REMOTE MONITORING OF UNSTABLE SLOPES USING TIME DOMAIN REFLECTOMETRY[*]

William F. Kane
University of the Pacific
Stockton, California, U.S.A.

Timothy J. Beck
California Department of Transportation
Sacramento, California, U.S.A.

Neil O. Anderson
Neil O. Anderson & Associates
Lodi, California, U.S.A.

Hernan Perez
University of Nevada
Reno, Nevada, U.S.A.

ABSTRACT

Time domain reflectometry (TDR) was originally developed to find breaks in power and communication cables. When a coaxial cable is deformed, the impedance characteristics of the cable change. Changes in impedance are noted as changes in the characteristic TDR signature of the cable. This technology has been adapted to monitor slope and embankment movements. Coaxial cables were placed in boreholes and slope movements monitored remotely by a cable tester and computer at the site, or by using a data logger and cellular phone. Four sites in California were monitored using TDR and the data compared with conventional inclinometer monitoring. Results showed that TDR can reliably determine the depth and location of shear planes. The advantages of TDR are that: 1. cumbersome equipment need not be brought to, or maintained at, the site to monitor movement; 2. slope monitoring can be done from any location with a modem and computer, and 3. installation and monitoring can be economically accomplished. The result is increased safety, and a considerable cost savings.

1.0 INTRODUCTION

Monitoring unstable soil and rock slopes for movement is a continuing problem. In mountainous states such as California, a large amount of desirable residential property is located on or near slopes, and many transportation corridors exist in steep canyons. Heavy winter rains, coupled with soft and unstable soils and rocks, can result in catastrophic and life-threatening landslides. The monitoring of potentially dangerous slopes is essential to the safety of life and property.

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1.1 CURRENT METHODS OF SLOPE MOVEMENT MONITORING

1.1.1 Conventional Practice

Current methods of slope monitoring include extensometers, tiltmeters, surveys, shear strips, and inclinometers. Extensometers use a tape or wire tensioned across the head scarp, or another prominent feature. Any movement is measured as a change in extensometer length and can be used to predict a catastrophic failure. One problem with this system is that it can be triggered by birds, deer, or falling tree limbs (Cann and Steiner, 1992).

Tiltmeters measure the inclination or elevation change between two points. They are usually measured by placing what amounts to an electronic "level" on an imbedded plate with raised knobs. They can have a resolution as fine as 8-mm per 10-m (Franklin and Dusseault, 1989).

Conventional surveys, using electronic total stations or global positioning system (GPS) can accurately determine the three-dimensional coordinates of points. Slope movement is determined by comparing current with previous coordinates. Vectors of surface movement can then be determined.

Shear strips consist of an electrical conductor strip grouted into a borehole. The strip has a parallel string of resistors at fixed intervals along it. When slope movement occurs the strip is broken and the resistance changes. This location can be determined and the depth to the shear surface is then known.

The inclinometer is a probe manually lowered down a specially cased borehole drilled into the slope. Accelerometers detect the orientation of the probe as it moves down the hole. Changes in orientation over time indicate slope movement; rapid changes can suggest imminent failure. Differential movements as little as 0.5-mm to 1.0-mm per 10-m of hole length can be determined (Franklin and Dusseault, 1989).

All methods have inherent drawbacks in their use. One in particular is the necessity for workers to visit sites to collect data. By default, many unstable slopes are found in remote locations, have difficult access, and may be inherently dangerous to have personnel on them. A system that can be remotely contacted has tremendous advantages over conventional installations.

1.1.2 Time Domain Reflectometry

Time domain reflectometry (TDR) is a method of analyzing electrical signals for testing purposes. It originally was developed to find breaks in power transmission cables (Franklin and Dusseault, 1989). This testing method uses characteristics of a returned pulse to determine deformation or a rupture in a coaxial cable.

TDR is now used in geotechnical applications, especially mining (O'Connor and Wade, 1994). For example, a study by the U.S. Bureau of Mines determined the height of rock caving above longwall coal mines (Dowding et al., 1989). Coaxial cables embedded in bore holes before mining were used to infer deformation and collapse in the overburden. This information showed the extent of caving and shearing, and the associated bending of rock strata. Syncrude Canada Ltd. (Lord et al., 1991) and the Canada Centre for Mineral and Energy Technology (Aston et al., 1994) has also experimented with TDR systems in unstable ground in mining operations.

1.2 TIME DOMAIN REFLECTOMETRY

TDR is an electrical pulse testing technique where a cable tester, connected to a coaxial cable installed in a borehole, emits a stepped voltage pulse. Rock or soil mass movements deform the cable, changing the cable impedance and the reflected waveform of the voltage pulse, Figure 1. The time delay between a transmitted pulse and the reflection from a cable deformity determines the damage location. The sign, length, and amplitude of the reflected pulse define the type and severity of the cable deformation (Dowding et al., 1989).

The data consist of a series of TDR signatures. Different wave reflections are received for different cable deformations. A cable in shear reflects a voltage spike that increases in direct proportion to shear deformation. A distinct spike occurs just before failure. After failure, a permanent reflection is recorded. In tension, the wave reflection is a subtle, trough-like voltage signal that increases in length as the cable is deformed. At failure a small necking trough is visible, which is distinguishable from a shear failure (Dowding et al., 1989). By using the wave reflection data, the depth to the failure plane(s) can be established.

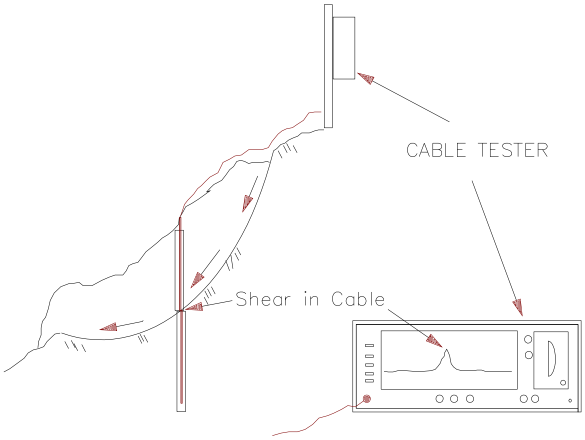

Figure 1. TDR System and Cable Grouted into Borehole

2.0 FIELD STUDIES

2.1 LAST CHANCE GRADE LANDSLIDE

The California Department of Transportation installed a TDR cable in the Last Chance Grade landslide along U.S. Route 101 in Del Norte County, California, Figure 2. (Kane and Beck, 1994). A coaxial cable was secured to the outside of an inclinometer casing for comparison of TDR and inclinometer data.

2.1.1 Site Description

This section of U.S. Route 101 was constructed on the west-facing flank of a 300-m high ridge. It is bounded on the west by the Pacific Ocean and on the east by Wilson Creek. The site is underlain by interbedded shale, sandstone, and conglomerate of the Franciscan Complex. These rocks are intensely fractured, sheared, and weathered to a depth of 15-m.

Superimposed on the ridge is a large landslide complex known as the Last Chance Grade landslide. This landslide is approximately 520-m wide and 460-m long in plan view. The slide is very active, affecting approximately 235-m of the roadway.

Two core borings were drilled into the slide, along the roadway, to obtain samples of the slide mass. Inclinometer casing was installed in the borings to allow the determination of the depth to the slide plane.

2.1.1 Installation and Results

A 6.0-mm diameter braided coaxial cable was attached to the outside of an inclinometer casing with nylon ties spaced approximately every 1.5-m. The cable was 82-m long. The hole was backfilled with coarse aquarium sand, and a tremie pipe was used to flood the hole and compact the sand. A groove was cut in the pavement and extended beneath a concrete barrier. The cable was laid in the groove and a cable connector attached to the end. The cable and connector were placed in a plastic bag for moisture protection. The groove and the top of the inclinometer hole were backfilled with asphaltic concrete.

Figure 2. TDR Locations in California

Inclinometer readings showed that the slide plane was approximately 40-m (130-ft) below the roadway at the center of the slide, Figure 3a. The TDR cable reading, Figure 3b, showed one notable spike. At a depth of approximately 40-m (130-ft), roughly the same depth as the inclinometer deflections, there is a peak in the TDR signature. This reading was interpreted as tension in the cable at the slide plane.

Initial results of this study indicated that TDR could be used instead of inclinometers for landslide investigations. A correlation between TDR signature and slide movement, as shown by the slope inclinometer, appeared to exist. To read the inclinometer, it was necessary to implement traffic control for the safety of personnel. The TDR cable was read from behind the concrete safety barrier. No traffic control was necessary and personnel were protected from vehicular traffic.

2.2 SAN FRANCISCO BAY AREA EMBANKMENT FILL

The TDR cables were successful in a large landslide such as Last Chance Grade, and computer software to view the cable signatures and store them for future comparisons was available. An embankment failure in Contra Costa County, California was chosen to test the system in a soil slope, Figure 2.

2.2.1 Site Description

The Contra Costa County site, near San Francisco, is overlain by Quaternary terrace deposits. The terraces make ideal sites for development, but slope stability is a problem. Several buildings in an apartment complex in the area were constructed partially on native material, and partially on 8-m of fill. The buildings were damaged by long-term creep of a soft layer near the base of the fill slope. Survey data showed differential settlements of up to 0.24-m. The structures underwent significant damage and the ground surface

(a) (b)

Figure 3. Comparison of Last Chance Grade Inclinometer Reading and TDR Signature
(1 foot = 0.3048-m)

developed large tension cracks. Test borings indicated a 1-m thick layer of a very soft, clayey fill at a depth of approximately 5-m.

2.1.2 Installation and Results

Two 10-m deep inclinometer casings were installed in the slope crest along with coaxial cables for TDR measurements. Coaxial cables were installed in different boreholes from the inclinometers and grouted with cement. Three types of coaxial cables (jacketed, 6-mm braided copper; unjacketed, 6-mm braided copper; and unjacketed 13-mm aluminum) were installed and the results compared.

Results from the inclinometer and the TDR cables suggested that no shearing was occurring in the slope. Differential movement of the buildings was due to vertical settlement of the fill material with no lateral movement. Monitoring of the slope is ongoing.

2.3 CALIFORNIA DELTA LEVEE STABILITY

The California Delta is a unique environment where several major rivers converge and flow into the upper reaches of the San Francisco Bay ecosystem, Figure 2. Large peat islands in the Delta are very fertile farmland. Levees have been built around each island to protect from flooding. Oxidation of the peat and drainage has resulted in overall subsidence of the islands, as much as 8-m below sea level at certain times. Levees must be maintained constantly as the weight of the levees causes them to sink into the soft strata below, requiring additional fill. The increased weight, and subsequent continued settling of the levee embankment, results in further deformation. Monitoring of the levees is constant and requires significant expenditures of time and equipment. A remote monitoring system, such as TDR, was ideal for the area, but questions of reliability of the data were important and needed to be answered.

2.3.1 Site Description

A levee undergoing movement was selected for a test of several TDR cables. The island chosen had a mean elevation of approximately 7.5-m below sea level. The levee, approximately 10-m high, was composed of clays and sands above a substrate consisting mostly of peat. The water side of the levee was covered with riprap. Slope movement was toward the interior of the island and a small head scarp of about 0.5-m was present. The head scarp daylighted in the roadway on top of the levee and extended for about 25-m along the top.

2.3.2 Installation and Results

Four coaxial cables were installed in the levee. One cable was a jacketed, 6-mm braided cable, the second was identical but with the outside jacket removed, the third was a 16-mm corrugated copper cable with a plastic jacket, and cable four was a 13-mm aluminum cable with a plastic jacket. The cables were separated by spacers and grouted with a cement grout into a 12.2-m borehole. An inclinometer casing was installed next to the cables about 8-m away.

Figure 4 shows the inclinometer profile approximately four months after installation. A slide plane is clearly developing at 6.4-m. Figure 5 shows TDR cable readings for June, August, and October. June is the intial reading after installation. The October reading was taken on the same day as the inclinometer profile. A spike is visible in the August and October readings, developing at the same depth as the base of the sliding mass shown by the inclinometer. The other cables showed a similar depth and development pattern.

2.4 GRAPEVINE LANDSLIDE

The California Department of Transportation has many landslides it must monitor. Many of these are in inaccessible and remote locations. A remotely accessed system to monitor slope movement would be beneficial to the Department. TDR appeared to have potential to provide such a system.

2.4.1 Site Description

The Grapevine landslide is on the west flank of Grapevine Peak in Kern County, California approximately 55-km south of Bakersfield, Figure 2. The toe of this slide daylights in the northbound truck lane of Interstate Highway 5. In plan view this slide is approximately 275-m wide and 275-m long. There is approximately a 150-m elevation difference between the head scarp and the toe.

The head scarp of this slide was already visible in air photos taken in April 1992. By April 1993 the toe of this landslide had moved enough to rupture a buried oil pipeline. In the winter of 1995, the California Department of Transportation installed inclinometers and TDR cables to monitor movement.

The slide occurred on part of a larger landslide that envelops most of the west face of Grapevine Peak. The dormant slide is approximately 1220-m wide and 1370-m long in plan view. The elevation

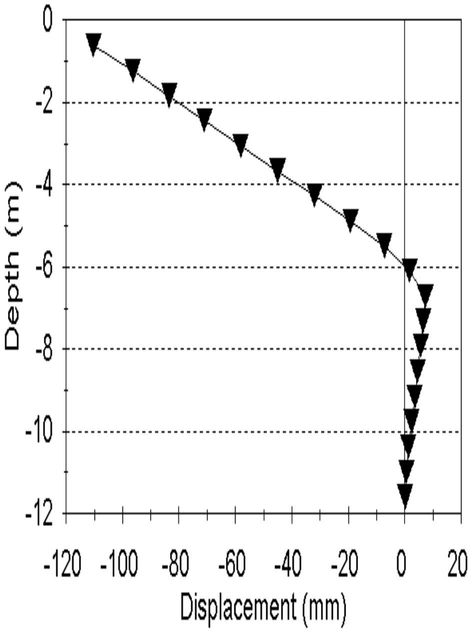

Figure 4. Inclinometer Profile for Levee

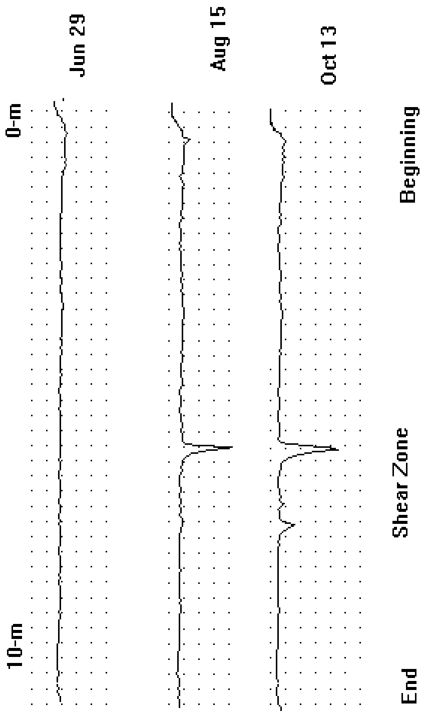

Figure 5. Coaxial Cable in Levee Showing Development of Signature Spike

difference between the head scarp and toe of the dormant slide is roughly 610-m. The dormant slide developed in intensely fractured gneiss. The slide mass is composed of angular blocks of gneiss in a sandy or clayey matrix.

This area is sandwiched between two major active faults, the Pleito thrust, 5-km to the north, and the San Andreas fault zone, 10-km to the south. Although the recent slide was triggered by rising groundwater, earthquakes probably played a role in the development of the dormant landslide.

2.4.2 Installation and Results

TDR cables were installed with other geotechnical instrumentation in three boreholes drilled at the site. Two of the boreholes were in a natural occurring upper bench. The third borehole was on the top bench of the highway cut.

On the upper bench, one borehole was cased with inclinometer pipe and the other with piezometer pipe. A TDR cable was attached to the outside of the inclinometer casing by electrical tape at 3-m intervals. This kept the cable from spiraling around the casing as it was installed. The casing was placed to a depth of 72.2-m. The TDR cable was attached on the downhill side of the casing and the annular space backfilled with cement grout. A second cable was attached to piezometer tubing which was placed to a depth of 91.1-m. The annular space was backfilled to the 30.5-m depth with pea gravel. A 1.5-m bentonite plug was then placed and the remainder grouted with cement.

The third TDR cable was attached to the outside of the inclinometer casing with electrical tape at 3-m intervals. It was placed to the 91.1-m depth and the annular space backfilled with cement grout.

A schematic of the system's remote data acquisition equipment is shown in Figure 6. The slide stopped moving after the instrumentation was installed and the TDR signatures have not changed since initial readings. Remote data acquisition will be continued throughout the next winter and spring.

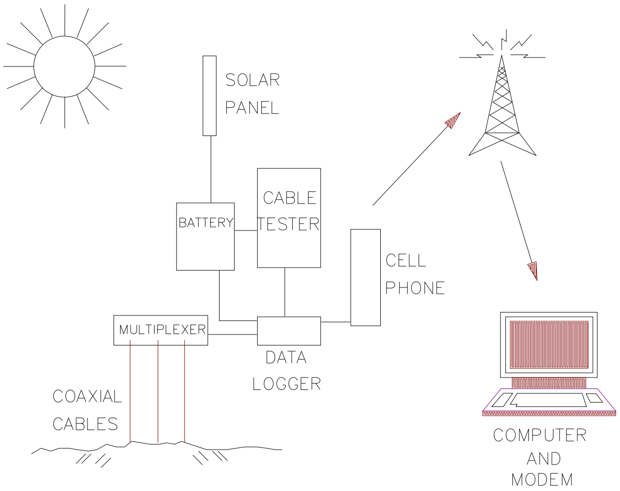

Figure 6. Grapevine Landslide Data Acquisition System

3.0 CONCLUSIONS

TDR uses the characteristics of a returned electrical pulse to detect deformation or rupture of a coaxial cable. It has the potential to be less expensive and labor intensive than an inclinometer for slope monitoring. Advantages include:

- Economic installation and monitoring
- Remote data acquisition so there is no need to visit the site physically. Monitoring can be done by radio, cellular phone, or satellite link
- Increased safety for personnel who do not have to be physically on a dangerous slide or in traffic lanes

Remote data collection also means that hazardous areas can be closely monitored by frequent sampling to detect incipient movements. Another application of this technology could be as part of an early warning system to alert highway officials of a possible catastrophic failure.

4.0 ACKNOWLEDGMENTS

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5.0 REFERENCES

T. Aston, M.C. Betourrar, J.O. Hill, and F. Charette, “Application for Monitoring the Long Term Behaviour of Canadian Abandoned Metal Mines,” In *Proceedings, Symposium and Workshop on Time Domain Reflectometry in Environmental, Infrastructure, and Mining Applications*, eds. K.M. O’Connor and L.V. Wade, U.S. Bureau of Mines Special Publication SP-19-94, pp. 515-527, 1994.

L.R. Cann and E.A. Steiner, "Major Landslide Repairs in Southern California," In *Engineering Geology Practice in Southern California*, eds. B.W. Pipkin and R.F. Proctor, Special Publication No. 4, Association of Engineering Geologists, Southern California Section, Star Publishing Company, Belmont, CA, pp. 503-530, 1992.

CH. Dowding, C.h., M.B. Su, and K.M. O'Connor, "Measurement of Rock Mass Deformation with Grouted Coaxial Antenna Cables," *Rock Mechanics and Rock Engineering*, Vol. 22, pp. 1-23, 1989.

J.A. Franklin and M.B. Dusseault, *Rock Engineering.* McGraw-Hill Publishing Company, New York, 1989.

J.M. Hamilton, A.V. Maller, and M.D. Prins, "Subsidence-induced Shear Failures Above Oil and Gas Reservoirs." In *Rock Mechanics. Proceedings of the 33rd U.S. Symposium*, eds. J.R. Tillerson and W.R. Wawersik, Balkema, Rotterdam, pp. 273-282, 1992.

W.F. Kane and T.J. Beck, “Development of a Time Domain Reflectometry System to Monitor Landslide Activity.” *Proceedings of the 45th Highway Geology Symposium*, ed. S.F. Burns, Transportation Research Board, pp. 163-173, 1994.

E. Lord, D. Peterson, G. Thompson, and T. Stevens, "New Technologies for Monitoring Highwall Movement at Syncrude Canada Ltd." Preprint CIM/AOSTRA 91-97, paper presented at CIM/AOSTRA 1992 Technical Conference, Banff, April 21-24, 97-1 to 97-8, 1991.

K.M. O'Connor and L.V. Wade, "Applications of Time Domain Reflectometry in the Mining Industry." In *Proceedings of the Symposium and Workshop on Time Domain Reflectometry in Environmental, Infrastructure, and Mining Applications*, eds. K.M. O'Connor and L.V. Wade, U.S. Bureau of Mines Special Publication SP-19-94, pp. 494-506, 1994.