# CURRENT AND POTENTIAL USES OF TIME DOMAIN REFLECTOMETRY FOR GEOTECHNICAL MONITORING

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# CURRENT AND POTENTIAL USES OF TIME DOMAIN REFLECTOMETRY FOR GEOTECHNICAL MONITORING

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**ABSTRACT**

The California Department of Transportation successfully used Time Domain Reflectometry (TDR) in a number of case studies to monitor the movement of landslides and embankment failures. This application of TDR technology uses a cable tester and a coaxial cable grouted in a borehole. TDR measures changes in cable impedance to determine the location of shearing, tension, or a break in the cable. The authors also deployed a remotely accessed TDR system (cellular phone, modem, data logger, and cable tester) to monitor landslide movement.

There are several advantages to TDR over the standard inclinometer technology. There is a cost advantage: \$0.16/foot (\$0.52/meter) for certain cables versus up to \$5.50/foot (\$18/meter) for inclinometer casing (the cost of the cable tester is comparable to the inclinometer probe and readout unit). The TDR reading is taken at the surface end of the cable, whereas the inclinometer probe is lowered down the casing and is occasionally lost. A TDR reading takes only a few minutes, regardless of length, compared to inclinometer readings which can be time consuming. If the monitoring location is inconvenient or unsafe, such as in a roadway, the cable end can be extended to a more convenient and safe "reading" location off the roadway, preferably behind a guardrail or other barrier. This also eliminates the traffic control which would be required for a inclinometer reading. Cables can be installed in smaller diameter boreholes, or in inclinometer casings that have deflected so much that the probe is blocked and readings can no longer be taken. Finally, readings can be taken on cables installed in borings at any inclination, horizontal through vertical.

The authors' research and experience suggest a number of additional geotechnical monitoring applications for TDR. For example, foam or air-filled coaxial cables can be used to monitor groundwater levels. The presence of water in the dielectric produces a characteristic change in cable impedance. Horizontal cables buried in shallow trenches can be used to monitor potentially unstable slopes and embankments. With the addition of some computer software, the remotely accessed TDR equipment could be used as a landslide warning system. Finally, rockfall barriers could be remotely monitored with TDR for rock impacts and damage.

## INTRODUCTION

Landslide repair and mitigation require information that can be obtained readily. The direction of slide movement can be determined by mapping the surficial features of the landslide. The amount and rate of slide movement can be measured by establishing survey points and/or installing extensometers. The depth to the slide plane, slide direction and movement rate can be determined by installing an inclinometer.

Inclinometers are the most widely-used method of monitoring unstable slopes. They measure the offset, over time, of an oriented slotted pipe placed in a borehole. Readings are made with a probe that is lowered into the casing. The time required for data acquisition increases with hole depth and closeness of reading spacing. The data is then entered into a computer and analyzed to determine the pipe deflection. In most cases, the depth to an existing failure plane is the most important information derived from the inclinometer data. That data is used to determine the shear strength of the slide mass by back-analysis and to develop a repair strategy.

Recently, a time saving and less costly alternative to inclinometers for landslide monitoring has been developed and is in use by the California Department of Transportation (Aston, 1994; Dowding et. al., 1988; Kane and Beck, 1994; Kane et al., 1996)). This alternative monitoring system, consists of a coaxial cable inserted in a borehole or trench and a cable tester to determine deformations or breaks in the cable. Figure 1 is a diagrammatic representation of this method. It is called time domain reflectometry (TDR).

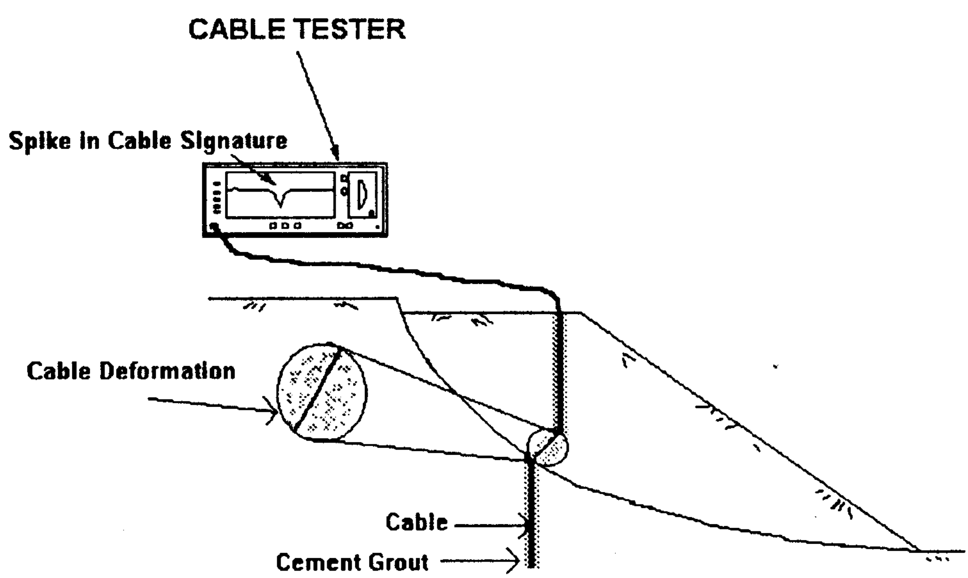



**Figure 1. Cable Tester and Coaxial Cable for TDR Monitoring of Landslide Movement (Anderson et al., 1996)**

## TIME DOMAIN REFLECTOMETRY

TDR was originally developed by the power and communications industries to find breaks or damage in cables. In TDR, a voltage pulse is sent down a cable. 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 returned pulse is compared with the emitted pulse and the reflection coefficient (in rho's or millirho's) is determined. If the reflected voltage equals the transmitted voltage, the reflection coefficient is +1 and the cable is broken. If the opposite occurs, and the cable is shorted, all the energy will be returned by way of the ground and the reflection coefficient will be -1. Deformation of the cable, usually shear or tension, will change the impedance and the reflection coefficient will be between -1 and +1.

Electrical energy travels at the speed of light in a vacuum. The speed at which it travels in a cable is less, depending on the impedance of the cable. This speed is known as the velocity of propagation and is a property of each cable. When the cable propagation velocity and time delay between transmitted and reflected pulses are known, the distance to any cable deformation can be determined.

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 (See Figure 2). All cables have a characteristic impedance determined by the thickness and type of insulating material between the conductors. This insulating material is called the "dielectric" and may be made of almost any non-conducting material. Common dielectric materials are PVC-foam, Teflon, and air.

If the cable is deformed, the distance between the inner and outer conductors changes as does the impedance at that point. The TDR cable tester determines the location of this change.

TDR data consist of "signatures" which show cable impedance versus length (See Figure 3). Cable shearing results in an abrupt impedance spike and while tension results in a pronounced trough. The length and amplitude of the spike indicate the severity of the damage to the cable. Determining ground movement with TDR 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 signature. This change can be used to determine the position of failure and the increase in impedance with time will correspond qualitatively to the rate of ground movement as shown in Figure 3.

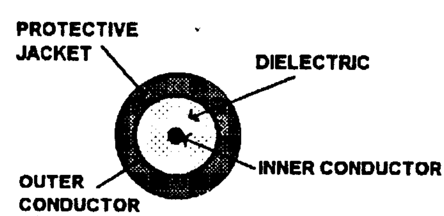



**Figure 2. Coaxial Cable Cross-Section**

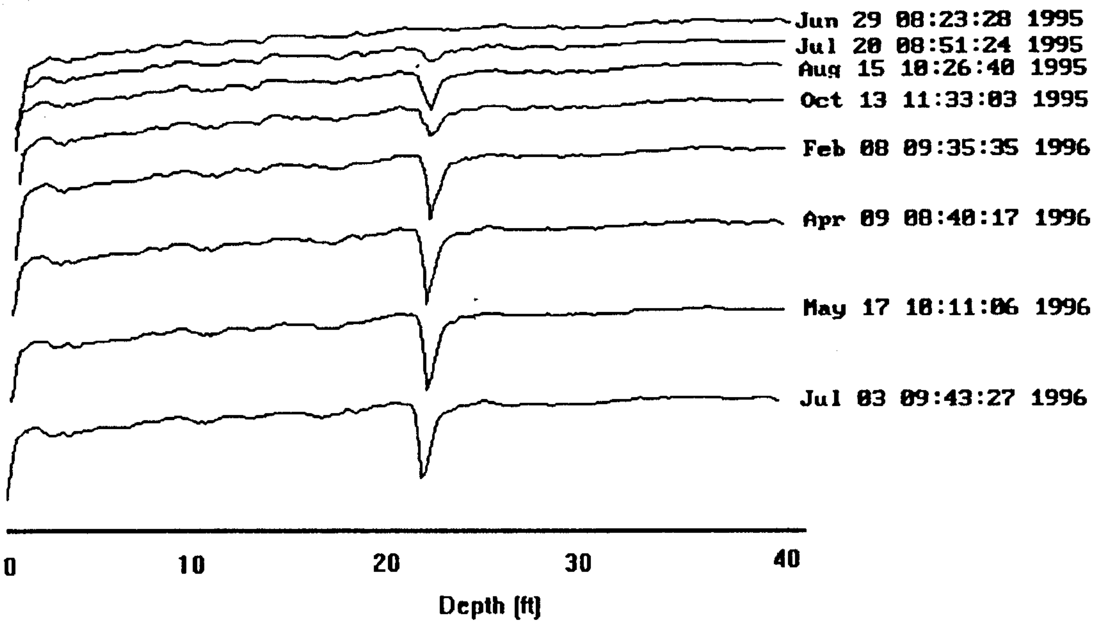



**Figure 3. Typical Cable "Signatures" Show Growth of Spike with Continued Deformation (Anderson et al., 1996)**

## CALIFORNIA DEPARTMENT OF TRANSPORTATION TDR INSTALLATIONS

The California Department of Transportation (Caltrans) has begun using TDR in conjunction with inclinometers in their slope failure investigations (See Figure 4). Described below are a number of Caltrans TDR installations that highlight some unique features of using TDR for geotechnical monitoring.

### *Willits Landslide*

A small landslide damaged State Highway 20 in Mendocino County just west of Willits (See Figure 4) during the winter of 1996. The failure also damaged a private road below the highway. Three inclinometers were installed in this slide. Coaxial cables were taped to the outside of the inclinometer casings.

Because a TDR measurement is taken at the surface, it has a distinct advantage over inclinometers . For example soon after installation at Willits, one inclinometer was offset so much that the inclinometer probe could no longer be lowered past that point. The cable attached to the casing was still intact and the TDR signature had a sharp spike at the depth where the casing was offset (See Figure 5). Although the inclinometer is no longer functional, the cable continues to provide information on the depth to failure plane and a qualitative feel for the rate of movement.


**Figure 4. Locations Where Coaxial Cables Were Installed For TDR Measurements**

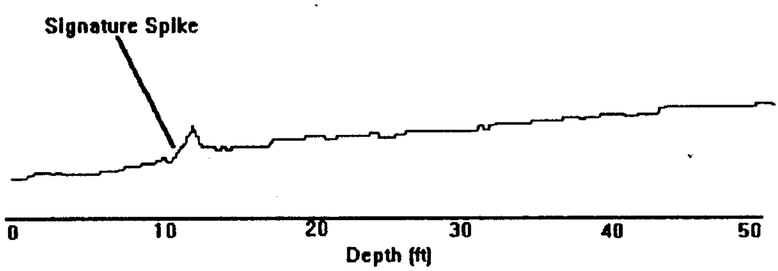



**Figure 5. Cable Signature from Willits Landslide Showing Spike at Location of Inclinometer Failure**

*Redwood National Park Landslide*

The Redwood National Park landslide is a failure of the cut slope adjacent to Highway 101 in Humboldt County just south of the town of Klamath (See Figure 4). In the winter of 1996, the debris from this slide blocked the northbound truck lane.

The terrain around the slide is steep. Drilling holes to obtain subsurface samples and install inclinometers will require pioneering a road into the slide area. Since this slide is in a sensitive region (national park) obtaining the necessary drilling permits is time consuming.

A large diameter borehole is not necessary to install a coaxial cable for TDR. Cables can be installed in a small diameter hole while doing routine soil investigations. In order to get some preliminary subsurface data, three one inch (25.4 mm) soil probe holes were driven into the slide with a "Wacker" - a hand-held, gasoline powered hammer. The hole depths ranged from 20 to 26 feet (6.1 to 7.9 meters) deep. In two of the holes, coaxial cables were installed through the center of the probe rod as it was withdrawn.

*Devil's Slide*

Devil's Slide is massive slope failure in San Mateo County south of the town of Pacifica (See Figure 4). The first historic record of this slide indicates that it was caused/reactivated by the 1906 San Francisco Earthquake. State Highway 1 was built across this slide in the early 1940's and movement of the slide has periodically damaged the highway since then. In the winter of 1995, sliding caused significant damage to the roadway which made it impassable for several months while repairs were made.

TDR can save time when monitoring deep holes or multiple locations. In the winter of 1996, as part of Caltrans' ongoing monitoring of the slide, an inclinometer 356 feet (111 meters) deep was installed in the slide. A coaxial cable was attached to the outside of the inclinometer casing. The inclinometer shows a shear zone from roughly 124 to 164 feet (38 to 50 meters) below the ground surface. The cable shows an impedance spike at a depth of roughly 144 to 152 feet (44 to 46 meters). A TDR reading of the cable takes about five minutes. In contrast, the inclinometer reading takes at least an hour.

*South Willow Creek Landslide*

This installation is a good example of the cost advantage of TDR. The South Willow Creek Landslide is a moderately sized failure of the sea cliff in Monterey County along the Big Sur coast (See Figure 4). This failure removed a portion of the southbound lane of State Highway 1. An inclinometer was installed in the slide to a depth of 56 feet (17 meters). A coaxial cable was attached to the outside of the casing. The coaxial cable purchased for this project was $0.16 per foot while the inclinometer casing cost $5.50 per foot, or about 35 times greater than the TDR cable.

*Cuesta Grade Landslide*

The Cuesta Grade Landslide is in San Luis Obispo County north of the city of San Luis Obispo (See Figure 4). This slide is an embankment failure that damages a section of the southbound lanes of Highway 101. This embankment has a 30 year history of instability.

The traffic is extremely heavy on this section of Highway 101. An inclinometer was installed in the roadway because of the narrow shoulder at this location. Reading the inclinometer requires traffic control and is hazardous for the technicians involved.

To increase technician safety by reducing the number of inclinometer readings needed to monitor this slide, a coaxial cable was installed during May 1996. The cable was attached to a 1.5 inch (38 millimeter) tremie tube grouted in a 94 foot (28.7 meters) deep borehole, and was extended off of the road behind a guard rail. In this instance, Caltrans was able to use TDR to increase safety while not jeopardizing data collection.

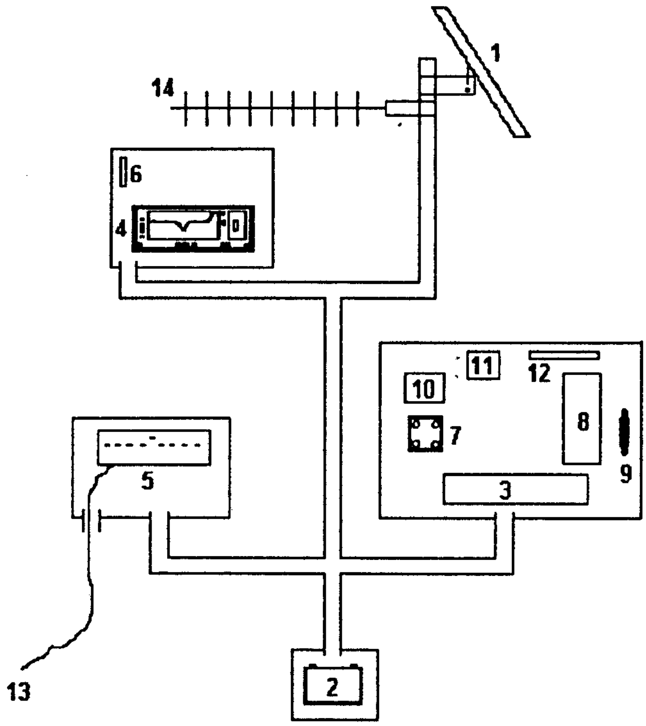
*Grapevine Grade Landslide*

The Grapevine Grade Landslide is in Kern County south of Bakersfield, California (See Figure 4). This slide is a failure of the cut slope next to Interstate Highway 5, a major transportation route between the Mexican border and Oregon. The toe of this slide daylights in the northbound truck lane. The head scarp was already visible in aerial photographs taken in April 1992. By April 1993, the toe had moved enough to rupture a buried oil pipeline.

In the winter of 1995, the California Department of Transportation installed geotechnical instrumentation (inclinometers and piezometers) to determine the slide depth and monitor groundwater levels. Coaxial cables were attached to the outside of the casings on two of the inclinometers and one of the piezometers.

The Grapevine location is in a steep and remote area. Two technicians have been assigned the task of reading the inclinometers. Driving from their office to the site requires two hours. At the site, a steep and difficult climb is required to access the instrumentation locations. All told, reading the instrumentation at this site requires a full day from both technicians.

A remote data acquisition system was installed to do the TDR readings at this site. The system consisted of a cable tester, data logger, multiplexer, cellular telephone, modem, solar panel and battery (See Figure 6). The system allows TDR readings to be taken by computer and modem from anywhere with telephone access.



**KEY**

1 Solar Panel
2 12V Marine Battery
3 Datalogger
4 Cable Tester
5 Multiplexer
6 Transient Suppressor
7 Relay
8 Cellular Phone
9 Hand Set
10 Phone Modem
11 Interface
12 Keyboard Display
13 Coaxial TDR Cable
14 Antenna

**Figure 6. Remote TDR Data Acquisition System**

## POTENTIAL APPLICATIONS OF TDR TO GEOTECHNICAL MONITORING

Caltrans is currently considering additional applications of TDR in geotechnical monitoring. The following is a brief discussion of those applications.

When an inclinometer is installed in an active slide, the deflection of the casing eventually reaches a point where the probe will no longer will pass through it. If the casing is still open, a coaxial cable can be inserted past the bend to the bottom of the casing and grouted in place. In this way, the monitoring life of the borehole can be extended.

Due to the restricted access around many landslides, subsurface samples can only be obtained by drilling angle borings. Since drilling permits require most abandoned borings to be grouted anyway cables can be grouted in place and the holes used for monitoring. Gravity does not affect TDR readings. On the other hand inclinometer readings can have large errors if a boring deviates significantly from vertical (or horizontal for horizontal inclinometers).

The presence of water in the cable dielectric changes its impedance (Dowding and Huang, 1994). By selecting a cable whose dielectric allows rapid water infiltration and has a minimal capillary effect, TDR could be used to monitor groundwater levels. One such cable is currently being manufactured, it has an air-filled helical chamber that serves as the cable dielectric.

Frequent site visits are required where private property or public safety are threatened by continued slide activity. Examples are where the uphill migration of a head scarp would engulf a private residence or where continued sliding would remove part of the roadway. The number of site visits could be substantially reduced by installing a monitoring system consisting of a coaxial cable grouted in a trench and cable tester with remote data acquisition system. Reduced site visits will result in a significant time saving. A computer program could be written and combined with the remote data acquisition system to create a landslide warning system

Flexible wire rope barriers are often used to protect highways from rockfall. These barriers typically are in remote locations, and site visits are required to assure that they are not damaged or overloaded. The number of visits to the barriers could be reduced by attaching coaxial cables and a remotely-accessed TDR system

## CONCLUSIONS

The reliability of TDR technology in determining landslide depths has been demonstrated by the six slopes described in California. TDR cables can be used to reduce or eliminate inclinometer installations in landslides.

TDR costs less and saves time when compared to inclinometer technology. Coaxial cable can be less than 5% of the cost of inclinometer casing. TDR readings require less than 10% of the time it takes to collect inclinometer readings. Remotely accessed TDR systems save additional time by eliminating site visits and the travel time required to collect geotechnical data.

Beside the economic advantages, the safety benefit of collecting TDR readings from the cable end justifies its use for landslide monitoring. In situations where monitoring locations only can be placed in the roadway, TDR can be extended off the roadway. This eliminates the need for traffic control and thereby increases worker safety.

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