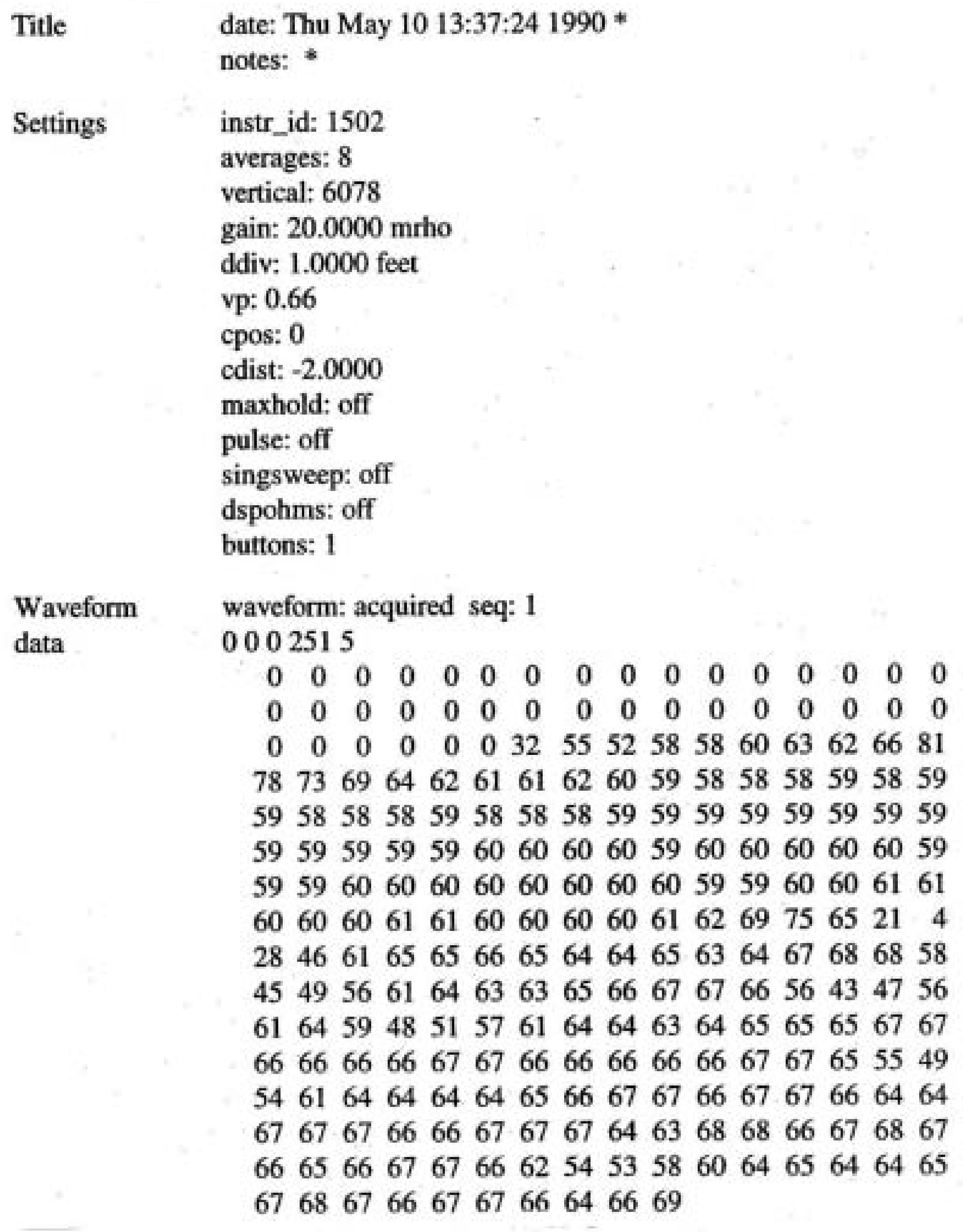


```
First screen setting      (acquire data from -2 ft to 8 ft)
________________________________________________________________

instr_id: 1502            <----- instrument ID
averages: 8               <----- number of wave forms to be averaged
vertical: 6078            <----- vertical offset
gain: 20.0000 mrho        <----- vertical scale (mrho/vertical div)
ddiv: 1.0000 feet         <----- horizontal scale (distance per division)
vp: 0.66                  <----- propagation velocity along cable
cpos: 0                   <----- cursor position (cursor location on screen)
cdist: -2.0000            <----- cursor distance (position of 1st data point)
maxhold: off
pulse: off
singsweep: off
dspohms: off
buttons: 1
________________________________________________________________
Second screen setting     (acquire data from 8 ft to 18 ft)
________________________________________________________________

instr_id: 1502
averages: 8
vertical: 6078
gain: 20.0000 mrho
ddiv: 1.0000 feet
vp: 0.66
cpos: 0
cdist: 8.0000             <----- set cursor at 8 ft
maxhold: off
pulse: off
singsweep: off
dspohms: off
buttons: 1
```

Figure 7-2: SP232 settings file for a 20 ft cable (Dowding and O’Connor, 1999)

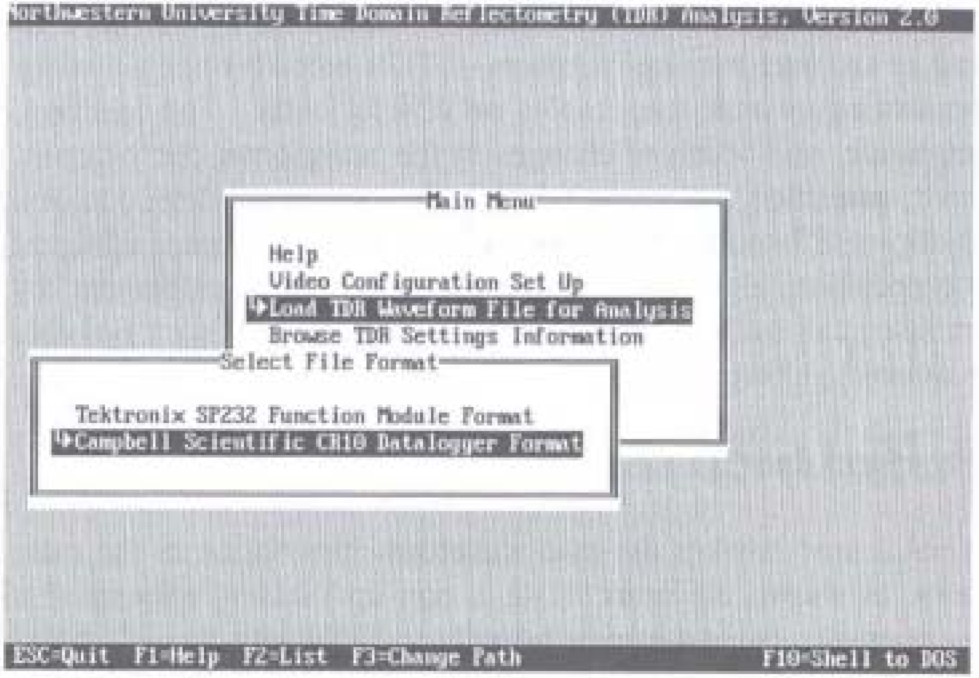


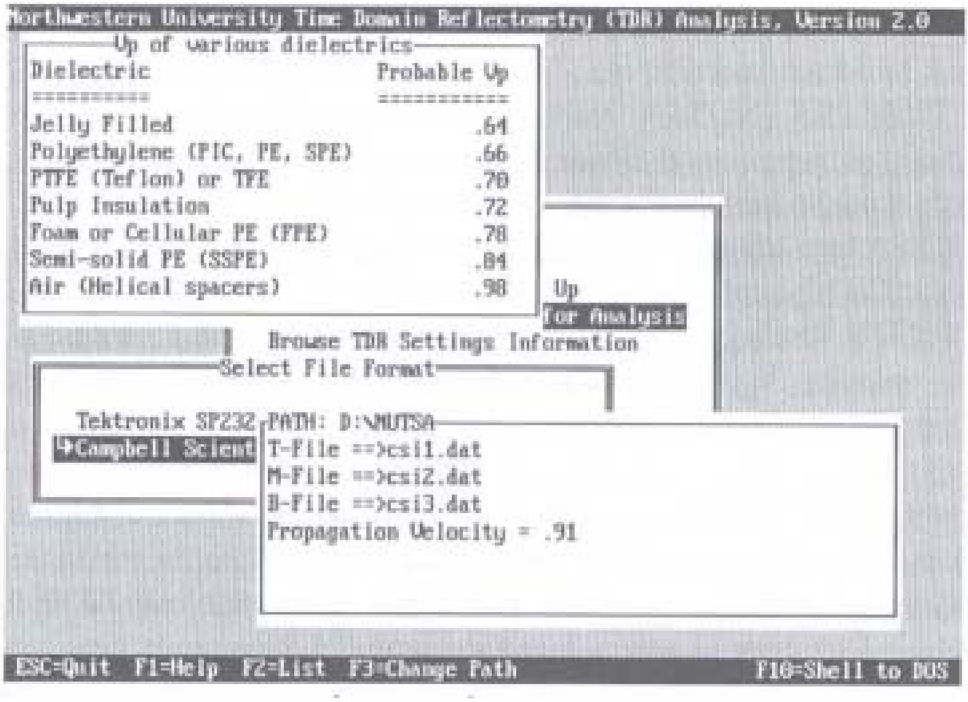
```
Title          date: Thu May 10 13:37:24 1990 *
               notes:  *

Settings       instr_id: 1502
               averages: 8
               vertical: 6078
               gain: 20.0000 mrho
               ddiv: 1.0000 feet
               vp: 0.66
               cpos: 0
               cdist: -2.0000
               maxhold: off
               pulse: off
               singsweep: off
               dspohms: off
               buttons: 1

Waveform       waveform: acquired  seq: 1
data           0 0 0 251 5
                  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
                  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
                  0  0  0  0  0  0 32 55 52 58 58 60 63 62 66 81
                 78 73 69 64 62 61 61 62 60 59 58 58 58 59 58 59
                 59 58 58 58 59 58 58 58 59 59 59 59 59 59 59 59
                 59 59 59 59 59 60 60 60 60 59 60 60 60 60 60 59
                 59 59 60 60 60 60 60 60 60 60 59 59 60 60 61 61
                 60 60 60 61 61 60 60 60 60 61 62 69 75 65 21  4
                 28 46 61 65 65 66 65 64 64 65 63 64 67 68 68 58
                 45 49 56 61 64 63 63 65 66 67 67 66 56 43 47 56
                 61 64 59 48 51 57 61 64 64 63 64 65 65 65 67 67
                 66 66 66 66 67 67 66 66 66 66 66 67 67 65 55 49
                 54 61 64 64 64 64 65 66 67 67 66 67 67 66 64 64
                 67 67 67 66 66 67 67 67 64 63 68 68 66 67 68 67
                 66 65 66 67 67 66 62 54 53 58 60 64 65 64 64 65
                 67 68 67 66 67 67 66 64 66 69
```

Figure 7-3: Output file for first screen for the cable and settings presented upwards (Dowding and O'Connor, 1999).

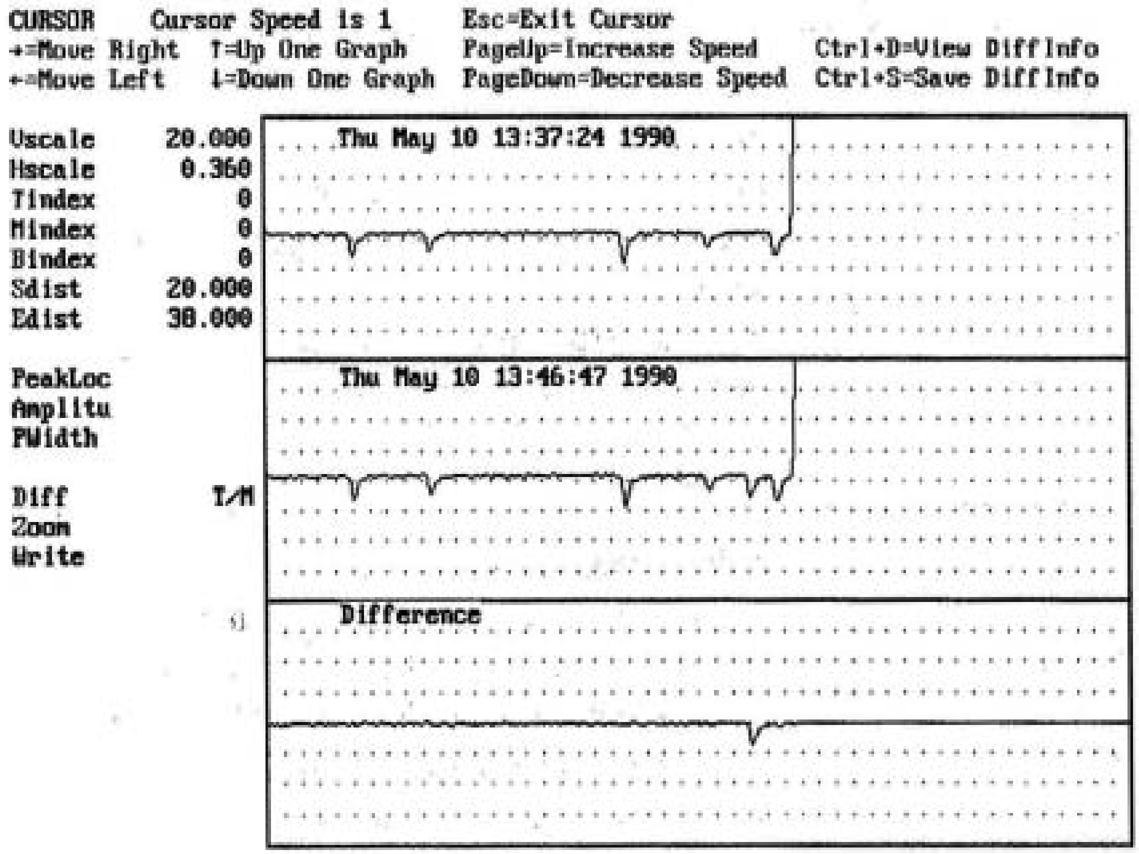




Dielectric	Probable Up
Jelly Filled	.64
Polyethylene (PIC, PE, SPE)	.66
PTFE (Teflon) or TFE	.70
Pulp Insulation	.72
Foam or Cellular PE (FPE)	.78
Semi-solid PE (SSPE)	.84
Air (Helical spacers)	.98

PATH: D:\NUTSA
T-File ==>csi1.dat
M-File ==>csi2.dat
D-File ==>csi3.dat
Propagation Velocity = .91

Figure 7-4: Menu window of NUTSA (TRAP) TDR Data acquisition program (Dowding and O'Connor, 1999).



Vscale 20.000
Hscale 0.360
Tindex 0
Mindex 0
Bindex 0
Sdist 20.000
Edist 30.000

PeakLoc
Amplitu
PWidth

Diff T/M
Zoom
Write

Figure 7-5: NUTSA (TRAP) display window where the difference between two waveforms can be plotted, (Dowding and O'Connor, 1999).

HOT Keys

<ESC>	escape
<F1>	online help
<F2>	write waveform to an ASCII file
<F7>	redraw waveforms after changing display parameters
<F8>	reset to initial display parameters
<F10>	invoke cursor in waveform display

Waveform Display

Vscale	vertical scale (mrho/division)
Hscale	horizontal scale (feet, meters, or arbitrary)
Tindex	vertical position of waveform in top window
Mindex	vertical position of waveform in middle window
Bindex	vertical posisition of waveform in bottom window
Sdist	distance value at start of window
Edist	distance value at end of window
Zoom	invoke option to zoom into a portion of waveform (use cursor to change Sdist and Edist)

Waveform Analysis

Peak Loc	location of cursor
Amplitu	amplitude of waveform at cursor location
Diff	invoke option to calculate the difference between two waveforms
<Ctrl><D>	compute magnitude and width of spike in difference waveform
PWidth	width of spike in difference waveform
<Ctrl><S>	save information about spike in difference waveform
Write	write waveform data to an ASCII file for use use with other spreadsheet and plotting software

Figure 7-6: List of parameters and options used in NUTSA (or TRAP) for TDR waveform analysis (Dowding and O'Connor, 1999).

Automatic waveform acquisition

Data acquisition system

When an installation comprises many TDR cables, a Data Acquisition System (DAS) based on multiplexers, allows simultaneous and autonomous acquisition of signatures for all the cables with only one pulser. If a system has multiple functions like rock/soil shearing, water level or soil moisture monitoring, it can be multiplexed to allow simultaneous monitoring. Low loss lead cables should connect the different TDR probes to a single multiplexer system. The newest multiplexer models like the Campbell Scientific SDMX50 allow measurement of up to 500 TDR probes by using two levels of multiplexing and only require 12 Vdc power. The first level can receive eight, eight channel, multiplexers (i.e. 64 probes) each eventually connected to another eight channel multiplexer (level 2) which increase the capacity to 512 probes. The multiplexer system is connected to a single TDR pulser that is often controlled by a datalogger.

Figure 7-7 below shows equipment involved in a typical DAS installation, comprising a laptop computer equipped with PC208 software (which controls the CR10X datalogger), wiring panel, interface and finally a TDR 100. A datalogger is a programmable control and data storage unit for a multiplexer and a TDR pulser. Two of its main components are the wiring panel shown in detail in Appendix 3, and an external data storage and interface unit. A datalogger is remotely programmable using a support software. It controls scheduled and autonomous interrogation of the cables by the pulser and stores and retrieves obtained data. The most commonly used datalogger is Campbell's CR10 series however PC based dataloggers have been used but have been found to be too fragile.

As shown in Figure 7-7 for a field installation, a laptop polling computer is directly plugged into the datalogger interface and storage device. This is connected to the CR10X datalogger wiring panel, energized by a lead-acid 12V battery or AC power. The datalogger is then linked to the TDR 100 pulser and controls and energizes it. The next level in the installation is connecting the TDR 100 pulser to the eight channel multiplexer. The multiplexer allows the pulser to send both waveform and information to as many as eight cables (in this case), plugged into the multiplexer.

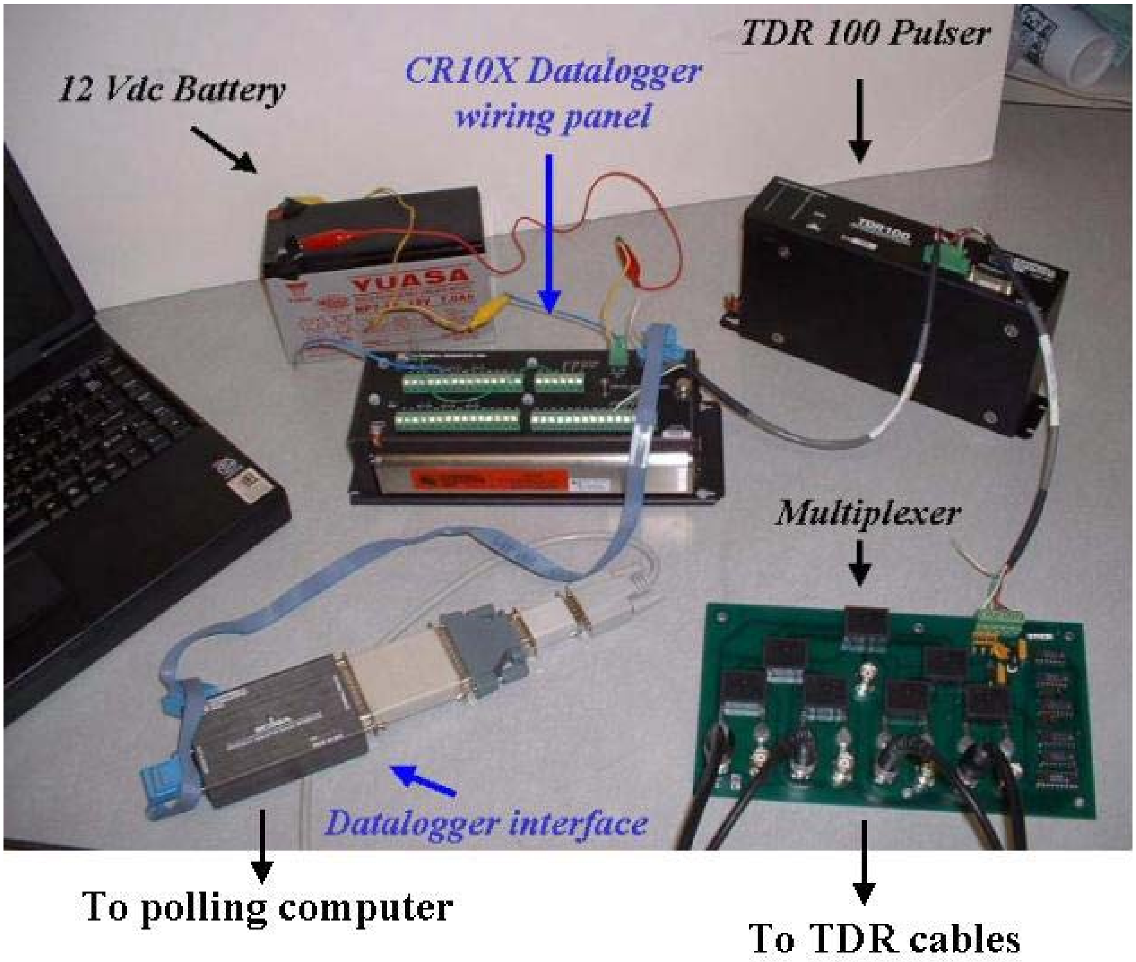


Figure 7-7: Data acquisition system for automated TDR data acquisition composed of a datalogger unit and a multiplexer.

Certain precautions are needed when first using a DAS. First, connections have to be well made: a loose connector can impair waveform transmission. The datalogger’s memory also has to be emptied on a regular basis otherwise new data will overwrite the older. The battery energizing the system has to be recharged before it reaches 75% of its initial charge. If the datalogger doesn’t receive enough power, it can’t communicate with the TDR pulser. Any problem with the DAS will appear in the raw data and the error code –6999 will replace the expected reflection values.

PC208 datalogger control software

Campbell Scientific PC 208 software controls Campbell CR 10 datalogger. It allows also manual or remote operation, continuous data acquisition, logical control, measurement, data processing and data storage. Direct connection, as shown in Figure 7-7, allows manual data acquisition, whereas connection through a modem and a phone line allows automated remote data acquisition.

PC 208 software facilitates programming, communication and exchange of data between a PC and CR10 datalogger. PC 208 is organized around the free-floating toolbar displayed in Figure 7-8, used to launch and control independent windows allowing communication with the datalogger (Setup and Connect), editing of programs with EDLOG (Program), viewing and displaying real-time data (View), retrieving stored data (Stg Modulus) and processing data files with SPLIT (Report).

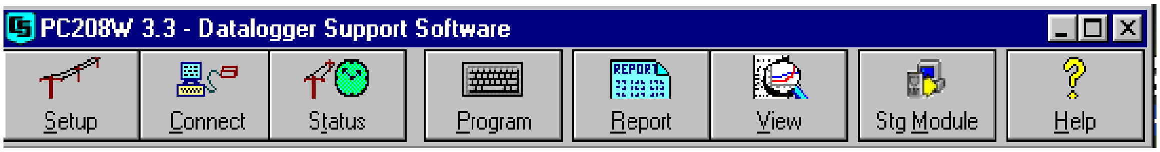


Figure 7-8: CSI PC208 Datalogger Support Software free floating toolbar.

The sequence of operations for the programming of a datalogger and data retrieval are as follows:

Step #1 -- write a datalogger program with EDLOG (Program button on the toolbar)

Step #2 -- configure your communication links with Setup.

Step #3 -- contact and program each datalogger with Connect

Step #4 -- collect data with Connect or Setup | Schedule or SMS (Stg Module button on the toolbar)

Step #5 -- write data reports with Split (Report button on the toolbar) or your own spread sheet program

Step #6 -- if desired, look at data and reports with View

Waveforms collected automatically and continuously by the datalogger have a specific format made of blocks of data presented in rows. A waveform is divided into a defined number of data blocks like for the SP232 format (ie. Tektronix TX 1502 format), but a typical block structure as presented in Figure 7-9 is made of 263 raw data numbers. Each data block, as shown in Figure 7-9, starts with an instrument ID (108 in this case) followed by 11 data values (ending with 53264 here). Julian year, day ,hour-minutes and seconds are times at which the measurement is made. Battery voltage and module temperature are parameters that monitor the datalogger’s voltage and enclosure temperature. The data window number indicates the position of the acquired data block within a series of other blocks acquired when incrementally interrogating a transducer cable. Cursor distance, distance between points and gain control data resolution or density. Offset is the value of the vertical position of the waveform within the window. A detailed tutorial for the PC 208 is given in the software Help menu but some programming issues are worth discussing.

Programming of the datalogger is possible through EDLOG. An EDLOG program has to be written for each site as shown in Appendix 3 and comprises information to control the datalogger operations such as when and how to interrogate TDR cables or Tiltmeters, sequence of data uploading from the polling compute etc.Once an EDLOG .CSI program file is written, it must be compiled by PC208 on the polling computer to check for errors. Program compilation creates DLD, PTI and FSL files from the original .CSI program file. In order to use the program, the DLD file has to be linked with the monitored site by pressing “Connect” and “Associate DLD Program” for the selected site. Once connection is established with the site (press “Connect”), the program must be sent to the datalogger by hitting “Send”. The datalogger will erase its memory, compile the program on its side and send a success or error message back to the polling computer. The operator has to wait for a few minutes until the datalogger reset itself. Then the datalogger is ready to interrogate the instruments and send data to the polling computer. A copy of the program stored into the datalogger can be retrieved by the polling computer by pressing “Retrieve”.

Structure of an EDLOG program

As explained above, the EDLOG program controls Campbell Scientific dataloggers. A new EDLOG program has to be written for each new datalogger. The first step is to create a new EDLOG file and choosing a datalgogger type from the list. Then an execution interval (time in seconds) has to be set before programming. The following step is to press “Edit/Insert instructions” and then enter the required instruction in a logical order.

As shown in Appendix 3, the structure of any EDLOG program is built around 3 tables. Table number 1 begins with the execution interval and followed by the main program. Table 2 can host a second program, but is not usually used. The driver program calls subroutines located in the Table 3. Each sensor has its own subroutine. For example for the DAS setup in Florida where 5 TDR cables are installed there are 5 subroutines, one for each cable.

The driver program is based on instructions. The first instructions given are usually Input/Output instructions such as check battery voltage or temperature. The body of the program consists of control instructions. These instructions allow logic based on time or data and control serial data output and CR10X-initiated telecommunications. The logic controls are called flags and can be set high or low. In other words, the control instructions initiate internal or external actions by launching subroutines. Instructions are made of different parameters that can be set by the user.

All Subroutines are placed in Table number 3. They are a mix of output, control and process instructions. A typical subroutine for TDR measurement performs the following actions in this order: Beginning of subroutine, turn on power to TDR pulser, acquire current waveform, turn off TDR pulser, prepare to send data to datalogger storage device (external or internal), set active storage area, save voltage, temperature and 9 header values plus the waveform’s data points and finally send these data to datalogger’s storage device, end of subroutine.

Changing acquisition parameters

In order to change TDR waveform acquisition parameters, the user has to find in Table number 3 the subroutine corresponding to the sensor. The following acquisition parameters: number of points, cable length, window length and memory output location are located under the TDR measurement instruction for the subroutine. (Instruction P119, or P100 respectively for the TDR 100 pulser or any other pulser) The user can increase the interrogated length or just interrogate a specific window.

To modify the acquisition parameters, the new acquisition distance is set up and the number of data points is calculated by dividing the distance in meters by the desired resolution in meters per point. The new number of data point is inserted in parameter 6, the distance to beginning of interrogated length is inserted in parameter 7 and the new interrogated length is placed in parameter 8. The user has to keep in mind that the maximum number of data points allowed by the CR10X, including the headers, is 2048.

The advantage of the automatic data acquisition is not only that it allows scheduled interrogation of many cables, but it is designed for remote data acquisition via a modem and a phone line. Complex site instrumentation including deformation TDR, water TDR and Tiltmeter can be setup around one data acquisition unit.

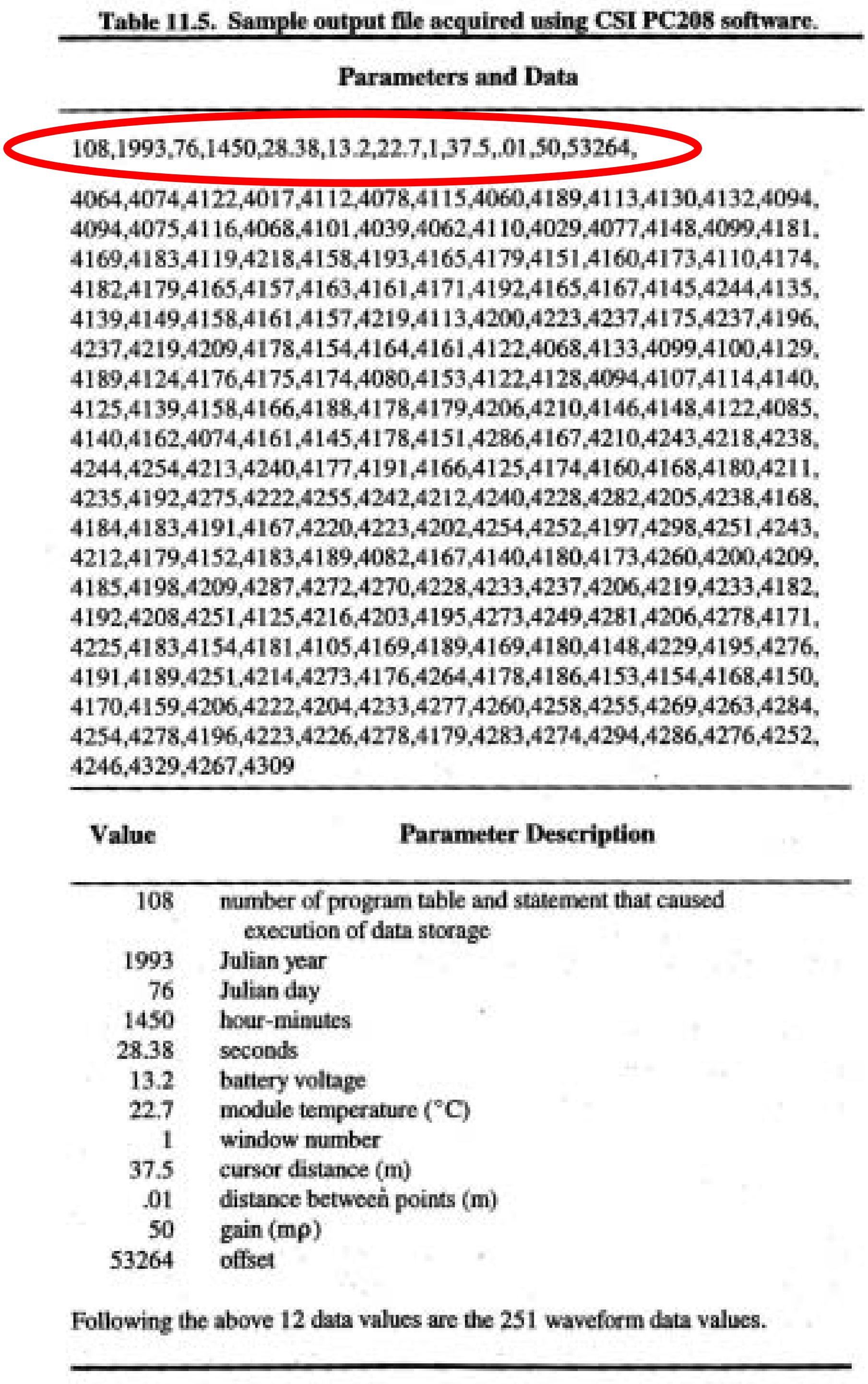


Table 11.5. Sample output file acquired using CSI PC208 software.

Parameters and Data

```
108,1993,76,1450,28.38,13.2,22.7,1,37.5,.01,50,53264,

4064,4074,4122,4017,4112,4078,4115,4060,4189,4113,4130,4132,4094,
4094,4075,4116,4068,4101,4039,4062,4110,4029,4077,4148,4099,4181,
4169,4183,4119,4218,4158,4193,4165,4179,4151,4160,4173,4110,4174,
4182,4179,4165,4157,4163,4161,4171,4192,4165,4167,4145,4244,4135,
4139,4149,4158,4161,4157,4219,4113,4200,4223,4237,4175,4237,4196,
4237,4219,4209,4178,4154,4164,4161,4122,4068,4133,4099,4100,4129,
4189,4124,4176,4175,4174,4080,4153,4122,4128,4094,4107,4114,4140,
4125,4139,4158,4166,4188,4178,4179,4206,4210,4146,4148,4122,4085,
4140,4162,4074,4161,4145,4178,4151,4286,4167,4210,4243,4218,4238,
4244,4254,4213,4240,4177,4191,4166,4125,4174,4160,4168,4180,4211,
4235,4192,4275,4222,4255,4242,4212,4240,4228,4282,4205,4238,4168,
4184,4183,4191,4167,4220,4223,4202,4254,4252,4197,4298,4251,4243,
4212,4179,4152,4183,4189,4082,4167,4140,4180,4173,4260,4200,4209,
4185,4198,4209,4287,4272,4270,4228,4233,4237,4206,4219,4233,4182,
4192,4208,4251,4125,4216,4203,4195,4273,4249,4281,4206,4278,4171,
4225,4183,4154,4181,4105,4169,4189,4169,4180,4148,4229,4195,4276,
4191,4189,4251,4214,4273,4176,4264,4178,4186,4153,4154,4168,4150,
4170,4159,4206,4222,4204,4233,4277,4260,4258,4255,4269,4263,4284,
4254,4278,4196,4223,4226,4278,4179,4283,4274,4294,4286,4276,4252,
4246,4329,4267,4309
```

Value	**Parameter Description**
108	number of program table and statement that caused execution of data storage
1993	Julian year
76	Julian day
1450	hour-minutes
28.38	seconds
13.2	battery voltage
22.7	module temperature (°C)
1	window number
37.5	cursor distance (m)
.01	distance between points (m)
50	gain (mρ)
53264	offset

Following the above 12 data values are the 251 waveform data values.

Figure 7-9: Sample raw data file acquired using CSI PC208 software (Dowding and O'Connor, 1999)

7.2 Real time monitoring

This section describes the architecture of the real-time monitoring system. It will first concentrate on the system installed in the field and then on the polling and display side of the system.

Real-time monitoring of soil deformation using TDR - Field equipment

General architecture

Real time, remote, autonomous TDR data acquisition is based on the acquisition system discussed above. It comprises a datalogger which controls a digital TDR pulser and stores the data and a multiplexer to allow multiple instruments interrogation. Power still has to be brought to the datalogger and TDR pulser. In addition to this system, communication equipment has to be added to provide the link with the polling computer.

The communication equipment will allow a polling computer equipped with PC 208 to remotely control the datalogger, program it and download the data stored in its memory. A phone modem connected to a phone line provides the best link between the polling computer and the site. While the labs or offices where polling computers are located, always have telephone jacks and a controlled environment, the conditions in the field can be different and three modem based communication devices have been developed for field use.

Communication equipment

The first two communication systems used are a regular telephone line with a modem or a cell phone together with a cellular modem. New cellular digital modems using Cellular Digital Packet Data (CDPD) technology can also be found. We can mention satellite and ULF communication for extremely remote places, but they are more expensive. The choice criterion for the communication system is the proximity of adequate infrastructure.

A regular phone line connected to a landline modem is at this time the most reliable and efficient communication system to speak with a datalogger. It has been used with success in Cambridge Ohio and Sulfur, Indiana. Two Campbell landline modems can be used with a regular phone line: the COM 210 Telephone Modem and the COM 300 Voice Synthesizer / Phone Modem. The use of Campbell modems is dictated by the excellent compatibility between this equipment and the CR10 series dataloggers. These modems operate at 9600 bits per seconds and can work in adverse weather conditions. They enable a PC with a Hayes-compatible modem to contact the datalogger at any time.

As shown in Figure 7-10, if no phone line can be brought to the site, a cell phone can be installed to allow remote communication with the datalogger. If TDR probes are installed in relatively remote places, the system is limited in terms of data transmission. The basic system is based on Campbell’s Analog Cellular telephone package Model COM 100. This package is made of three parts. First, the phone package comprising a Motorola AMPS cellular connection transceiver, RJ11C interface, coaxial antenna cable with male mini-UHF and male type “N” connectors and power control cable with a built-in Crydom relay. The second part is the COM 200 built-in modem or CSI voice synthesizer modem. The third part of the system is the Yagi ASP 962 8 dB antenna.

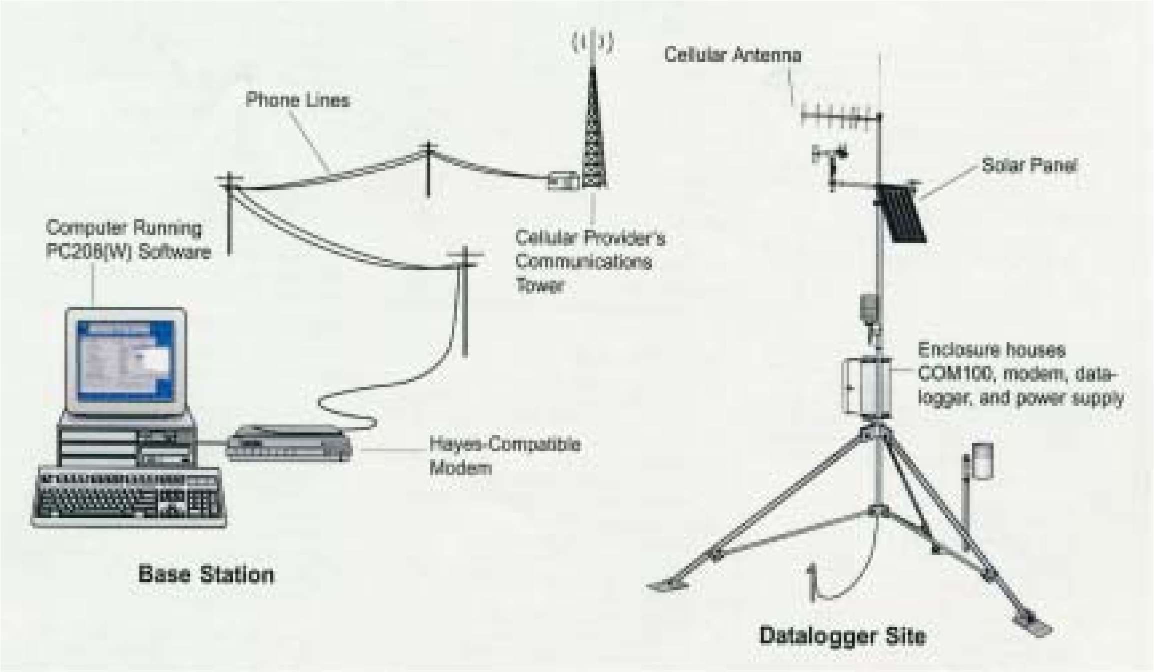


Figure 7-10: Typical cell phone communication system for a Campbell datalogger. (Campbell Scientific, 2002)

The analog cellular telephone package has limitations for data transfer. First, the bandwidth is limited to 4800 bps and thus, reduces the reliability of data transmission. It also cannot work close to heavy construction sites, tunnels or power lines. Cellular coverage of the instrumented site may be poor or cellular traffic congestion can also impeach the automated data retrieval. The final issue concerns the high demand in energy of the cell phone, often powered by solar panel recharged batteries.

In order to reduce the problems of cell phone data transmission, a few things can be done. First, one has to be sure that the cell phone yagi antenna is accurately aimed at the provider's closest cell phone tower and that no topographic obstacle hides it.

However, little can be done to really improve the quality of communication, except using the most appropriate settings for cellular communication on the polling computer's modem. A recommended modem for cellular communication is the paradyne Comsphere 3810 modem In order to save power, the datalogger can also be programmed to turn the cell phone on at predermined time slots to allow remote interrogation.

An alternate to analog cellular modems, one can use cellular digital technology. Campbell Scientific offers a CDPD modem compatible with its datalogger: the Redwing 2 CDPD Cellular Digital Modem manufactured by Airlink Inc. CDPD modems communicate via a cellular network able to transmit data to an IP address. The service provider must assign an IP address where data from the datalogger will be transferred. The polling computer will be able to extract the data through an FTP protocol. The transmission rate is high (19.2 Kbbs) and it avoids any problem due to dialing. The operator also pays for data throughput instead of air time and avoids long distance fees. However, the CDPD network coverage is not as good as regular GMS network coverage.

An alternate solution to cell phone communication when instrumenting a remote site is point to point communication. A point to point communication device can be directly connected via a RS 232 jack to a CR10 X datalogger. At the other end, another point to point communication device is connected to a modem plugged into an active telephone jack, on a telephone pole for example. The two point to point devices have to be within sight distance. (32 Km-20 miles) This system has been used previously by ITI and proved robust and reliable.

Real-time monitoring of soil deformation using TDR - Lab equipment

Polling computer

The polling computer has a dual role. It retrieves data from the datalogger memory and also controls it. Commonly used polling computers are PC's with a Windows operating system. The polling computer currently used at ITI runs an AMD K6 3D processor and Windows 2000. It communicates through an Hayes External V92 Voice fax Modem. It is also equipped with Campbell Scientific's PC 208 software. This software is fully Windows compatible except for Windows Millennium Edition. Data can be displayed in real time on the polling computer, but the solution chosen at ITI is to send them on the server where the TDR website is located. Thus, the polling computer is connected to the local network to allow data transfer to the server through File Transfer Protocol.

In a fully autonomous mode, the polling computer works on its own. The polling computer and PC 208 must be always turned on. The user should never forget to hit the "Schedule On" box in the "Setup" window. At the scheduled times, the computer will call the site, run the downloading program and retrieve data automatically and save them on the hard drive.

Server

To display TDR waveform in real time, one can to post data on a dedicated web site. The data are retrieved from the polling computer to the server which hosts the website. The server which equips ITI's lab is a Dell Power Edge 2500 with Windows 2000/IBM DB2 and Apache HTTP Server, Version 1.3.26. A home made java based software called IRMS (Infrastructure Remote Monitoring Software, Kosnik and Kotowski, 2002) retrieve data through an FTP connection with the polling computer and display them at the following address: http://www.iti.northwestern.edu/tdr/operational.

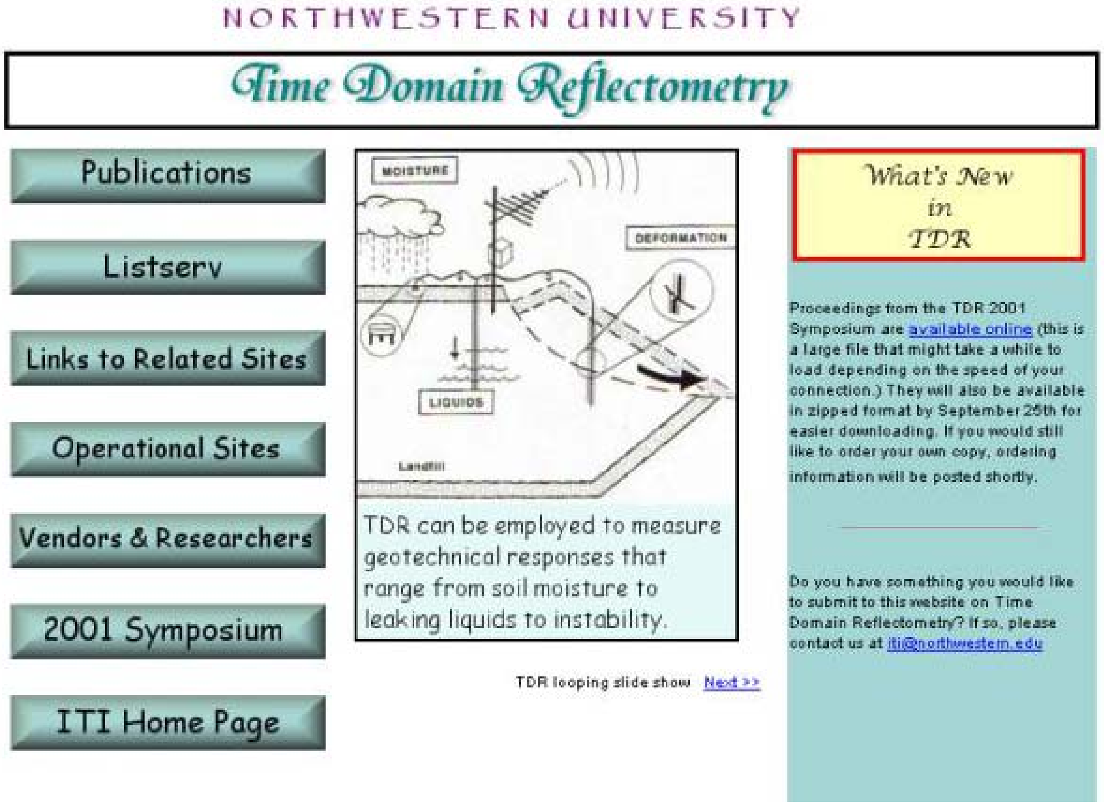
The software is organized around four Java Packages called iti.graph, iti.util, iti.acm and iti.tdr. The iti.graph package encapsulates all the common graphing functions. It allows the dynamic generation of images of the waveforms that the user's web browser understands as a simple GIF image that can be bookmarked. This package generates time histories of the data and plots of parametric data for Tiltmeter readings for example. The iti.util package is a support for the graphical package. iti.acm is a specific package for the autonomous crack monitoring data, and iti.tdr is specific for TDR waveforms.

The IRMS allows the display in real time of all kind of dynamic data under static GIF format. It allows an outside user like a DOT engineer to follow from his desktop at home equipped with a slow modem connection, the evolution of deformation below a bridge for example. A whole range of modifications can be made to the way data are displayed without recompiling the program. By modifying the software's properties files, one can quickly and easily modify the X or Y scale of the plots or zoom on a zone of interest.

7.3 Web display of TDR waveforms

Structure of the TDR website

The TDR website is located inside Northwestern University ITI's website. As shown in Figure 7-11, this website offers free recent publications about TDR technology, links to TDR related websites such as Campbell scientific website, an exhaustive list of vendors and researchers, minutes of the 2001 TDR symposium held at Northwestern University. But the main use of this website is to display realtime TDR and Tiltmeter waveform from 3 operational sites instrumented together by Northwestern and GeoTDR Inc.



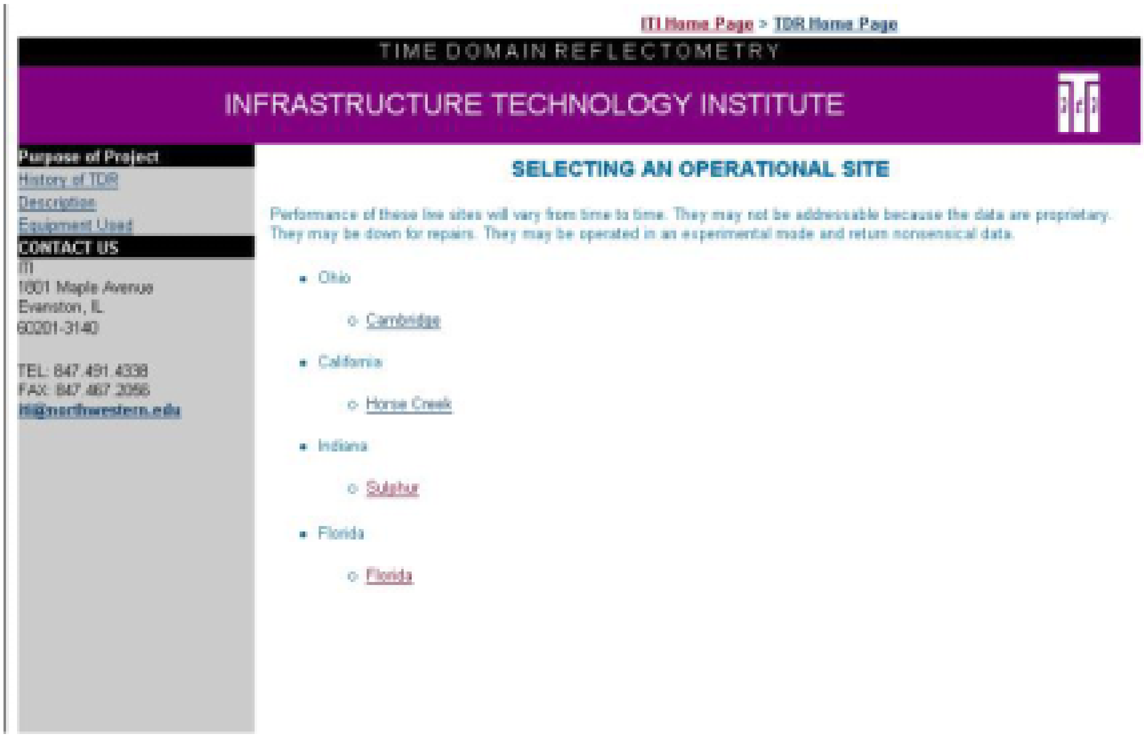
TDR can be employed to measure geotechnical responses that range from soil moisture to leaking liquids to instability.

Proceedings from the TDR 2001 Symposium are available online (this is a large file that might take a while to load depending on the speed of your connection.) They will also be available in zipped format by September 25th for easier downloading. If you would still like to order your own copy, ordering information will be posted shortly.

Do you have something you would like to submit to this website on Time Domain Reflectometry? If so, please contact us at iti@northwestern.edu

Figure 7-11: Printed screen of the TDR website "Home Page". (http://www.iti.nwu.edu/tdr)

As shown in Figure 7-12, the Operational Site page offers different options. The user can either learn about TDR technology or choose to view real time data from three operational sites: Ohio, Indiana or Florida. The site in California is no longer operational but may be reequipped soon for real time monitoring. All the other sites offer deformation TDR data. Indiana and Florida offer also Tiltmeter data whereas Florida only displays water TDR data.



SELECTING AN OPERATIONAL SITE

Performance of these live sites will vary from time to time. They may not be addressable because the data are proprietary. They may be down for repairs. They may be operated in an experimental mode and return nonsensical data.

- Ohio
  - Cambridge
- California
  - Horse Creek
- Indiana
  - Sulphur
- Florida
  - Florida

Figure 7-12: printed screen of the "Operational Site" page of ITI's TDR website.

Example of web display, Sulfur, Indiana

The Indiana site was choosen to illustrate the waveform display because it's a simple but complete example. As shown in Figure 7-13, the viewer has 4 options: "Static site information" like project background, "Dynamic site information" like current weather or stream flow at the site. The last two choices are "Monitored data" and "Archived data". Under Monitored data, one can see the latest deformation or water TDR waveform compared with a reference waveform and also an up to data time history of Tiltmeter together with temperature readings to see the influence of the former on the latter. Under Archived data, one can select the waveform acquired at a certain date and see the raw data as well as the area of interest.

TIME DOMAIN REFLECTOMETRY - SULPHUR

INFRASTRUCTURE TECHNOLOGY INSTITUTE

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
Archived Data
View by Date
CONTACT US
ITI
1801 Maple Avenue
Evanston, IL
60201-3140

TEL: 847 491 4338
FAX: 847 467 2056
iti@northwestern.edu

SULPHUR, IN

How to Navigate this Site

The different types of information are available by clicking on the toolbar at left. For example, by clicking one of the links under "Static Site Info" you can read about the purpose of the project, see a map of the site, and view pictures of the structure being monitored.

Figure 7-13: Printed screen of the home page for the Indiana site on ITI's TDR website.

As shown in Figure 7-14, the waveforms plotted under Displacement TDR are just the portion of the waveform corresponding to the sensor TDR cable, without its connecting lead cables. Restriction of the length of the cable signature displayed allows a better resolution of the area where deformations are expected. As shown in Figure 7-15, the entire waveform, taken from the pulser to the very end reflection of the cable is displayed in Archived data. As shown in Figure 7-16, tiltmeter data are plotted as time histories and often compared with temperature data.

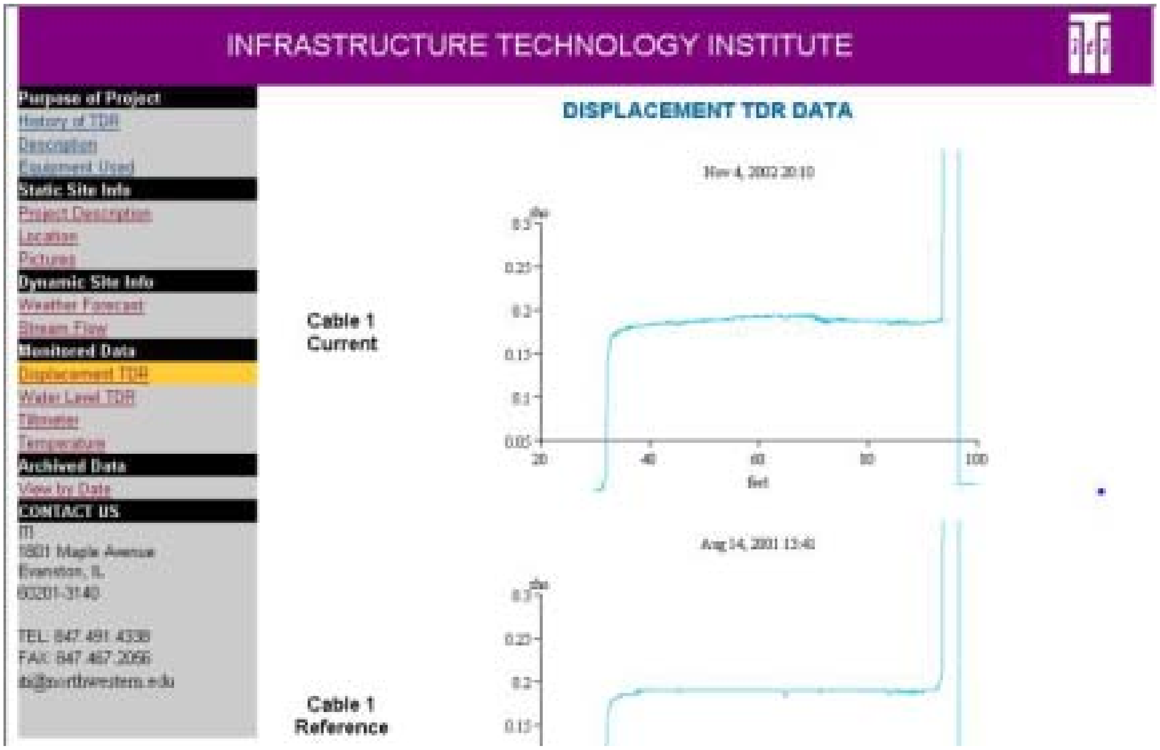
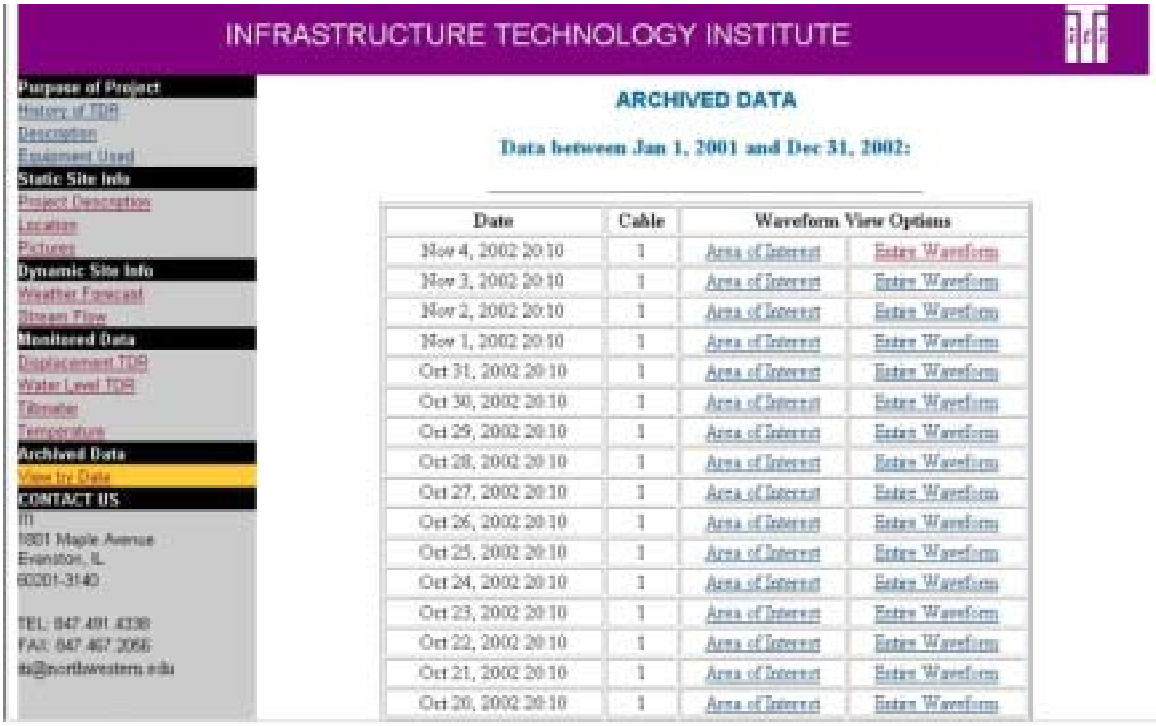


Figure 7-14: Comparison of current deformation TDR waveforms with a reference waveform for Sulfur, Indiana on ITI's TDR website.



ARCHIVED DATA

Data between Jan 1, 2001 and Dec 31, 2002:

Date	Cable	Waveform View Options	
Nov 4, 2002 20:10	1	Area of Interest	Entire Waveform
Nov 3, 2002 20:10	1	Area of Interest	Entire Waveform
Nov 2, 2002 20:10	1	Area of Interest	Entire Waveform
Nov 1, 2002 20:10	1	Area of Interest	Entire Waveform
Oct 31, 2002 20:10	1	Area of Interest	Entire Waveform
Oct 30, 2002 20:10	1	Area of Interest	Entire Waveform
Oct 29, 2002 20:10	1	Area of Interest	Entire Waveform
Oct 28, 2002 20:10	1	Area of Interest	Entire Waveform
Oct 27, 2002 20:10	1	Area of Interest	Entire Waveform
Oct 26, 2002 20:10	1	Area of Interest	Entire Waveform
Oct 25, 2002 20:10	1	Area of Interest	Entire Waveform
Oct 24, 2002 20:10	1	Area of Interest	Entire Waveform
Oct 23, 2002 20:10	1	Area of Interest	Entire Waveform
Oct 22, 2002 20:10	1	Area of Interest	Entire Waveform
Oct 21, 2002 20:10	1	Area of Interest	Entire Waveform
Oct 20, 2002 20:10	1	Area of Interest	Entire Waveform

Figure 7-15: View of the Achieved data page on ITI's TDR website.

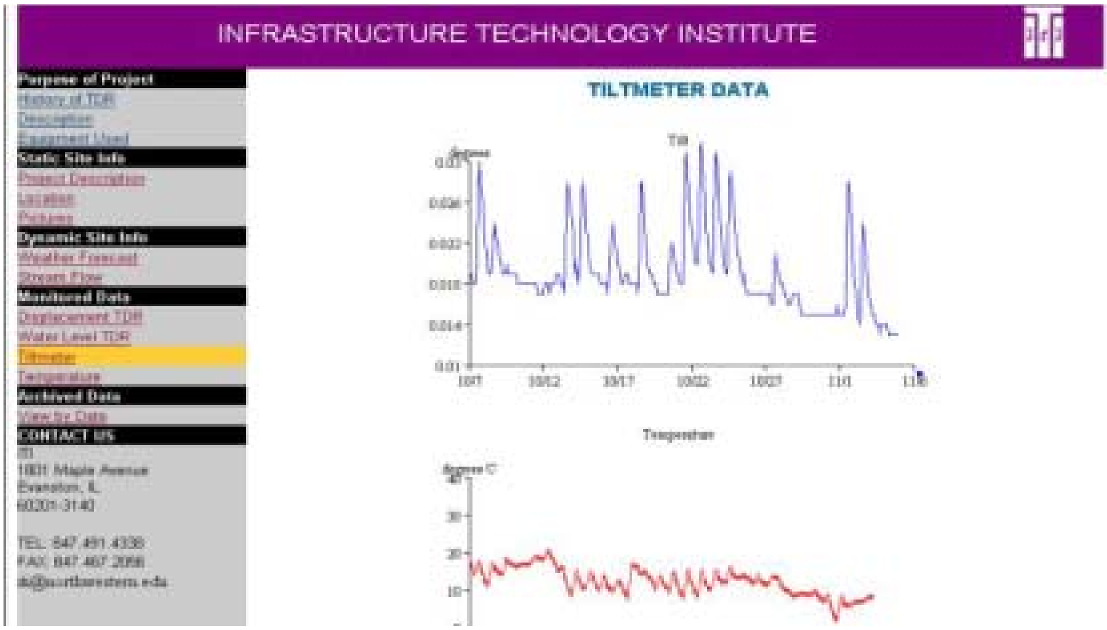


Figure 7-16: Comparison between current tilt angle and temperature variation for Sulfur, Indiana on ITI’s TDR website.

Chapter conclusion

Waveform acquisition can be realized either manually by directing connecting a tester to the TDR probes or automatically with a Data Acquisition System based on datalogger and multiplexer. The automated data acquisition is particularly useful when many different systems monitor deformation, ground water level or tilt angle or when the site is too remote for frequent access. In that case, the data acquisition system can be linked to a modem and a communication device in order to transmit retreived data to a remote polling computer. This remote monitoring opens the door to real time display of the waveforms on a dedicated web site. Such a system allow an unlimited number of users of the monitoring system to check deformation data in real time from their personal computer.

Chapter 8

Conclusion and Recommendations

This thesis has presented Time Domain Reflectometry (TDR) cable technology applied to monitor soil deformation in nine installations. Each case history includes description of project geometry, cables employed, grout placement, drilling considerations, as well as typical TDR reflection responses. Instrumentation necessary to acquire data manually or remotely is described in sufficient detail to support installation by others. Summarizing of these case histories allowed the development of the “best practice” guidelines that follow. They are divided into two groups: cable installation and data acquisition.

While use of TDR technology has grown rapidly in rock where it can be deployed easily, more care is required in soil because of the differences in stiffness and the degree of localization of deformation. These and related differences produce several overarching considerations for “best practice”. First, in soft soils the grout must be strong enough to deform the cable, yet weak enough so as not to deform the soil around the grouted hole. Second, softer cables can be built from commercially available components that will enhance cable reflection in soft soil with sufficiently weak grouts. Third and last, to maximize cable response to local shearing, cables should be installed in their own hole and not strapped to the outside of Slope Inclinometer casing.

8.1 Cable installation

1. A TDR cables must be installed in a separate hole. Strapping flexible cables to Slope Inclinometer (SI) casing degrades TDR sensitivity. Shearing response is reduced by the stiffening provided by the grouted SI casing.

2. Installation with hollow stem augers leads to degradation of response through two mechanisms: significant grout losses and disturbance resulting upon removal of the auger. Slumping of the grout into the hole void reduces the length of possible shear band detection in and above these zones. Extra grout should be available to stabilize the volume extracted with the auger.

3. Use of TDR cables in soft soil requires special cement-bentonite grout mixes (with prehydrated bentonite), which should be carefully designed to match the soil properties. It must not be too stiff so as to enlarge the shear zone through local failure but it must be stiff enough to shear the cable.

4. Relatively stiff cable can be installed with strong/stiff grouts in rock because of the localization of rock mass deformation at joints in the stiff rock matrix.

5. Bentonite grouts easily pumped by drilling rig water pumps are prepared by adding fluidizing agents such as Intrusion Aid Type R. The fluidity of the cement-bentonite mix will have to be demonstrated to the drilling crew who may not wish to pump it for fear of blocking their drilling equipment.

6. Before cable insertion, the bottom end tip of a cable should be properly sealed to prevent intrusion of water between the inner and outer conductor. Cable insertion is also facilitated by either, attaching a plastic cone to the cable tip to be pushed down the hole

end with a flush coupled PVC grout pipe or by fitting the down-hole end of the cable with a PVC or steel pipe as a stiffener/penetration load.

7. Miscellaneous recommendations include making orientation crimps just before lowering the cable to avoid accidental kincking at the crimp and ensuring up hole connectors are moisture proofed and placed in a locked protective cover.

8.2 TDR data acquisition

1. If cables are interrogated manually with a Tektronix 1502 cable tester, it should be equipped with SP 232 module to acquire digital records for precise comparison.

2. Connections between different component cables (ie transmission and transducer cables) are a weak link and should be made as robust and water proof as possible.

3. Long connecting cables should be of the low loss, 75 Ohm variety. The often employed standard 50 Ohm connecting cables have to be kept as short as possible (<50 m, 160 ft) to minimize losses.

4. Automated surveillance from a remote polling computer as well as callback alarm notification have been successfully implemented with hard wire connections.

5. Real-time posting of TDR waveforms on the internet has been successfully implemented for monitoring deformation of multiple cables on a daily basis from multiple locations.

6. PC based data acquisition systems with off-the-shelf components should be avoided because of integration problems. Already integrated systems should be employed such as those based on Campbell Scientific Inc dataloggers.

7. Hard-wired phone and power lines are preferable at this time to cell phone connection or solar power for TDR operation. However, several truly remote operations have been successfully installed with radio connection.

8. Tiltmeters and TDR cables can be interrogated together through the use of a multiplexer.

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http://www.tektronix.com/

Will, D.M. (1996), “Cement Bentonite Grouts Compatible with Compliant TDR Cables”, M.S. Thesis, *Department of Civil and Environmental Engineering*, *Northwestern University*, *Evanston*, IL, USA.

Appendix 1

List of Hardware and Tools for S.R. 62, Indiana.

Deformation Monitoring Cable

CommScope 7/8 in. foam dielectric solid aluminum coaxial cable (P3-75-875 JCA)

Gilbert Engineering F-type connector and 90 degree coupling

Metallic primer spray

Belden RG8 Lead cable (8214)

Grout

Quikrete Portland cement

Specrete-IP, Inc Intrusion Aid type R

Baroid Quick-Gel bentonite

Tools and cable tester

Cablematic coring and stripping tool (CST 875 R)

Tektronix 1502C cable tester with SP 232 serial communication module and software

Manufacturers and Suppliers

CommScope, Inc, P.O. Box 1729, Hickory, NC 28603-1729

(800) 982-1708, www.commscope.com

Gilbert Engineering, 5310 Camelback, Glendale, AZ 85301-7597

Belden Wire and Cable, P.O. Box 1980, Richmond, In 47375, www.belden.com

Quikrete, Atlanta, GA

(404) 634-9100, www.quikrete.com

Baroid Drilling Fluids, Inc., 3120 SW Freeway, Suite 300, Houston, TX 77098

(713) 620-7100, www.Baroid.com

Specrete-IP, Inc., 10703 Quebec Avenue, Cleveland OH 44106

(216) 721-2050

List of Hardware and Tools for Clark landfill, Indiana.

Deformation Monitoring Cable

CommScope 7/8 in. foam dielectric solid aluminum coaxial cable (P3-75-875 JCA)

Gilbert Engineering N-type connector

Grout and cable plug anchor

EPCO mini plastic plug

Portland Type I cement

Specrete IC Intrusion Aid Type R

Tools and cable tester

Cablematic coring and stripping tool (CST 875 R)

Tektronix 1502C cable tester with SP 232 serial communication module and software

List of Hardware and Tools for S.R. 64, Indiana.

Deformation Monitoring Cable

CommScope 7/8 in. foam dielectric solid aluminum coaxial cable (P3-75-875 JCA)

Gilbert Engineering F-type connector

Metallic primer spray

rubberized undercoat spray

Grout

Portland Type I cement

Specrete-IP, Inc Intrusion Aid type R

Tools and cable tester

Cablematic coring and stripping tool (CST 875 R)

Tektronix 1502C cable tester with strip chart recorder and SP 232 serial communication module and software (later)

Appendix 2

Pictures of TDR hole Drilling

Rotary drilling of TDR hole under bentonite slurry

Close up on a hollow stem auger, drilling in soft Chicago clays

Casing removal for TDR hole drilling

Grout mixing and pumping into a TDR hole

Flexible cable insertion with a cone attached to it and pushed down with a PVC pipe

Above ground TDR cable after installation

TDR cable equipped with a GRS F type connector and a lead cable for interrogation

Sealed PVC casing protecting a TDR connector

Appendix 3

Analyze TDR Waveforms with NUTSA

When the user highlights “Analyze TDR Waveforms”, and presses enter, the program plots the TDR Waveforms from the files previously imputed. If no files have been opened, the program displays “no data to view”.

After the program reads the data, the plots are shown on the screen. The program can only analyze and plot 3 TDR waveforms that are displayed in three large windows on the right.

At the top of the windows, information for the function keys is displayed. (<Esc>, <F1>, <F2>, <F7>, <F8>, <F10>)

<Esc> to go back to the main menu

<F1> to go to the Help section

<F2> to save the plots on the hard disk

<F7> to redraw the plot after every modification

<F8> to restart the program

<F10> to use the cursor that gives the peak location on the X axis (in graphical units) and the amplitude of the signal (in Millirhos)

The menu window along the left side of the screen is used to change display parameter values and to invoke plot options.

If the cable is long, the resolution of the screen does not enable us to see all the small pikes along the waveform. The TRAP program provides two approaches.

The user can either run the <Vscale> and <Hscale > options to magnify the Vertical or Horizontal scale. The user has to highlight the option, press <Enter> and choose the scale.

To select a specific location of interest, the user can highlight <Sdist> to specify the first point of interest and <Edist> to specify the end point.

By selecting the <Zoom> option, one can specify an interval of interest with the cursor. This option is very similar to the <Sdist> and <Edist> commands.

The user will not forget to press <F7> to redraw the plots after each modification.

In order to modify the vertical position of the waveform in the original window, the user can choose <Tindex>, <Mindex> or <Bindex>. (T, M, B refer to the top, middle or bottom plots) and enter the desired value.

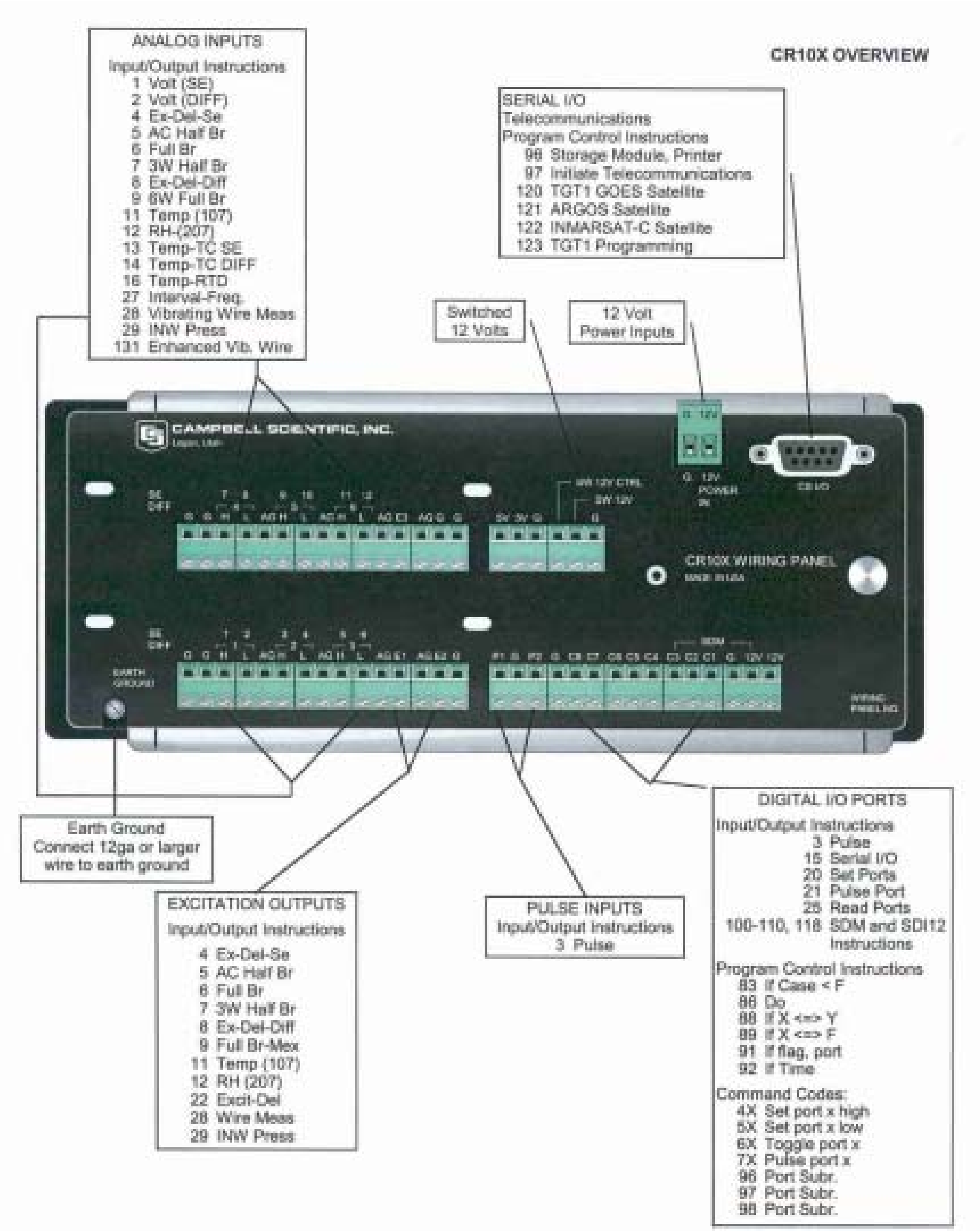
In order to compare the waveforms, one can highlight <Diff>.

The program will prompt the user to “enter waveform difference desired, T/M, T/B, M/B”

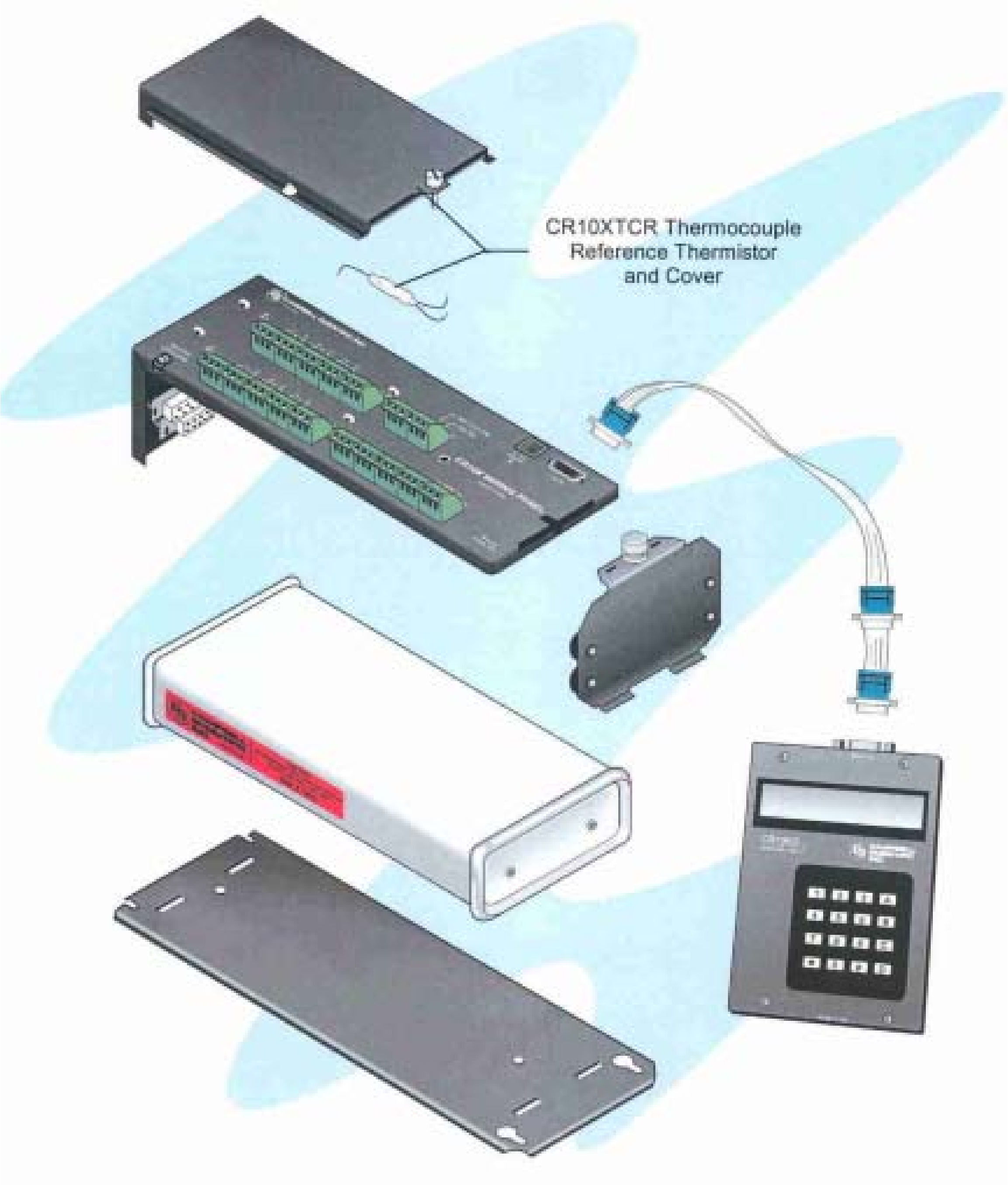
The program will then compute an arithmetic difference between the first and the second waveform selected. The result will be displayed in the window that is not used.

To save the plots on the disk, the user can select <Write> and give a name to the file.

Different views of Campbell's CR10 X datalogger



View of the CR10X wiring panel. (Campbell Scientific, 2000)



Different components of CSI’s CR10X Datalogger (Campbell, 2000).

Extract from TDR acquisition program for CR10X

```
;{CR10X}
;*********************************************************************
;*********************************************************************
;*********************************************************************
; Extract from the Program for acquiring tiltmeter and TDR data along
; SR66 west of Sebring, Highlands County, Florida
;
;
;
;   Table 1  Driver Program for Tiltmeters and TDR cables
;
;   Subroutine 1  interrogate TDR cable on Multiplexer Ch. 1
;   Subroutine 2  interrogate TDR cable on Multiplexer Ch. 2
;   Subroutine 3  interrogate TDR cable on Multiplexer Ch. 3
;   Subroutine 4  interrogate TDR cable on Multiplexer Ch. 4
;   Subroutine 5  interrogate TDR cable on Multiplexer Ch. 5
;   Subroutine 6  acquire tiltmeter data
;   Subroutine 7  compare tilt values with alarm level
;
; Port use
;             Port 1  TDR/SDMX50 data
;             Port 2  TDR/SDMX50 data
;             Port 3  TDR/SDMX50 data
;             Port 4  Tektronix 1502B cable tester power control
;             Port 5
;             Port 7  Tiltmeter multiplexer control
;             Port 8  Tiltmeter multiplexer control
;             Port 3H,3L   Tiltmeter X-axis
;             Port 4H,4L   Tiltmeter Y-axis
;             Port 5H  Tiltmeter temperature
;             Port 5L  Tiltmeter signal ground
;
; Flag use
;             Flag 0  output to final storage
;             Flag 1  toggle TDR subroutine 1
;             Flag 2  toggle TDR subroutine 2
;             Flag 3  toggle TDR subroutine 3
;             Flag 4  toggle TDR subroutine 4
;             Flag 5  toggle TDR subroutine 5
;             Flag 6  toggle tiltmeter subroutine
;
;
;*********************************************************************
;*********************************************************************
;*********************************************************************
```

```
*Table 1 Program
  01: 30        Execution Interval (seconds)
;execute every 30 seconds
;----------------------------------------------------------------------
;  Main Program to Monitor Tiltmeters and
;                  Interrogate Coaxial Cables using TDR
;----------------------------------------------------------------------

;.......................................
; store battery voltage
;.......................................

1:  Batt Voltage (P10)
 1: 1        Loc [ batt      ]


;...........................................
; Automatically acquire Tiltmeter data
;...........................................

2:  If time is (P92) ;check tiltmeters once every 5min into each hour
 1: 0        Minutes (Seconds --) into a
 2: 120      Interval (same units as above)
 3: 6        Call Subroutine 6

3:  If time is (P92) ;store data and check vs alarm every 10min into hr
 1: 5        Minutes (Seconds --) into a
 2: 120      Interval (same units as above)
 3: 7        Call Subroutine 7


;..............................................
; Automatically acquire TDR data
;...............................................


4:  If time is (P92) ;interrogate cable on ch.1 at 0615
 1: 375      Minutes (Seconds --) into a
 2: 1440     Interval (same units as above)
 3: 1        Call Subroutine 1


5:  If time is (P92) ;interrogate cable on ch.2 at 0635
 1: 395      Minutes (Seconds --) into a
 2: 1440     Interval (same units as above)
 3: 2        Call Subroutine 2


6:  If time is (P92) ;interrogate cable on ch.3 at 0655
 1: 415      Minutes (Seconds --) into a
 2: 720      Interval (same units as above)
 3: 3        Call Subroutine 3
```

```
7:  If time is (P92) ;interrogate cable on ch.1 at 0715
 1: 435      Minutes (Seconds --) into a
 2: 720      Interval (same units as above)
 3: 4        Call Subroutine 4


8:  If time is (P92) ;interrogate cable on ch.2 at 0735
 1: 455      Minutes (Seconds --) into a
 2: 1440     Interval (same units as above)
 3: 5        Call Subroutine 5



;......................................................
; Toggle CR10X to acquire TDR data
;......................................................


9:  If Flag/Port (P91) ;toggle TDR to interrogate cable on ch.1
 1: 11       Do if Flag 1 is High
 2: 1        Call Subroutine 1

10:  Do (P86)
 1: 21       Set Flag 1 Low

11:  If Flag/Port (P91) ;toggle TDR to interrogate cable on ch.2
 1: 12       Do if Flag 2 is High
 2: 2        Call Subroutine 2

12:  Do (P86)
 1: 22       Set Flag 2 Low

13:  If Flag/Port (P91) ;toggle TDR to interrogate cable on ch.3
 1: 13       Do if Flag 3 is High
 2: 3        Call Subroutine 3

14:  Do (P86)
 1: 23       Set Flag 3 Low

15:  If Flag/Port (P91) ;toggle TDR to interrogate cable on ch.4
 1: 14       Do if Flag 4 is High
 2: 4        Call Subroutine 4

16:  Do (P86)
 1: 24       Set Flag 4 Low

17:  If Flag/Port (P91) ;toggle TDR to interrogate cable on ch.5
 1: 15       Do if Flag 5 is High
 2: 5        Call Subroutine 5

18:  Do (P86)
 1: 25       Set Flag 5 Low

;.................................................
; Toggle CR10X to acquire tiltmeter data
```

```
;................................................

19:  If Flag/Port (P91); toggle CR10 to acquire tiltmeter data
 1: 16       Do if Flag 6 is High
 2: 6        Call Subroutine 6

20:  If Flag/Port (P91)
 1: 16       Do if Flag 6 is High
 2: 7        Call Subroutine 7

21:  Do (P86)
 1: 26       Set Flag 6 Low

*Table 2 Program
  02: 0.0000    Execution Interval (seconds)

*Table 3 Subroutines
;******************************************************************
;******************************************************************
;*******                SUBROUTINE 1                        ******
;*******         interrogate cable attached to              ******
;*******           ch. 1 of  coax multiplexer               ******
;*******                                                    ******
;******************************************************************
;******************************************************************

1:  Beginning of Subroutine (P85)
 1: 1        Subroutine 1

   ; turn on power to Tektronix cable tester

     2:  Do (P86)
      1: 44       Set Port 4 High

     3:  Excitation with Delay (P22)
      1: 1        Ex Channel
      2: 0000     Delay W/Ex (units = 0.01 sec)
      3: 500      Delay After Ex (units = 0.01 sec)
      4: 0000     mV Excitation


     4:  Z=F (P30)
      1: 0.0      F
      2: 00       Exponent of 10
      3: 2        Z Loc [ Wind      ]

   ;-----------------------------------------------------
   ;  loop over the desired number
   ;  of windows for cable
   ;----------------------------------------------------

     5:  Beginning of Loop (P87)
      1: 0000     Delay
      2: 9        Loop Count
```

```
; acquire a window
  6:  TDR Measurement (P100)
    1: 0        SDM1502 ADDRESS
    2: 1        Waveform (256 locs)
    3: 1.0      Probe Length (meters) ;cursor location for first window
    4: -57.9    Cable Length (meters) ;neg. value to collect succ wind.
    5: 1001     MMMP  Mux & Probe Selection ;ch1 of coax multiplxr
    6: 3        Loc [ wave_1    ]
    7: 1        Mult
    8: 0        Offset

  7:  Extended Parameters 4 Digit (P68)
    1: 4        Option ;average 4 values
    2: 81       Option ;propagation velocit Vp=0.81
    3: 3        Option ;Ddiv = 0.25 m/div
    4: 112      Option ;gain = 20 mrho/div
    5: 0        Option ;offset = 0
    6: 0000     Option
    7: 0000     Option
    8: 0000     Option

  ;increment window


   8:  Z=Z+1 (P32)
    1: 2        Z Loc [ Wind      ]

   ;prepare to send data to external stroage device


    9:  Do (P86)
     1: 10       Set Output Flag High

    10:  Real Time (P77)
      1: 1221     Year,Day,Hour/Minute,Seconds (prev day at midnight,
2400 at midnight)

   ;save voltage

     11:  Sample (P70)
       1: 1        Reps
       2: 1        Loc [ batt      ]

    ;save temperature

      12:  Sample (P70)
        1: 1        Reps
```

```
        2: 4        Loc [ Temp_1    ]

     ;save window #

       13:  Sample (P70)
         1: 1        Reps
         2: 2        Loc [ Wind      ]

      ;save cursor distance (Cdist)
      ; and distance between data points (Ddiv)

          14:  Sample (P70)
           1: 2        Reps
           2: 5        Loc [ Cdist     ]

       ; use higher resolution for Gain and Offset

          15:  Resolution (P78)
           1: 1        High Resolution

      ;save vertical Gain and Offset

          16:  Sample (P70)
           1: 2        Reps
           2: 7        Loc [ Gain      ]

      ;reset to lower resolution

          17:  Resolution (P78)
           1: 0        low resolution

      ;save 251 data points for waveform in current window

          18:  Sample (P70)
           1: 251      Reps
           2: 3        Loc [ wave_1    ]

      ;send data to external storage device
;
;          19:  Serial Out (P96)
;           1: 71       SM192/SM716/CSM1

     ;------------------------------------------
     ;-----       bottom of loop         ------
     ;------------------------------------------

     19:  End (P95)

     ;turn off the Tektronix cable tester

     20:  Do (P86)
      1: 54       Set Port 4 Low

;-----------------------------------------------
;------      End of Subroutine 1        -------
```