New Developments in TDR Cable Surveillance of Potential Instability

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ABSTRACT: This paper employs a case history to describe deployment of new TDR cable and communication technologies to monitor stability. It involves remotely monitoring possible sinkhole-induced deformation near a "land bridge" installed over a recent subsidence event. A TDR cable was installed horizontally along with more typical vertical cables to detect possible subsidence induced shearing. In addition, vertical air dielectric (hollow) TDR cables were installed to monitor changes in ground water regime that might be associated with the onset of sinkhole-induced deformation. Finally tiltmeters were installed to monitor rotation of the land bridge. The objective is also for the polling to be autonomous and wireless. A number of communication systems were tested and a point to point radio device was finally selected. The foundation for design of optimally compliant cables for use in soft soil is also discussed.

1 FLORIDA-SINKHOLE SUBSIDENCE: HORIZONTAL AND AIR DIELECTRIC CABLES

1.1 *Issues of monitoring and installation*

Atypical sinkhole activity in Highlands County, Florida USA has lead to a need for continued surveillance involving TDR technology. Normally in this geology when a sinkhole opens, the most economical approach is to wait several days to allow full development; then backfill and repair pavement, utilities, etc. This particular sinkhole continued to grow over a period of one week, and the geotechnical investigation did not reveal a definitive source. Because of the inconclusive nature of the failure mechanism, a land bridge was built over the sinkhole and instrumented to monitor future movement, if any. The land bridge is composed of six 28 m (94 ft) AASHTO Type 4 pre-cast concrete beams, the cross sections of which are shown in Figure 4, supported on spread footings at each end.

It is hypothesized that the sinkhole is of raveling chimney type as shown in Figure 1 along with the subsurface soil profile. As can be seen, the surface 1.8 m (6 ft) of poorly graded sand with silt (SP-SM), is underlain by 4.2 m (14 ft) of medium dense silty sand (SM), 5.8 m (19 ft) of stiff clayey sand (SC) all overlying very loose poorly graded sand with silt (SP-SM), which extends to depths greater than 45 m (150 ft). 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.

The issues addressed by monitoring at this site are deformation of the bridge's spread footings and the correlation between water level changes and subsurface movement. Two, 15m long vertical deformation-TDR cables (TDR-1 and TDR-2) have been installed at diagonal abutments as shown in Figure 2 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 beside the sinkhole as it expands laterally. In either case shearing of the cable would accompany upward development of the sinkhole. CommScope 7/8-in. foam dielectric solid aluminum (P3-75-875) cables were used for the vertical cables.

As shown in Figure 2, a coaxial cable (TDR-5) has also been installed horizontally in a trench that extends the entire length of the bridge. Horizontal cables have an advantage over vertical cables in that they can monitor larger surface area. While vertical cables can only detect upwards migration or expansion at one map location, 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. Again CommScope 7/8-in. foam dielectric solid aluminum (P3-75-875) cable was used.

To monitor changes in the ground water table at 6.5m (20 ft), monitoring wells on each side of the bridge were fitted with air dielectric cables (TDR-3 and TDR-4). Water level is important in the development of sinkholes because for sinkholes to develop soil must ravel or pipe into and through cavities. Raveling is usually enhanced by water flow during precipitation events or periods of increased ground water withdrawal. The hollow, air dielectric cables, Cablewave Inc HCC12-50, were perforated to allow water to penetrate between the outer and inner conductors. Water creates a large reflection at the air-water interface like that shown in Figure 7.

Tiltmeters (Applied Geomechanics Little Dippers) have also been installed in the soil and on the bridge along each side of the bridge to detect expansion of the sinkhole as well as to differentiate between soil and structure deformation. Locations of these tiltmeters are also shown in Figure 2. Tiltmeters were chosen to be polled by the same datalogger that is employed for the TDR cables so that all data could be acquired with a single data logger.

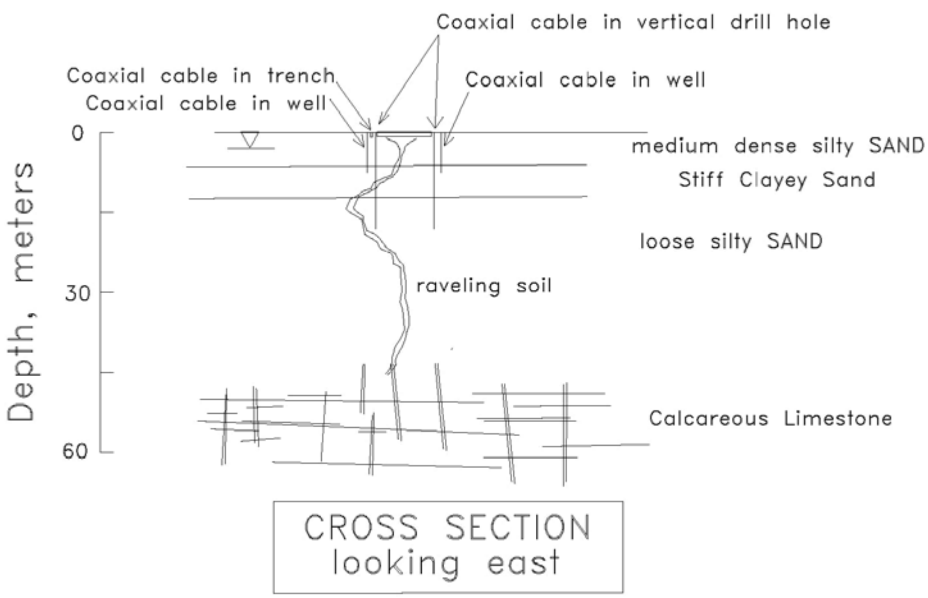

Figure 1. Startigraphy and raveling process at SR 66, Highlands County, Florida

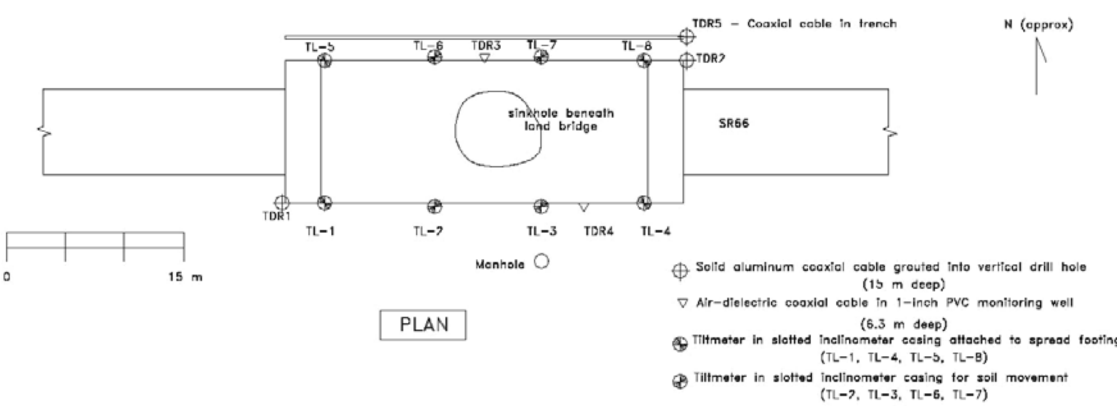

Figure 2. Plan view of the installed instruments (TDR & Tiltmeters), SR 66, Highlands County, Florida

1.2 *Installation Details*

Each vertical cable has been grouted into its own hole as recommended in the June 2003 Geotechnical Instrumentation News (GIN) article (Dowding et al, 2003). Separate holes without other instrumentation are necessary so that deformation of the cable results from ground deformation that is unmodified. Attaching small diameter, flexible, TDR cables to the outside of slope inclinometer (SI) casing obscures localized effects because of the reinforcing effect of the casing. Otherwise classical drilling & grouting techniques were used for the two vertical TDR cables: rotary drilling with water and steel casing. As shown in Figure 3, the horizontal cable TDR-5 was placed in the bottom of a trench and encapsulated in concrete brought to the site in traditional premix trucks.

The grout mix for the vertical holes is important as well as it must be 1) pumpable by the drilling rig's water pump, 2) strong (stiff) enough to kink the cable, but 3) not so strong as to cause local failure of the of the soil around the grout-cable composite. Details of these issues are also discussed in the GIN article and are based upon design of controllable, but low strength grouts (Pierce, 1998 and Blackburn, 2002). In this case grout with a water cement ratio of 1.74 was employed. The estimated strength is 1.17 Mpa.

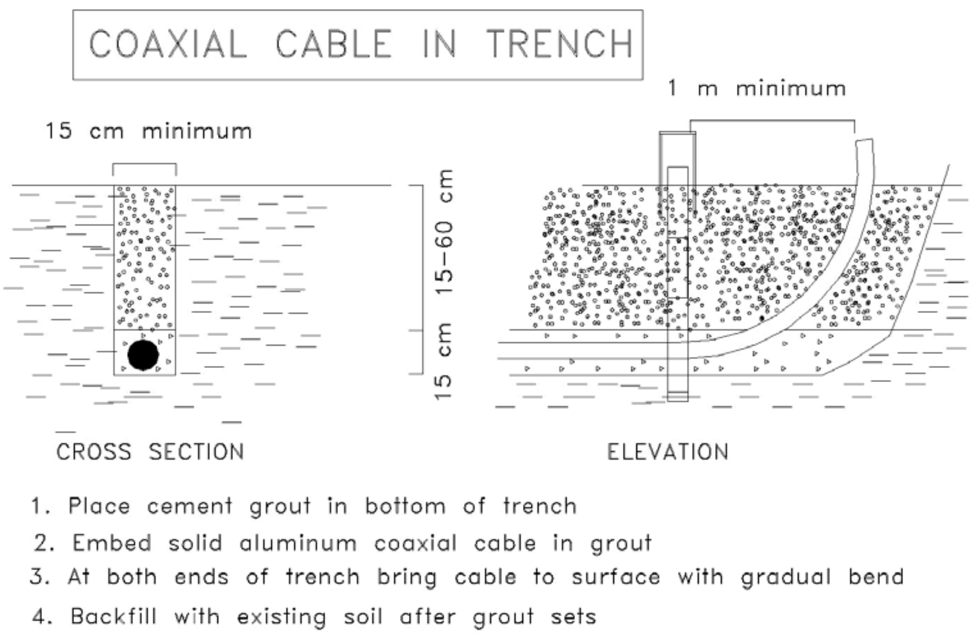

Figure 3. Installation details for horizontal TDR-5 cable, SR 66, Highlands County.

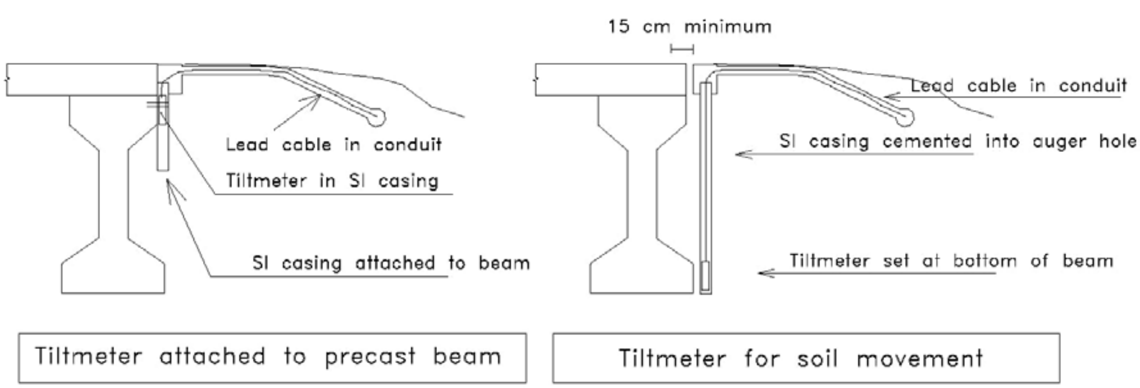

Figure 4. Cross section of the precast concrete beams and installation details for tiltmeters, SR 66, Highlands County, Florida.

The air dielectric TDR cables were placed in wells that were constructed as Casagrande piezometers. They were inserted through the riser pipe into the porous stone collector and attached at the top to the transmission cable with a standard type N connector as were the TDR displacement cables. They were perforated with a hand drill every 15 cm to allow water to enter the annulus between the inner and outer conductor.

As shown in Figure 4, four tiltmeters were installed in slope indicator (SI) casing grouted into the ground (TL-2,3,6,7), and four others (TL-1,4,5,8) were installed in SI casing attached to the land bridge. The tiltmeters were not grouted into the SI casing and can be replaced if any fail.

1.3 *Data acquisition system*

The data acquisition system (DAS) is built around a Campbell Scientific (CSI) CR10X datalogger. It controls the TDR cable tester, stores data and allows communication with a distant polling computer. The testing instruments are connected to two multiplexers with lead cables: the Applied Geomechanics Model 797 multiplexer for Tiltmeters and CSI SDMX 50 for TDR cables. The TDR cable tester is a CSI TDR-100 and is employed (with different script) to pulse both the TDR deformation and water level cables. DAS components are placed in a leak-proof box and powered with two 12V batteries recharged with a single 20 W solar panel.

Long connecting lead cables should be of the low loss, 75 Ohm F11 variety. The often employed, standard 50 Ohm RGU connecting cables should be kept as short as possible (<50 m) to minimize attenuation and noise. However, in that case, the short runs and short transducer cables did not require the attention to losses that accrue on most installations, and the 50 Ohm transmission cable was employed. In other installations the same cable (P3-75-875) has been employed as for both the transmission and transducer portions of the cable runs (Dowding et al 2003).

1.4 *Communication system*

Hard-wired phone and power lines are preferable at sites that involve real time monitoring and callback alarms. However, the Florida Department of Transportation was interested in testing at this remote site a fully wireless and autonomous data polling system. This approach involved wireless communication between the datalogger and the polling computer as well as the use of solar power to energize the monitoring system.

The first installation was based on Campbell Scientific analog cellular telephone package model COM 100. This package is made of three parts (Dussud, 2002). First, the phone package comprising a Motorola AMPS cellular connection transceiver, RJ11C interface, coaxial antenna cable and a power control. The second part is the COM 200 built-in modem and the third part is the Yagi ASP 962 8dB antenna. The first and second components are directly connected to the datalogger and placed in the instrument box while the antenna is mounted on a pole and aimed towards the closest relay tower.

The analog cellular telephone showed limitations in this particular case. First, together with the power draw of other instruments, it has a very high demand in energy. As a result, the solar panel was unable to recharge the battery at a rate sufficient to keep up with the draw of the instruments. Second, cellular coverage of the instrumented site is very poor. The weak signals considerably reduced the reliability of data transmission.

As an alternate to analog cellular modems (GMS), cellular digital technology can be employed (CDPD). Campbell Scientific offers a CDPD (Cellular Digital Packet Data) modem compatible with the CR10X datalogger. These CDPD modems communicate via a cellular network able to transmit data to an IP address. The transmission rate is high (19.2 Kbbs) and it avoids problems due to dialing. However, the CDPD network coverage is not yet as broad as regular GMS network coverage and this solution was not chosen to replace the analog communication package.

An alternate solution to cell phone communication when instrumenting a remote site is point to point radio communication. A point to point radio device can be directly connected via a RS232 jack to the front panel of a CR10X datalogger. 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 communication devices have to lie along an unobstructed sight line at a distance less than 32Km (20 Miles).

Such a solution was pursued at the site. A waterproof box housing a Freewave radio device, an industrial modem and a 12V deep cycle battery was constructed and placed on a pole 600 m away from the data acquisition system. The box is connected to a phone line and the battery is recharged by a single 20W solar panel. The COM 100 cellular telephone package was removed from the data acquisition system and the other radio device replaced it.

1.5 *Data polling and web display*

The objective is for the polling to be autonomous as it is for other TDR & tiltmeter sites that communicate by land-line. For sites with autonomous polling, data are automatically uploaded daily by a polling computer at Northwestern University (Kosnik and Kotowski, 2002). These data are then automatically transferred to the web server that archives and graphically displays over the internet the data along with that already acquired.

Saving energy is essential at this site. The testing and communication equipment are set on a low power mode and in addition, the datalogger is programmed to turn on the radio system only during a short time period every day. Communication between the site and the polling computer is only possible during this short time window.

Data from the sinkhole site can be found at: www.iti.northwestern.edu/tdr/operational/florida and data from other completely autonomous systems at a bridge in Indiana, and an abandoned coal mine in Ohio, USA also can be found at www.iti.nwu.edu/tdr/operational.

2 EXAMPLE DATA

2.1 *Deformation TDR readings*

A summary of instrument response is informative. As shown in Figure 5 a. and b., since November 26, 2002, no deformation TDR reflections have been observed. However, the reflection at the connector location for TDR-5 illustrates the importance of connections in TDR systems. They are a fragile link and their condition should be monitored and maintained when necessary. (Dowding et al, 2003)

There is essentially no change in the TDR signal in Figure 5 a. and b. between November 26, 2002 and February 22nd, 2003 even thoroughly the average reflection amplitude differs considerably. The reflection details are the same. The lengths are the same and the deliberate crimp reflection at 15 meters along TDR-2 has the same raw amplitude for both dates.

2.2 *Water level TDR readings*

Water level is easily tracked by the large reflection at the air-water interface as shown in Figure 7 for cable TDR-4. A time history of the evolution of the water level is available at : www.iti.northwestern.edu/tdr/operational/florida. A portion of this archived time history is represented in Figure 6.

The air dielectric cable at TDR-4 extends to a depth of 6.5 m and is located 40 m away from the TDR pulser. The air water interface is the very large downward reflection located at 42.8 m from the TDR pulser (4.2 m from the surface). This reflection is some 0.1 to 0.2 rho, which is much larger than the 0.01 rho crimp reflection in TDR-2 shown in Figure 5a.

The large reflection at the air-water interface allows TDR to be employed as a retrofit to existing Casangrande piezometers even at long distance from the uphole polling instrumentation. As described by O'Connor and Dowding (1999), up to 600 m long 25 pair and 2 pair lead wires can be employed as transmission cables with a 5 V sine wave pulser like the Textronix 1503.

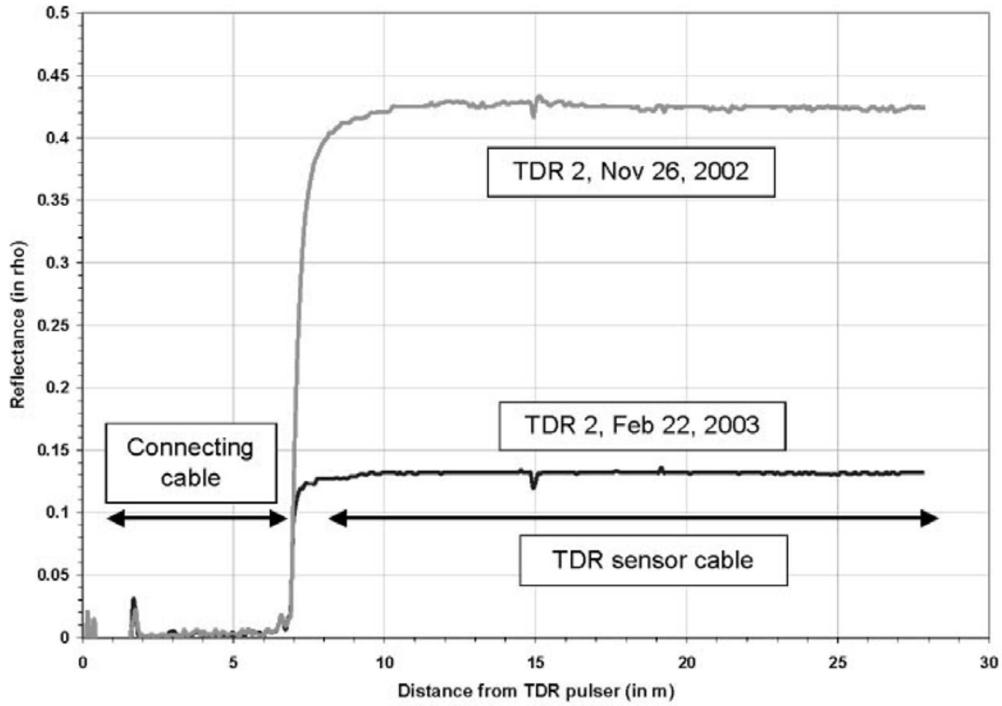

Figure 5a. Deformation readings for TDR-2, SR 66, Highlands County, Florida.

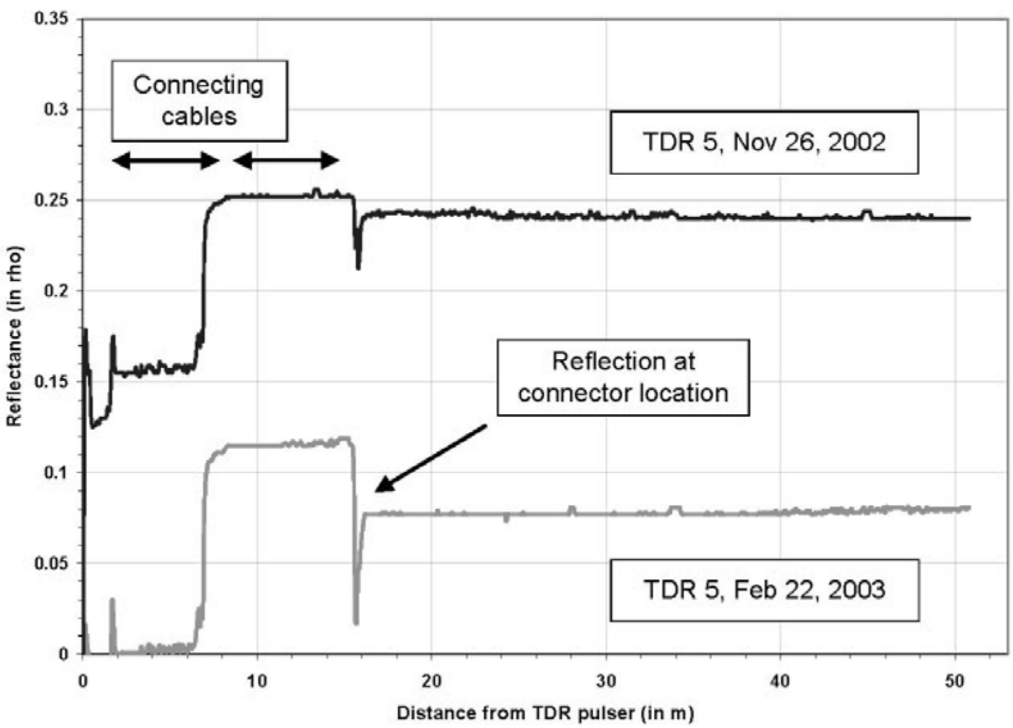

Figure 5b. Deformation readings for TDR-5, SR 66, Highlands County, Florida

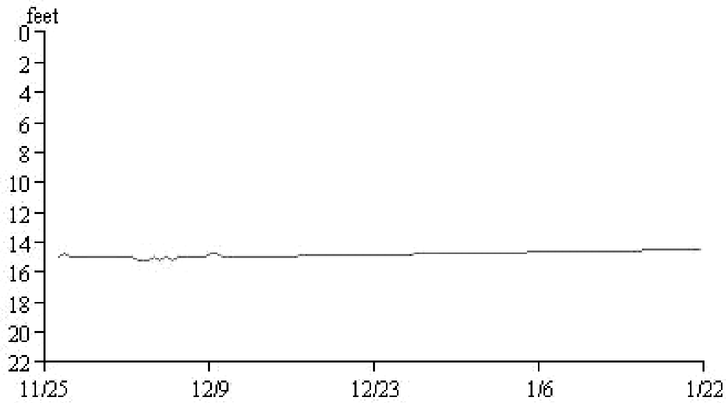

Figure 6. Time history of the water table level depth measured by TDR-4 between November 2002 and January 2003, SR 66, Highlands County, Florida.

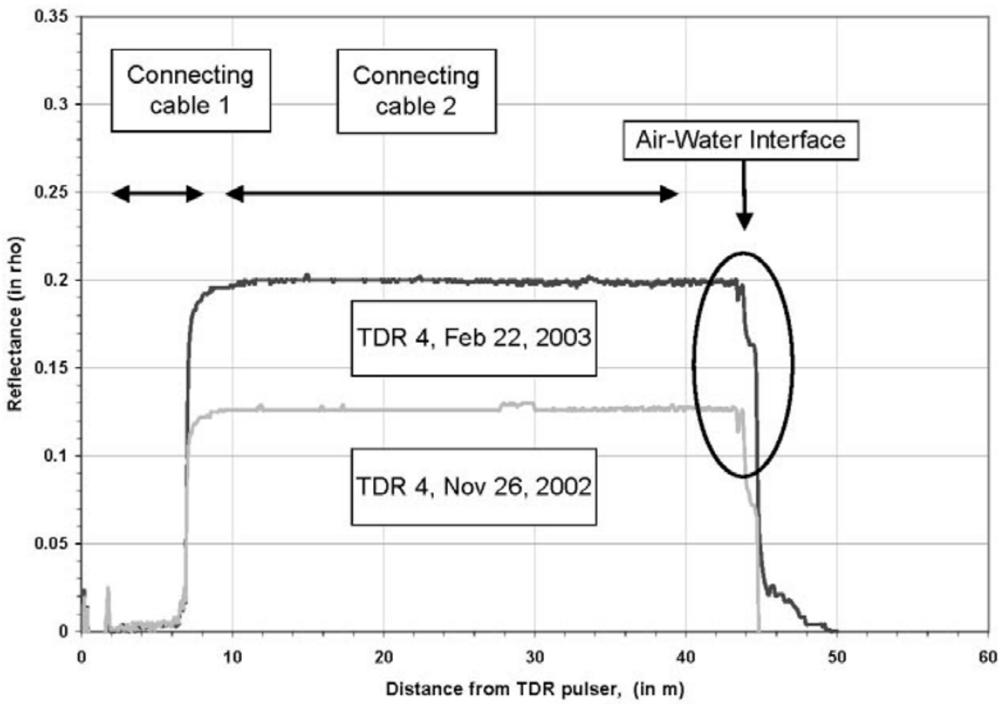

Figure 7. Water TDR-4 readings SR 66, Highlands County, Florida.

2.3 *Tiltmeter response*

Sinkhole expansion can also be monitored by measuring the tilt of the structure or the soil. Combining tiltmeter and TDR cable surveillance has been employed to monitor potential scour induced movements for California Department of Transportation and longwall mining subsidence for Pennsylvania DoT (O'Connor et al., 2001). A time history of the structure and soil tilt at this Florida site is available at: www.iti.northwestern.edu/tdr/operational/florida. A portion of this time history is also presented in Figure 8.

The eight tiltmeters allow a close monitoring of soil and structure movement in the east-west as well as north-south direction. Their response give an early warning for sinkhole expansion and they complement the deep monitoring provided by the TDR cables. There has been essentially no significant tilt of neither the structure nor the soil (never more than 1 degree), except in fall 2002 due to repaving of S.R. 66 by the Florida Department of Transportation.

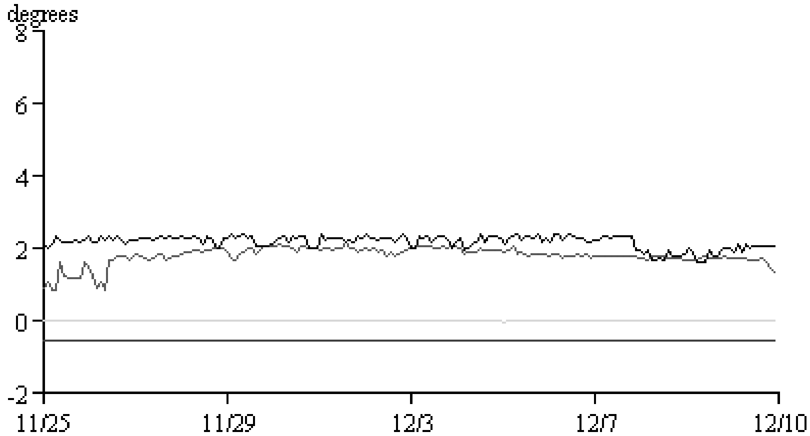

Figure 8. Time history of the evolution of the tilt angle for the soil in the east-west direction, between November and December 2002, SR 66, Highlands County, Florida.

3 DESIGN OF OPTIMALLY COMPLIANT CABLES FOR USE IN SOFT SOILS

TDR cables are locally sheared or kinked when both of the following conditions are met. First the grout strength must be sufficiently high to shear the cable. Second the grout strength must be small enough relative to the soil strength so that soil around the localized shear zone is not failed by the grout and thus smears or enlarges the shear zone to the point that the cable does not kink but simply bends (Blackburn, 2002). Laboratory tests indicate that braided cable will develop localized failure and thus a TDR reflection with grout strengths, c, of 200 kPa. In addition finite element modeling of TDR cable shearing shows that grout strengths shown in Figure 10 can be as high as 5 times that of soil before local shearing of the cable declines. A grout strength of 5 times that of the soil would yield to a ratio: soil to grout strength of 0.2 on Figure 9.

Figure 10 compares the calculated response of braided and solid outer conductor cables (shown in Figure 9) when sheared 15 mm. Each cable is surrounded by grouts of different strength, which are in turn emplaced in differing strength soils. These graphs then display shear stresses in the cables (Y axis) when the soil surrounding the various grout-cable composites is sheared 15 mm. The shear stresses developed for 3 different soils follow the 3 curves and vary as the ratio of soil strength (stiffness) to grout strength varies along the X axis.

For each cable there is a critical shear stress (dashed horizontal line on Figure 10) which is necessary to produces a reflection. It is 350 Kpa for the braided cable and 2000 Kpa for the solid aluminum outer conductor cable. The more compliant braided cable develops less shear stress than the stiff cable when the soil is sheared 15 mm no matter the ratio of grout to soil strength. However, less shear stress is necessary to reach the critical shear stress for this braided cable. Thus, the compliant braided cable is more sensitive in softer soils. In other words, in the same soil and deformation conditions, the compliant braided cable is more likely to develop the critical shear stress level necessary to produce a kink in the cable and thus a voltage reflection.

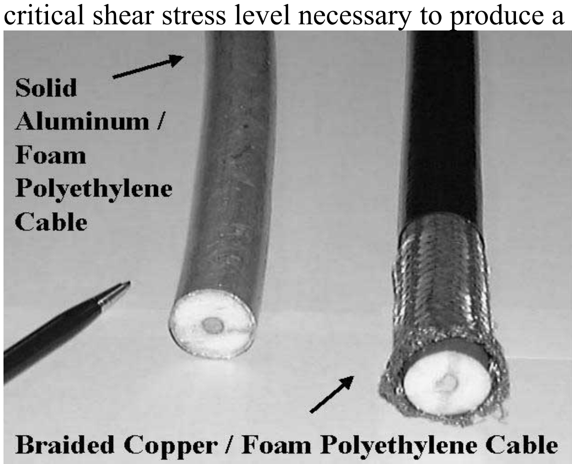

Figure 9. Two most common types of coaxial TDR sensor cables.

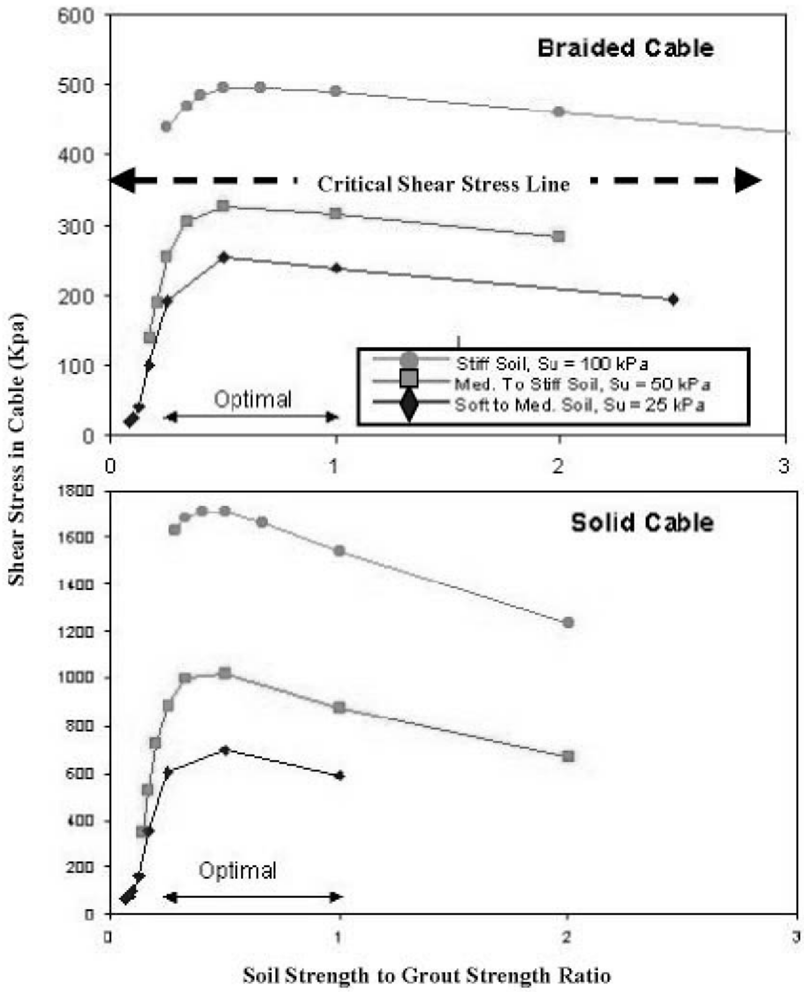

Figure 10. Cable shear stress vs. soil strength to grout strength for solid & braided outer conductor cables (Blackburn, 2002).

4 CONCLUSION

Instrumentation at this site was innovative in both the number of instruments and the installation of an horizontal cable. Use of radio devices to communicate with a distant computer was also innovative and may prove to be a n inexpensive and efficient alternate to cellular communication.

This case and related information also demonstrates the diversity of installation geometries and transducer cables that are possible with TDR cable technology. Cables have been installed vertically as well as horizontally. They have been installed as manufactured for signal transmission and have been modified to reduce their stiffness. They have been employed to monitor water depth as well as deformation with the same pulser.

Both slope inclinometers and TDR cables are capable of providing responses in locations of high shearing strains. Since TDR cables are especially sensitive to thin localized shearing, they respond early in soils in locations of highly concentrated and localized shear strains. On the other hand, slope inclinometers are especially sensitive to gradual, general shear that occurs before localization along a concentrated shear plane. These differences in sensitivity do not imply that one method is correct, but that the two methods respond optimally to different modes of shearing.

While TDR cables are deceptively simple to employ in stiffer rock and landslide geologies, this case and related information show that care must be exercised for their deployment in soil. For use in soil it is necessary to design and subsequently control precisely the strength and stiffness of the grout-soil composite. The grout must be 1) pumpable with the drilling rig pump, 2) stiff enough to locally shear (or kink) the cable, 3) yet compliant enough not to shear the soil adjacent to the localized shear plane.This control is challenging when operating drillers who are unfamiliar with the pumpability of the various grout mixes.

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