ADVANCES IN HIGHWAY SLOPE STABILITY INSTRUMENTATION

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ABSTRACT

Many options are available for monitoring unstable highway slopes. These range from inexpensive, short-term solutions to more costly, long-term monitoring programs. The location of many unstable slopes has created a need for systems that can be accessed remotely and provide immediate warning in case of a failure. Advances in electronic instrumentation and telecommunications make it possible to monitor these slopes economically.

Available electronic instrumentation includes piezometers, electrolytic bubble inclinometers and tiltmeters, and time domain reflectometry (TDR) for sensing changes in slope conditions. This instrumentation can be used in the field by technicians, or remotely by dataloggers and telemetry. By combining instrumentation types, a full array of stability parameters can be gathered. Computer software is available to quickly plot data allowing immediate assessment of the situation.

Several case studies in California illustrate where these technologies were implemented. The use of a technological advance like TDR alone can provide a robust array of data. Budget constraints limited the monitoring of a landslide along the San Andreas fault in San Mateo County to one conventional probe inclinometer and four exploration holes. Instead, the inclinometer was not used and all five holes were instrumented with TDR. This allowed determination of the sequence and extent of the failure. In another case study, TDR was used to locate the depth of a landslide in Mendocino County.

A potentially unstable slope above a sand pit next to Interstate 15 in Riverside County was instrumented using piezometers and TDR. Data on movement and groundwater levels was monitored by cellular phone and modem 350 km away. A soldier pile wall in Santa Cruz County was instrumented with an extensometer and tiltmeter. Data was collected daily by cellular phone. An alarm circuit in the unit notified geotechnical personnel by pager if threshold movements were exceeded. A large landslide in Monterey County employed electrolytic bubble inclinometers in conjunction with a 180 m TDR cable. Threshold movement of the slope triggered a page notifying personnel of changed conditions at the site.

INTRODUCTION

Landslide monitoring involves determining certain parameters and how they change with time. The two most important parameters are groundwater levels in the slope and movement. Movement involves depth of failure plane(s), direction, magnitude, and rate. Depending on the complexity of the problem, one or all of these variables are desired. Piezometers allow the determination of water levels; inclinometers and tiltmeters allow determination of direction and rate, and to some extent, failure plane location; extensometers provide an indication of magnitude; and TDR allows determination of failure plane depth.

Conventional slope monitoring utilizes several methods or a combination of methods. This includes surveying to track the movements of targets on the slope surface, extensometers which record the movement of a wire firmly attached to the slope, and inclinometers. Inclinometers are the most common means of long-term monitoring of slopes.

Critical facilities adjacent to many unstable slopes has created a need for monitoring systems which can provide immediate warning if movement occurs. Advances in telecommunications and electronic instrumentation make it possible to economically monitor slope movements from a distance. Many types of sensors and data transmission systems are available. Several systems were installed in Central and Northern California using extensometers, tiltmeters, inclinometers, and TDR. Telemetry was by either cell phone or hard wire phone. Power was provided by rechargeable lead/acid batteries and solar panels.

There are many manufacturers of the various instruments described in this paper. The authors do not specifically endorse any of these products. Design philosophies and suitability to particular problems vary. Readers are urged to investigate all opportunities before purchasing any instrumentation.

INSTRUMENTATION FOR LANDSLIDE MONITORING

The critical data that are required from a slope monitoring program are the water level(s) in the slope and the depth and rate of movement. There is a wide array of instrumentation used, ranging from simple, mechanical devices to sophisticated electronic equipment.

WATER LEVELS

The usual method of monitoring water levels in a slope is to drill and case a borehole. The water surface is located by dropping a measuring tape down the boring. While useful for simple water table situations, and where monitoring can be done on an infrequent basis, other methods may be more desirable. These methods involve the use of more sophisticated instruments which may be mechanical or electrical.

Vibrating Wire Piezometers

A vibrating wire piezometer, Figure 1, works on the same principle as tuning a guitar or piano (Slope Indicator Company, 1994). A steel wire is stretched over a distance. The wire is set to vibrating by "plucking" it with an electromagnetic field. The natural frequency of the wire is a function of the tension in it. By reducing or increasing tension in the wire, the frequency becomes lower or higher. The frequency of vibration can be sensed by the electromagnetic coil and this is output to a readout device.

One end of the wire is attached to a diaphragm that is deforms by water pressure entering through a porous tip. An increase in water pressure, reduces the tension in the wire by deforming the diaphragm inward. The magnetic coil in the piezometer "plucks" the wire to vibrate it. The wire is plucked using variable excitation frequencies and then allowed to return to its natural frequency. The magnetic coil then becomes a sensor which is used to "count" the number of vibrations. The output signal is then converted into units of pressure or head. Two piezometers are considered ideal. One

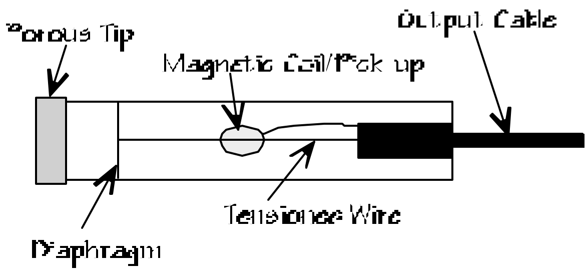

Figure 1. Schematic of vibrating wire piezometer.

should read atmospheric pressure and the other downhole pressure. By subtracting the atmospheric from the downhole pressure, the true water level can be obtained.

MOVEMENT

Inclinometers and tiltmeters are commonly used to monitor slope movement. These instruments use two basic types of sensors. Force balance accelerometers are used in probe inclinometers (Dunnicliffe, 1993). Electrolytic bubbles are used in tiltmeters and “in-place” inclinometers. Probe inclinometers require manual operation. Tiltmeters and “in-place” inclinometers, when coupled with a datalogger, can be used for continuous monitoring. It is also possible to string several force balance inclinometers together in a casing to make an “in-place” inclinometer.

Electrolytic Bubble Inclinometers “In-Place” and Tiltmeters

An electrolytic level is similar to an ordinary “bull’s eye” level. The fluid in this level, however, is an electrical conductor. Also in the level vial are three electrical nodes, Figure 2. One node is located at the base of the vial (B), and two are located on the top (A and C) at an equal distance from Node B. An electrical current is applied to the nodes and the resistance through the fluid is measured. As the vial tilts clockwise the resistance between A and B increases, and the resistance between B and C decreases. The change in resistance can be measured, and is directly proportional to the angle of tilt.

Extensometers

Extensometers often use a steel wireline firmly implanted on the slope face. Movement of the slope pulls a weight along a track. The amount and rate of movement can then be measured.

Extensometers can also use potentiometers to measure movement. Much like the rheostat controls of a model electric train, the extensometer uses a variable resistance mechanism to measure the amount of expansion. A moveable arm makes an electrical contact along the fixed resistance strip as shown in Figure 3. The circuit’s resistance is based on the position of the slider arm on the resistance strip. A regulated DC current is applied and the output voltage corresponds to the amount of expansion and ground movement.

Time Domain Reflectometry (TDR)

Time domain reflectometry (TDR) is a new approach to monitoring slope movement (Kane and Beck, 1994, 1996a, 199b; Mikkelsen,1996; O’Connor and Dowding, 1999). Originally developed to locate breaks and faults in communication and power lines, TDR can be used to locate and monitor the locations of slope failures. This technology uses coaxial cable and a cable tester.

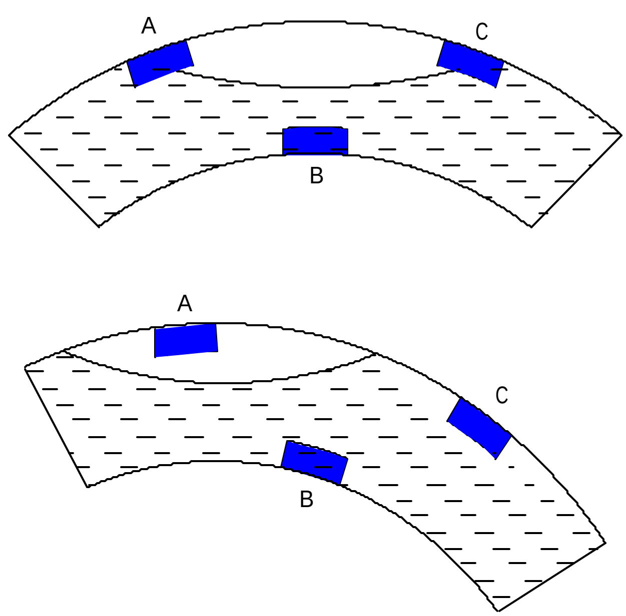

Figure 2. Schematic of electrolytic bubble. See text for explanation.

The basic principle of TDR is similar to that of radar. The cable tester sends an electrical pulse down a coaxial cable grouted in a borehole, Figure 4. When the pulse encounters a break or deformation in the cable, it is reflected. The reflection shows as a "spike" in the cable signature. The relative magnitude and rate of displacement, and the location of the zone of deformation can be determined immediately and accurately. The size of the spike increase correlates with the magnitude of movement. A laptop computer is connected to the tester and cable signatures are written to disk for future reference.

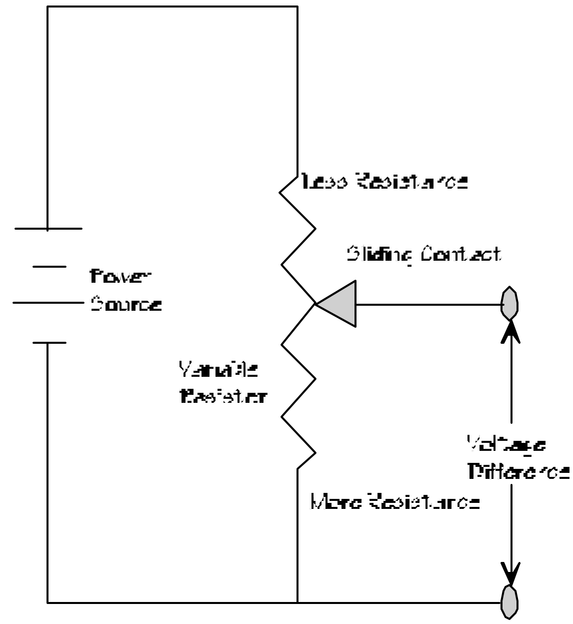

Figure 3. Schematic diagram of variable resistance potentiometer as used in an extensometer.

REMOTE DATA ACQUISITION COMPONENTS

The remote data acquisition equipment includes a datalogger, multiplexer, communication devices, and a power source. In addition, software is necessary to program and interact with the datalogger. Many different manufacturers and equipment exist. Only the equipment used in the case studies are described here. The reader is urged to investigate other manufacturers and approaches.

DATALOGGER

A datalogger is a essentially a small computer CPU/voltmeter with memory. It is programmed to do certain tasks. The Campbell Scientific CR10X logger used for this work can be programmed to output specified voltages over certain durations, read voltages, and store values (Campbell Scientific, Inc., 1997). It can also be programmed to do calculations and store the results such as converting the readings of a piezometer to feet of head.

Instruments are wired to connections, or "ports," on the logger. Control ports and excitation ports can be programmed to output voltages at certain times to turn on peripheral equipment, such as cell phones or cable testers,. Other ports are wired to the sensors and are used to measure output voltages.

MULTIPLEXER

A multiplexers allows many sensors to be attached to a single datalogger. The multiplexer is wired to a single set of ports on the datalogger. A set of contacts in the multiplexer switches between each sensor attached to it.

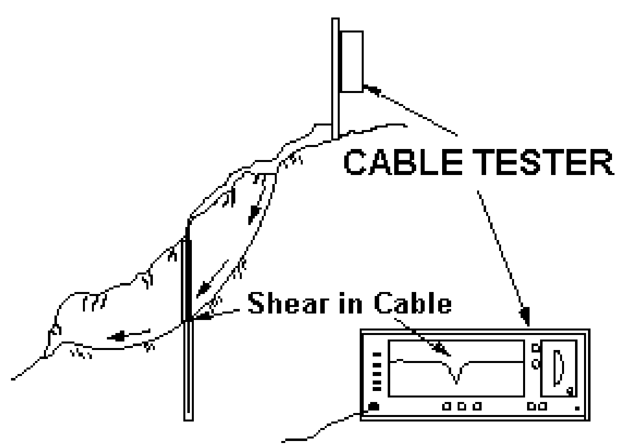

Figure 4. Deformed cable resulting in signature "spike" on cable tester screen.

The data is collected sequentially by the logger. Multiplexers can even be multiplexed to each other creating the ability to read a very large number of instruments. To read more than one TDR cable a multiplexer for this purpose, such as a Campbell Scientific SDMX50 which has 8 connectors for TDR cables, must be used.

COMMUNICATIONS

Communications with the datalogger can be by several means. "Hardwired" telephone lines are best, but not always available. Cellular and satellite telephones can be used as well as conventional and spread-spectrum radios. A telephone line only requires a modem to transmit data and receive instructions. The other methods require modems and cell phones and/or radio transceivers.

POWER

Power requirements vary depending on the number of instruments and the communications device. Ideally, power is available at the site but that is often not the case. A small system with a phone line and one or two sensors requires only a small rechargeable gel-type battery. A large system with cellular phone and cable tester requires a 12 V deep cycle marine battery. The battery is recharged by regulated solar panels.

SOFTWARE

Specialized software is required to process the raw data. When TDR cables are read, signatures can be digitized and downloaded to a laptop computer when using Tektronix, Inc. software (Tektronix, 1994). Plotting several TDR signatures on the same plot requires the user either write a specialized spreadsheet or use a commercially available program such as TDRPlot (Kane and Parkinson, 1998). Piezometer data is best viewed with a spreadsheet. Electrolytic bubble tiltmeters and inclinometers used in the work described here were plotted using TBASEII (AGI, 1998).

In order to program and communicate with the datalogger Campbell Scientific developed PC208W (Campbell Scientific, Inc., 1998). The program allows the user to write code for datalogger control; contact the remote station, either automatically or manually; monitor instrument readings; and download data.

CASE STUDIES

The 1998 El Niño storms of January and February caused a large number of landslides in California (CDMG, 1998; USGS, 1998). Repair of these landslides required immediate action in often hazardous conditions. At some locations, the relative ease and cost-effectiveness of TDR allowed the determination of the depth to the shear plane. At other locations, remote automated monitoring was required during construction to assure the safety of workers and the general public. The locations of the sites described below are shown in Figure 5.

MUSSEL ROCK LANDSLIDE, SAN MATEO COUNTY

Continued long-term movement of the Mussel Rock Landslide necessitated its repair. Repair measures required determining the location of the depth to the failure. Initial plans called for a site investigation of five borings and the installation of a single inclinometer to monitor movement. Because of the cost advantages of TDR, it was decided instead to use TDR cables in all five borings. The TDR was monitored periodically for a fraction of the cost of monitoring the single inclinometer hole. Because five borings were monitored, the depth and areal extent of the slide plane was determined.

Figure 6 contains example of TDR signatures from two cables. Note that failure began at the lowest of the two, B-15 and then progressed to B-18. Cable B-19 showed a similar pattern indicating progressive movement of the slide slices up the slope. Cables B-16 and B-17 showed no change, thus locating the head and toe of the slide as shown in Figure 7.

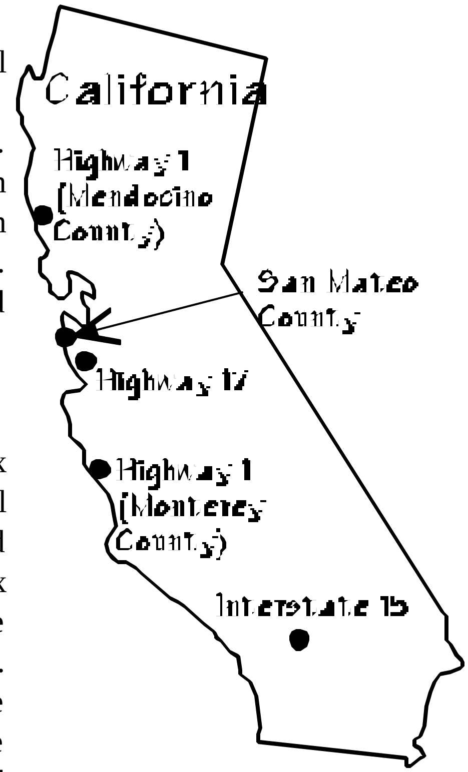

Figure 5. Location map of case studies.

HIGHWAY 1, MENDOCINO COUNTY

A portion of California Highway 1 crosses a landslide complex approximately 200 m (650) wide. In November 1997, a coaxial cable was grouted in a borehole at the site. The boring encountered relatively weak soil on top of competent rock. The slide complex became active as the winter rains infiltrated into the slide mass. The cable deformed at a depth of 6.4 m (21 ft), as shown in Figure 8. This is the soil/rock interface. A second cable was installed in the slide later that winter. It failed accurately located the depth to the shear zone. to detect any movement probably because the slide had stopped moving. The TDR installation accurately located the depth to the shear zone.

INTERSTATE 15, RIVERSIDE COUNTY, CALIFORNIA

Over-steepened slopes in a sand pit adjacent to Interstate 15 in Riverside County, led the California Department of Transportation (Caltrans) to install a monitoring system.

Two TDR cables 52 m (170 ft) deep and two vibrating wire piezometers were installed between Interstate 15 and the pit. A remote data collection system was also installed. It included a datalogger, piezometer signal conditioner, a multiplexer to attach the two TDR cables, and a cell phone and modem for data transmission. Power was supplied by a 12 V deep cycle marine battery and 20 W regulated solar panel. Because the cell phone requires significant current, it could not be kept on at all times.

The system was programmed to read the two piezometers every morning, calculate the head of water present in the slope, and store the values in memory. It then turned on the cable tester and sequentially accessed and digitized the cable signatures from the TDR installations. After data collection the cell phone was turned on and a computer in Sacramento about 350 km (218 mi) away dialed the cell phone number and downloaded the data. The piezometer data was plotted using a spreadsheet program and the TDR data with TDRPlot. Data was collected for over a year before the system was removed for installation at another site.

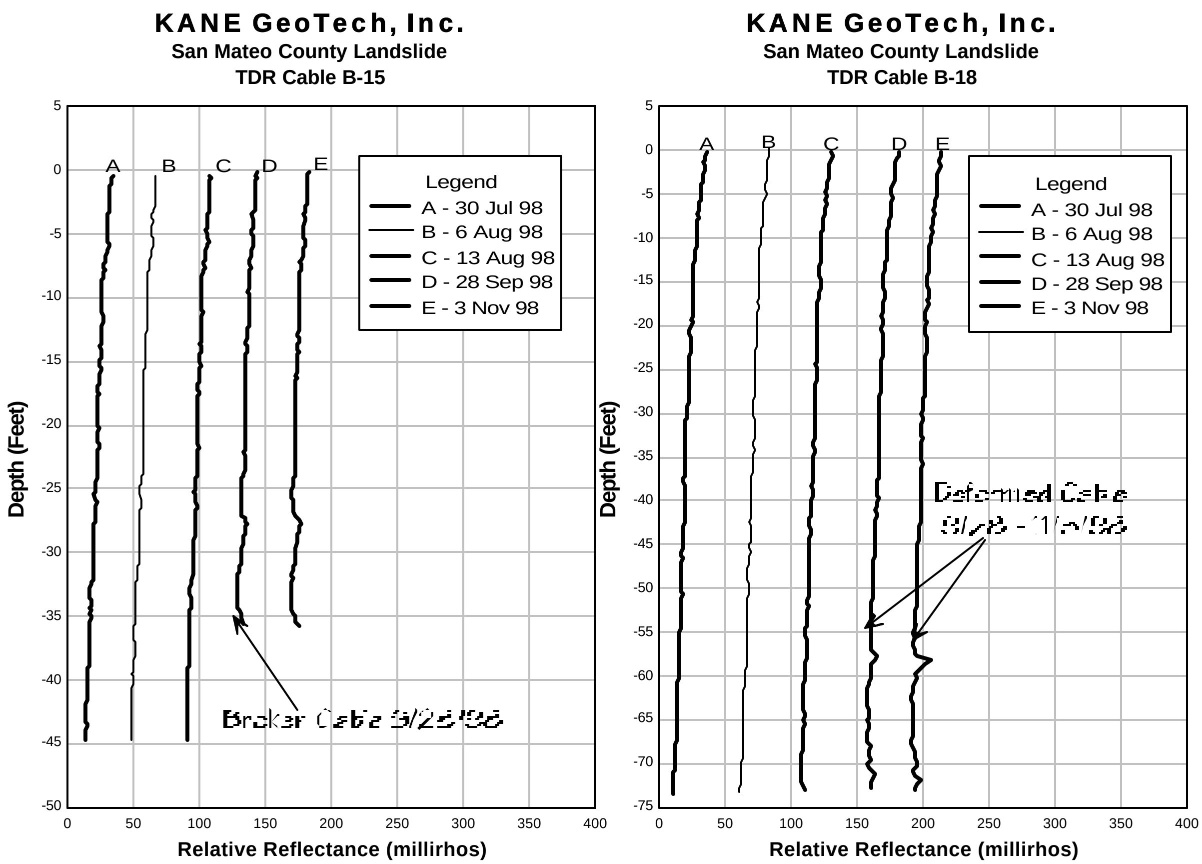

Figure 6. TDR cable signatures from San Mateo County.

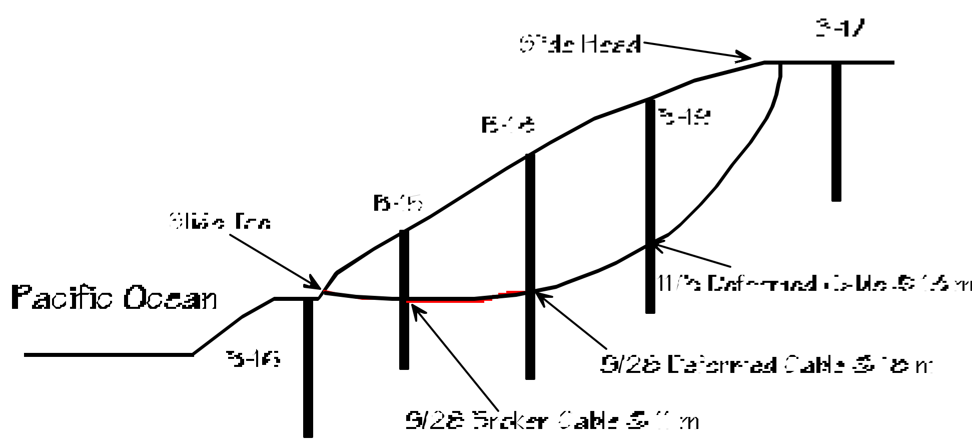

Figure 7. Cross-section of San Mateo County landslide showing dates and locations of cable damage.

HIGHWAY 17, SANTA CRUZ COUNTY, CALIFORNIA

In January 1998, a landslide/debris flow destroyed a small Santa Cruz County road adjacent to California Highway 17. Caltrans constructed a soldier pile wall at the head of the slide to protect Highway 17 from future movement. Caltrans was concerned that progressive failure at the head scarp would jeopardize the wall stability.

A monitoring system consisting of a datalogger, cell phone, and phone dialer was installed. The system monitored a clinometer attached to the wall, and the movement of an extensometer anchored to the wall and embedded at the head of the scarp. The datalogger was programmed to monitor both instruments and determine if a threshold movement was reached. If the threshold was exceeded, the phone dialer immediately notified personnel by means of pagers. The system also was automated to download data everyday to an office computer.

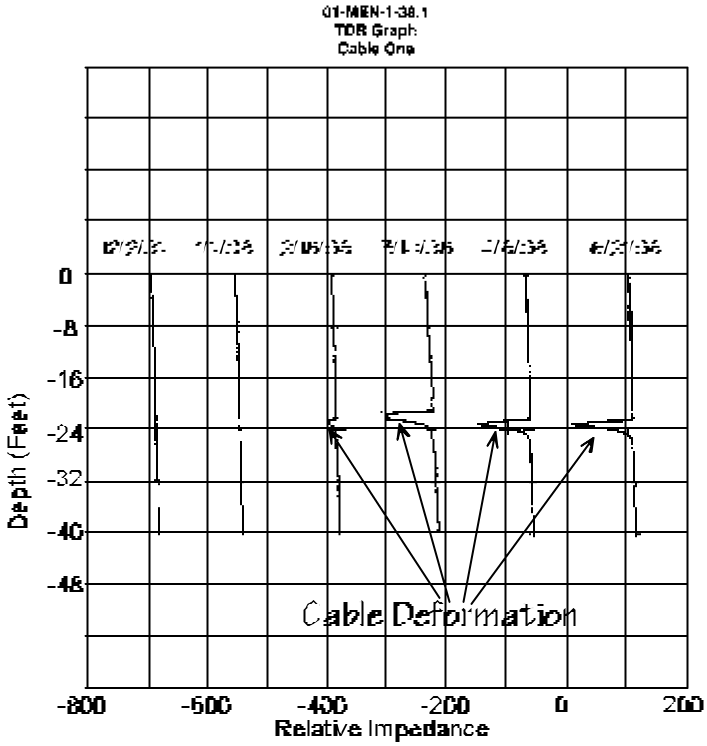

Figure 8. TDR cable signatures from Mendocino County.

STATE HIGHWAY 1, MONTEREY COUNTY, CALIFORNIA

Numerous slides along California Highway 1 in San Luis Obispo and Monterey Counties closed portions of the road throughout the winter of 1998. Grandpa's Elbow Landslide in Monterey County was a reactivation of a older, much larger landslide complex. To protect motorists and clean-up crews, Caltrans instrumented the slide with four downhole, in-place inclinometers attached to a TDR cable in a 200 ft borehole. The inclinometers were placed at the 150 ft, 100 ft, 50 ft, and 10 ft . Any movement of the slide changed the tilt of the inclinometers and triggered a warning by phone dialer and hard-wire telephone line. The system could also be monitored remotely by computer and modem.

Soon after installation, slight movement of the inclinometers triggered the telephone dialer and personnel were paged. TDR cable readings showed the development of a spike in the cable at a depth of 9 m (30 ft) indicating movement, Figure 9. Observation of tension cracks in the ground surface verified the fact that some movement had taken place.

CONCLUSIONS

The huge advances in electronic technology, coupled with rapidly falling prices, make remote monitoring cost-effective and a powerful tool in slope stability work. Instrumentation is available that will provide much of the information necessary, not only to monitor slopes but to obtain some of the necessary parameters for mitigation and remediation.

ACKNOWLEDGMENTS

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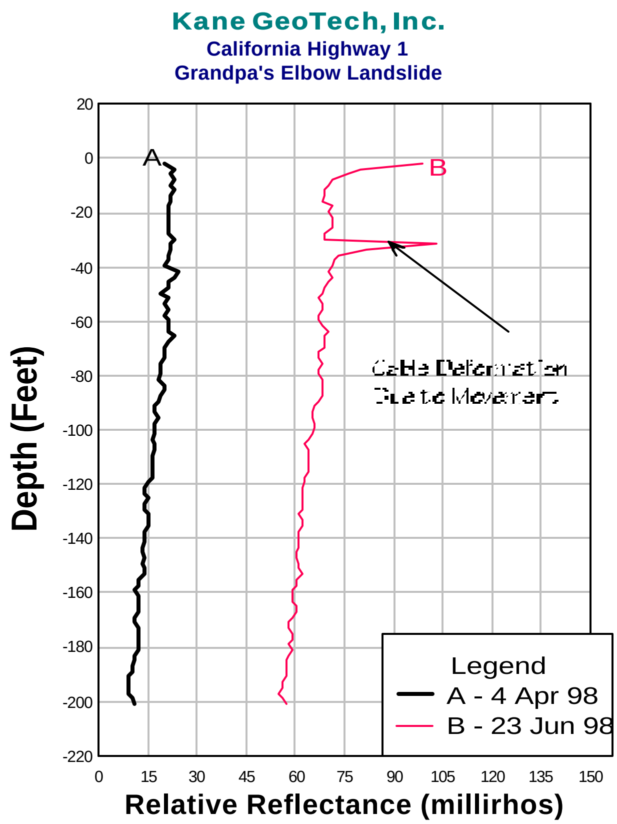

Figure 9. TDR cable signatures showing deformation which activated alarm circuit.

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