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Monitoring Slope Movement with Time Domain Reflectometry

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ABSTRACT

Time domain reflectometry (TDR) is a method of locating the depth to a shear plane or zone in a landslide. TDR uses an electronic voltage pulse that is reflected like radar from a damaged location in a coaxial cable. To monitor slope movement, coaxial cables are grouted in boreholes and interrogated using a cable tester. Characteristic cable signatures can be stored and compared over time for changes, indicating slope movement. Advantages of using TDR over conventional servo-accelerometer probes include relatively low cost, time savings, immediate determination of slope movement, and the capability to monitor cables remotely using dataloggers and telemetry.

INTRODUCTION

Time domain reflectometry (TDR) was originally developed by the power and communications industries to locate faults and breaks in cables (Rohrig, 1931)). The discovery that soil moisture content could be determined by TDR led to its extensive use in the agricultural area (Topp and Davis, 1985). In the late 1970's and during the 1980's, the U.S. Bureau of Mines used TDR extensively to locate coal mine roof failure zones above longwall coal mines (Dowding and Huang, 1994). Other geotechnical applications during this period included monitoring for metal mine roof caving by the Canada Centre for Mineral and Energy Technology (CANMET) (Aston et al., 1994), and attempts at monitoring slopes adjacent to a dragline by Syncrude Canada Ltd. (Lord et al., 1991; O'Connor et al., 1992).

In the early 1990's, the California Department of Transportation (Caltrans) did extensive research to evaluate the application of TDR to landslide monitoring using both remote and locally monitored stations (Kane and Beck, 1999). The results of this study, and the efforts of the U.S. Bureau of Mines, led to the strong interest by the geotechnical and geological engineering communities in using TDR for slope monitoring. This paper presents a review of the principles and equipment necessary for utilizing TDR as a single field installation or as a remotely monitored system that can incorporate other types of sensors. The definitive review of research and information on TDR is available in O'Connor and Dowding (1999).

TIME DOMAIN REFLECTOMETRY

Principle of TDR

In TDR, a cable tester sends a voltage pulse waveform down a cable grouted in a borehole, Figure 1. If the pulse encounters a change in the characteristic impedance of the cable, it is reflected. This can be caused by a crimp, a kink, the presence of water, or a break in the cable. The cable tester compares the returned pulse with the emitted pulse, and determines the reflection coefficient of the cable at that point.

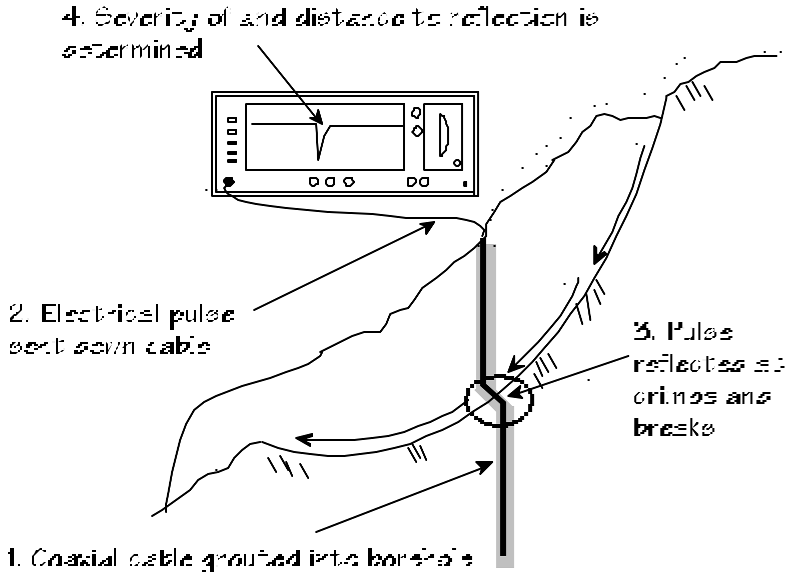

Figure 1. Cable tester attached to TDR cable undergoing deformation due to slope failure.

Electrical energy travels at the speed of light in a vacuum, but travels somewhat slower in a cable. This is called the velocity of propagation. When the propagation velocity of a particular cable is known, the distance to any cable reflection can be determined by the cable tester.

Coaxial cables are composed of a center metallic conductor surrounded by an insulating material, a metallic outer conductor surrounding the insulation, and a protective jacket. Each cable has a characteristic impedance determined by its material composition and construction. If the cable is deformed, the distance between the inner and outer conductors changes. It is this change that causes a difference in the impedance, and a resulting reflection of the voltage pulse.

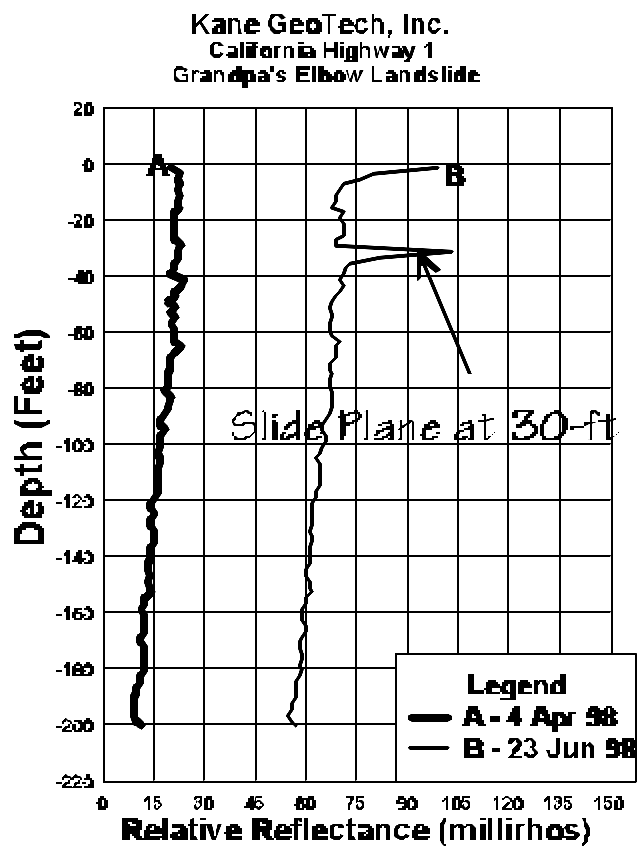

Figure 2. TDR cable signatures showing development of a shear zone.

Data consists of a TDR signature,

Figure 2, composed of the wave reflections for the cable. The length and amplitude of the reflections, a cable signature "spike," indicate the severity of the damage to the cable. TDR for determining ground movement requires reading the cable signature at regular time intervals. Ground movement, such as slip along a failure zone, will deform the cable and result in a change in cable impedance and a reflection of energy. This change can be used to determine the location of shear movement. The change in impedance with time corresponds qualitatively to the rate of ground movement.

Advantages

For geotechnical applications TDR has many advantages over conventional probe-type, servo-accelerometer inclinometers. These include:

1. **Cost.** Cable has a significant cost advantage vs. inclinometer casing. Some cables can be purchased for as little as $0.10/foot as opposed to $6 to $10/foot for inclinometer casing. The cost of the electronic equipment is approximately the same: roughly $9000 per unit, but the price of new generation TDR cable testers is much less. The cost of drilling is the same. However, with TDR there is no risk of losing an expensive probe due to a sharp bend in the inclinometer casing, only expendable cable is lost.

2. **Time.** Besides the cost savings in equipment, the rapid reading of TDR cables means that more holes can be read in less time -- an additional savings in man-hours. A single cable, no matter how deep, can be read in less than 5 minutes as opposed to ½ hour to an hours to read an inclinometer, depending on depth. Multiple cables at a site can be run to an easily-accessible central location and all cables read at the same time.

3. **Remote Access.** Telemetry using a datalogger and a hardwire or cellular telephone can be installed for real-time readings and/or difficult access areas without the need to visit the site. In-place inclinometers are available but, they are expensive and must be considered sacrificial. Another advantage of remote automated systems is that other sensors can be included such as vibrating wire piezometers for water level measurements, potentiometric extensometers for ground surface movement monitoring, and electrolytic bubble extensometers for monitoring tilt. Any of these sensors, including TDR, can be programmed trip an alarm should their output exceed a predetermined threshold. When TDR is installed in highways, traffic control is not necessary. Cables can be run under the pavement and accessed safely from the shoulder.

4. **Attachment to Inclinometer Casing.** TDR cables can be attached to the outside of conventional inclinometer casing. Although the cable will be affected by the presence of the casing, it usually outlasts the casing and can provide information about movement after the casing has been deformed too much for the probe to pass through.

5. **Installing in Unusable Inclinometer Casing.** If an inclinometer casing is not

deformed too much, a TDR cable may be passed through bends to the bottom of the casing. The casing then can then be grouted and the TDR cable read other.

6. **Safety.** With TDR, data collection can be done from a safe location, even from an office with remote data acquisition equipment. It is not necessary to expose a technician to dangerous traffic, or to landslide and rockfall hazards on moving slopes.

7. **Data.** In most unstable slope situations, the questions that need to be answered are: is it moving?; where is it moving?; and how fast is it moving? TDR provides this information quickly. It is not necessary to download data from a readout box into a computer and then plot the results. The screen on the cable tester shows the cable signature immediately. By comparing cable signatures over time, the location and changes in the rate of movement can be determined. Rates of deformation can be estimated by plotting the magnitude of the spike in the cable with time.

Disadvantages

TDR has some disadvantages when compared with inclinometers. Anyone contemplating using TDR should be aware of these:

1. **Tilt Measurement.** The coaxial cable used in TDR must be damaged by shearing, tension, or a combination of both to show up on a cable signature. For this reason, TDR cannot be used where shear zones do not occur and monitoring tilt is necessary. For example, inclinometers should be used behind retaining walls and other structures to monitor tilt.

2. **Magnitude of Movement.** Some attempts have been made to correlate the amount of slope movement with a corresponding change in size in TDR spike (Francke et al., 1994). While some correlation between spike size and movement as recorded in a laboratory experiment have been determined, few correlations have been made in the field.

3. **Direction of Movement.** TDR can only locate the shear plane. It cannot provide the direction of movement.

TDR CABLES

Types

Virtually any coaxial cable can be used for TDR measurements. Experience with many varieties of cable have led to the recommendation by this author that certain cables be used. RG59/U cable manufactured by Belden (www.belden.com) and other manufacturers is inexpensive and easy to use. However, it suffers from signal attenuation and should not being used in deep holes where fine signal resolution is desired.

For best results jacketed, foam-filled cable is recommended. Cablewave FLC12-50J cable (www.cablewave.com) has excellent properties and is easy to install. Unjacketed cables such as 7/8-in CommScope P3-875-CA (www.commscope.com) must be coated, for example with paint, prior to installation to prevent adverse interaction with grout. This is very time-intensive. The sensitivity of unjacketed cable is not good enough to warrant its use. Large diameter cables, such as the CommScope cable, greater than ½-in diameter are not recommended for most work because they are bulky and difficult to manipulate.

Preparation

Down-hole cable ends can be prepared by cutting them square, sealing the ends with liquid electrical "tape," and slipping a tight-fitting rubber or plastic boot over the end. The connection should be wrapped securely with electrical tape to prevent water infiltration. Care should be taken not to allow the inner and outer conductors of small diameter flexible cables to contact each other and cause a short circuit.

Crimping cables as a method to precisely locate movement zones is not recommended. Crimps cause the loss of energy and confusing cable spikes, masking actual deformations. In addition crimping cables is time intensive. The benefits are marginal at best and, more likely, detrimental.

Cables can be installed by weighting the end of the cable and lowering the cable end to the bottom of the hole. This may not always be necessary, and the cable may be pushed downhole, especially when installing in hollow stem augur or casing. Cables installed in this manner in dense grouts may float out of the hole and may need to be restrained until the grout sets.

Grout

Cables work best in shear. Grouts must be stiff enough to cause cable deformations. Grout consist of a 10% bentonite, 90% cement slurry works well, but 100% cement also can be used. Installing cables in ungrouted holes, or with sand backfill will likely result in poor performance. In some cases it may be quicker and easier to attach the TDR cable to the plastic grout pipe and leave the pipe after grouting.

Attaching Cables to the Outside of the Inclinometer Casing

As mentioned previously, TDR cables, especially small diameter flexible cables, can be attached to the outside of inclinometer casing. This is commonly done, and adds virtually nothing to the cost of the hole. However, the TDR cable will perform much better by itself and careful consideration should be given as to whether the inclinometer is needed at all. The bending of the casing strongly influences the behavior of the cable. This usually delays the onset of signature spike development.

If it is desired to attach cables to an inclinometer, plastic casing should be used. The use of square steel pipes should be avoided since the steel will not shear easily, if at all, and thus will result in inaccurate cable readings, if any can be recorded at all.

Connectors

When ½" foam-filled cable is used, N-Female connectors work well. Installation should be as per connector specifications and the connection made water-tight with shrink-fit tubing. A N-male-to-BNC-female adapter shall be placed on the of the N-female connector and protected with a small rubber or plastic boot.

When RG59/U cable is used, a BNC female connector should be installed on the cable end. Connector may be of the twist-on or crimped variety. Connections should be made water-tight with shrink-fit tubing.

After connections have been made they should be tested immediately with a cable tester to verify that they are installed properly. Cables can be made secure by protecting them in a "Christy"-type box, suitable for the traffic rating at the location.

CABLE TESTERS

Introduction

There are several types of cable testers on the market. Some cable testers work best for soil moisture or are for specifically for electronics, others are difficult to use, or do not work with all cables. The most versatile and useful cable testers on the market currently are the Tektronix 1502B/C/CS series (www.tek.com/measurement) and the Campbell Scientific, Inc. TDR100 (www.campbellsci.com).

Tektronix 1502B and 1502C

The Tektronix 1502B and 1502C are heavy, rugged cable testers that can withstand rough treatment. An LCD screen on the cable tester shows the cable signature immediately. The 1502B has a removable battery pack while the 1502C has permanent lead/acid rechargeable batteries. To digitize and store the cable signature as comma delimited ASCII in a computer file, a RS232 interface module must be installed. A standard 25/9 pin connector is attached to interface and the serial port of a laptop computer for downloading the digitized signature. SP232 software, described below, is necessary to interface with the tester. The price of the tester is around $9,000.

Only the 1502B (also called the 1502CS) can be used for remote monitoring using a Campbell Scientific CR10X datalogger. A 12-volt power interface replaces the battery pack and a datalogger communications interface replaces the RS232 module. Both of these accessories are available from Campbell Scientific, Inc. Data is in comma delimited ASCII format.

Campbell Scientific, Inc. TDR100

The Campbell Scientific TDR100 is a new product and shows great promise. It costs significantly less than the Tektronix testers, around $3,500, but does not have a screen. It is much smaller and lighter than the Tektronix testers. The TDR100 is easy to use on site with a laptop and PCTDR100 software, allowing the cable signature to be viewed. It can also be interfaced with a CR10X datalogger without additional accessories.

SOFTWARE AND DATA REDUCTION

SP232

SP232 is an MS-DOS computer program developed by Tektronix to digitize and store 1502B/C cable signatures. The format is ASCII and can be read and printed by the SP232 software, or modified and plotted with a spreadsheet such as Excel.

Some laptops, particularly newer models have trouble communicating with the 1502 using SP232. In this case, a lower averaging setting, say four, often solves the problem. Sometimes it is necessary to use a different computer before communication can be achieved. A good solution is to use an old 386 or 486 laptop running MS-DOS or Windows 3.1.

PCTDR100

PCTDR100 was written by Campbell Scientific, Inc. to view signatures from the new TDR100. It is Windows™ 98/NT compatible and easy to use. It has many features and can be even step through a multiplexer to which several cables are attached. Cable signature output is in tabular ASCII format and also can be plotted in a spreadsheet.

TDRPlot2000©

TDRPlot2000© (www.kanegeotech.com) is used for plotting and comparing TDR cable signatures from 1502B/C testers using SP232, Tektronix 1502B/CS remote testers, TDR100 testers using PCTDR100, and remote TDR100 testers. TDRPlot2000© is a preprocessor for DPLOT95, a Windows™-based scientific plotting program developed by the U.S. Army Corps of Engineers Waterways Experiment Station (www.smd4d.wes.army.mil). The program converts desired TDR signatures to DPLOT95 format and automatically plots the signatures. The advantage to this approach is that DPLOT95 allows the flexibility to manipulate and compare multiple TDR signature on one plot. Figure 2 is an example of a signature plotted using TDRPlot2000© and DPLOT95.

SUMMARY

TDR is becoming a widely accepted instrumentation method for monitoring slope movement. It uses an inexpensive coaxial cable as a sensor, and works like radar to locate shear planes or zones of deformation in a slope. In the right conditions, it has many advantages over conventional probe inclinometers, although it is not always the best solution. One outstanding advantage of TDR is that its digital signal is readily compatible to remote applications using a datalogger. Software is available to process data and produce report-quality plots.

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