

INSTRUMENTATION PRACTICE FOR SLOPE MONITORING

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ABSTRACT

Remote monitoring of slope movement using electronic instrumentation can be an effective approach for many unstable or potentially unstable slopes. Water levels can be observed using vibrating wire piezometers. Movements and deformation can be determined with electrolytic bubble "in-place" inclinometers and tiltmeters, extensometers, and time domain reflectometry (TDR). All of these instruments can be attached to a programmed on-site datalogger. The datalogger can collect readings at selected intervals and trigger an alarm or initiate a telephone message or page if pre-determined movement intervals are exceeded. These systems are self-contained using cellular telephone communications and batteries charged by solar panels. Case studies in Central and Northern California illustrate the use and flexibility of this technology in monitoring slope stability problems.

INTRODUCTION

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

Slope stability and landslide monitoring involves selecting certain parameters and observing how they change with time. The two most important parameters are groundwater levels and displacement. Slope displacement can be characterized by depth of failure plane(s), direction, magnitude, and rate. One or all of these variables may be monitored. Conventional slope monitoring utilizes a single method or a combination of methods. Piezometers allow the determination of water levels; surveying fixed surface monuments, extensometers, inclinometers, and tiltmeters allow determination of direction and rate of slope movement and depth and areal extent of the failure plane; extensometers provide an indication of displacement magnitude. Manually operated probe inclinometers are the most common means of long-term monitoring of slopes.

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

Critical facilities (dams, quarries, highways, housing developments, etc.) adjacent to unstable slopes have created a need for monitoring systems which can provide immediate warning if movement occurs. Advances in telecommunications and electronic instrumentation now make it possible to economically monitor slope movements remotely. Many types of sensors and data transmission systems are available. The case studies described in this paper are monitoring systems installed in Central and Northern California. These systems used one or more of the following types of electronic sensors: 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.

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.

Water Levels

The simplest 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 is required 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 (SINCO, 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 is transmitted to a readout device.

One end of the sensing wire is attached to a diaphragm that can be deformed by water pressure entering through a porous tip. An increase in water pressure from elevated piezometric levels 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 acts as 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 required to make accurate groundwater measurements. One should read atmospheric pressure and the other downhole pressure. By subtracting the atmospheric from the downhole pressure, the true water level can be obtained.

Vibrating wire piezometers should be considered at sites where frequent groundwater measurements are required. For example, a site where rapid groundwater fluctuations are suspected or where measurements are required during a critical event (rainfall, dam release, etc.) Is ideal for using the device. Vibrating wire piezometers cost approximately US \$350

to \$500 each.

Displacement/Movement Measurement

Probe inclinometers, “in-place” inclinometers, tiltmeters, extensometers, and TDR can be used alone or in combination to monitor slope movement (Dunncliffe, 1993). Probe inclinometers require manual operation while the other sensors can be read electronically. The electronic sensors can be coupled with a datalogger for automated data collection. These automated systems also can be combined with telemetry to allow remote data collection. Additional programming of the remote data collection system can be used to trigger a warning of critical situations.

“In-Place” Inclinometers and Tiltmeters. “In-place” inclinometers and tiltmeters can detect new movement, an acceleration of movement, and the direction of movement. “In-place” inclinometers are installed in a borehole cased with inclinometer casing. The wiring for the inclinometer can be buried and the boring covered with a locking cap to vandal-proof the installation. Tiltmeters are mounted at the ground surface. They are an option for those sites that are too steep for a drill rig or if the project budget does not allow for drilling. Tiltmeters also can be covered with a vandal-proof enclosure and wires can be buried.

Electrolytic bubbles are used in tiltmeters and “in-place” inclinometers. An electrolytic bubble is similar to an ordinary “bull’s eye” level, Figure 2. The fluid in this level, however, is an electrical conductor which moves between three electrical nodes. 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. Prices for tiltmeters and “in-place” inclinometers range from US \$400 to \$1000.

Extensometers. Simple mechanical extensometers use a steel wireline firmly connected to a fixed location on the slope face on one end and to a track-mounted weight, located off the

slide, on the other end. Movement of the slope pulls the weight along the graduated track. The amount and rate of movement can then be measured manually. They are very inexpensive, but critical events can be missed if readings are not taken in a timely fashion. These installations are also susceptible to vandalism and animal damage.

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 displacement. 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 displacement along the resistor due to ground movement. The wiring and sensor can be buried to make it vandal and animal proof. Potentiometer extensometers cost approximately US \$800.

Time Domain Reflectometry (TDR). Time domain reflectometry (TDR) is a relatively new approach to monitoring slope movement (Beck and Kane, 1996; Kane and Beck, 1994, 1996a, 1996b; Mikkelsen, 1996; O'Connor and Dowding, 1999). Originally developed to locate breaks and faults in communication and power lines, its first geotechnical use was around 1980 to locate shear zones in underground coal mines (Wade and Conroy, 1980). This technology uses coaxial cable and a cable tester. Some of the advantages of TDR over probe inclinometers are:

1. Coaxial cable costs less than inclinometer casing.
2. TDR readings take several minutes versus inclinometer readings that can take over an hour to complete.
3. The coaxial cable can be extended to a convenient reading location off the slope or away from a highway.
4. TDR readings can easily be automated.
5. Slope movement can be determined immediately during data collection rather than waiting until data is plotted on computer.

TDR does have some disadvantages as well:

1. TDR cannot determine the actual amount of movement. Relative amounts can

be estimated.

2. The direction of movement cannot be ascertained from a TDR signature.
3. The cable must be deformed before movement can be located. Simple bending of the cable, without damage, will not indicate any movement.
4. If water infiltrates a TDR cable, it will change the cable's electrical properties and may make signatures difficult to interpret.

Coaxial cable costs from US \$0.20 to \$2.50 per foot. Cable testers, for reading cable signatures vary from about US \$6000, for a used tester, to about \$10,000 for a new one.

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 roughly with the magnitude of movement, although there is limited research on exact correlations (O'Connor and Dowding, 1999). A laptop computer is connected to the tester and cable signatures are transferred to disk for future reference.

TDR may also be used as a piezometer to monitor water levels by allowing water to enter the cable through holes drilled in the cable. Experience to date is limited and it appears that it cannot measure deformation beneath the water surface. This is because of changes in the cable's electrical properties due to water infiltration (Kane and Parkinson, 1998).

AUTOMATED AND REMOTE DATA ACQUISITION

Automated data acquisition can be done with a datalogger and electronic sensors. This type of system requires periodic visits to the site to download the data. 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.

Datalogger

A datalogger is essentially a small computer and 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 (CSI, 1991a, 1991b). It can also be programmed to do calculations and store the results, for example, converting the readings of a piezometer to feet of head. Dataloggers cost about US \$1200.

Instruments are wired to connections, or “ports,” on the logger. Control ports and excitation ports can be programmed to transmit 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.

By far, the greatest advantage in using electronic instrumentation is the fact that dataloggers can be programmed to perform different tasks automatically. For example, a threshold magnitude of sensor movement can be programmed into the datalogger. If this threshold is exceeded, then the datalogger can trigger an action, such as activating a siren and/or flashing light alarm. In most cases, this action is a phone call using an automatic telephone dialer. These dialers are commonly used for home security systems. They are readily available and cost around US \$400. They can be programmed to deliver a recorded message or page to multiple telephone numbers.

Multiplexer

A multiplexer allows many sensors to be attached to a single datalogger. A single multiplexer can have as many as sixteen instruments attached to it, and multiplexers can be wired to one another for a theoretically unlimited number of instrument hook-ups. 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. The data is collected sequentially by the logger. Multiplexers can be multiplexed to each other creating the ability to read a large array of instruments. Multiplexers can be purchased for about US \$600.

Communications

Communications with the datalogger can be by several means. “Hardwired” telephone lines

are the most reliable, but not always available. Cellular and satellite telephones can be used as well as radio transceivers. 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. Modems cost around US \$400 while cellular telephones with antennas can be purchased for about US \$750 plus monthly service fees. Radio and satellite systems can run about US \$2000 and \$5000 respectively.

Power

Power requirements vary depending on the number of instruments and the communication 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 larger system with cellular phone and cable tester requires a 12V deep cycle marine battery. The battery is recharged by regulated solar panels. Regulated solar panels cost approximately US \$250. Batteries run from US \$25 to \$100.

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 (Huang et al., 1993; 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, 1997).

To program and communicate with the datalogger, programs such as Campbell Scientific's PC208W were developed (CSI, 1997). 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.

Security

Another consideration is instrument security. Weather and vandalism destroy equipment.

Weatherproofing the instrumentation can be done using a fiberglass enclosure that is sealed to the elements. These are available from instrument manufacturers at prices ranging from US \$200 up to around \$800. A protective enclosure often is necessary to prevent vandalism. An enclosure can be as simple as a 2-ft (0.6-m) corrugated metal pipe (CMP) with a steel plate lid. However, steel traffic signal control boxes, costing about US \$800, provide excellent protection.

INSTRUMENTATION CASE STUDIES

The 1998 El Niño storms of January and February caused a large number of landslides in California (CDMG, 1998; USGS, 1998; Bedrossian and Etzold, 1999). 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/warning systems were required during slope reconstruction 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 before construction of a park and golf course complex. 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 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, instead of a single inclinometer casing, the depth and areal extent of the slide plane was able to be determined, as shown in Figure 6. TDR was used in this case to locate the depth and determine the extent of the shear surface.

Figure 7 contains an 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 along the slide plane 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.

Highway 1, Mendocino County

A portion of California Highway 1 crosses a landslide complex approximately 200-m (650-ft) wide, just north of the town of Elk. The depth to the failure plane was required to design the fix for this slide. In November 1997, a TDR cable was grouted in a borehole drilled in the center of the southbound lane. The cable was extended in a groove in the pavement off the shoulder of the road. This allowed readings to be taken without stopping traffic. This saved a significant amount of labor cost and increased worker safety. The slide complex was activated 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, accurately locating the depth to the shear zone at the soil/rock interface. A second cable was installed in the slide later that winter. It failed to detect any movement, indicating that the slide had stopped moving for the year.

Interstate 15, Riverside County, California

The California Department of Transportation (Caltrans) installed a monitoring system in oversteepened slopes in a sand pit adjacent to Interstate 15 in Riverside County. 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 connected to the TDR cables, and a cell phone and modem for data transmission. Power was supplied by a 12 volt deep cycle marine battery and 20 watt regulated solar panel. Because the cell phone required significant current, it could not be kept on at all times without draining the battery completely. Instead, it was turned on for intervals during the day for automated data acquisition.

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 560-km (350-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. The data showed no change in slope conditions during the monitoring period.

State 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 stability of the wall.

A monitoring system consisting of a datalogger, cell phone, and phone dialer was installed. The system monitored a tiltmeter attached to the wall, and an extensometer. The extensometer was attached to the wall at one end and anchored near the head scarp at the other, similar to the diagram shown in Figure 3b. 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. No significant movement of the wall has occurred to date.

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 reactivated an older landslide complex. To protect motorists and clean-up crews, Caltrans instrumented the slide with four downhole, "in-place" electrolytic bubble inclinometers attached to a coaxial cable in a 200-ft borehole. The inclinometers were positioned at depths of 150-ft, 100-ft, 50-ft, and 10-ft, Figure 9. 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 10. Observation of tension cracks in the ground surface verified the fact that some movement had taken place. Because of the shallow nature of the movement and its location relative to the roadway, there was no imminent danger and no action has been taken to date.

CONCLUSIONS

Sensors, including vibrating wire piezometers, electrolytic bubble inclinometers and tiltmeters, and TDR are available to monitor groundwater and ground movement for slope stability. Advances in electronic technology, coupled with economical prices, make remote monitoring cost-effective and a powerful tool in slope stability work. This instrumentation will provide much of the information necessary, not only to monitor slopes, but to obtain some of the necessary parameters for mitigation and remediation.

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 will dictate the appropriate method. Readers are urged to investigate all opportunities before purchasing any instrumentation.

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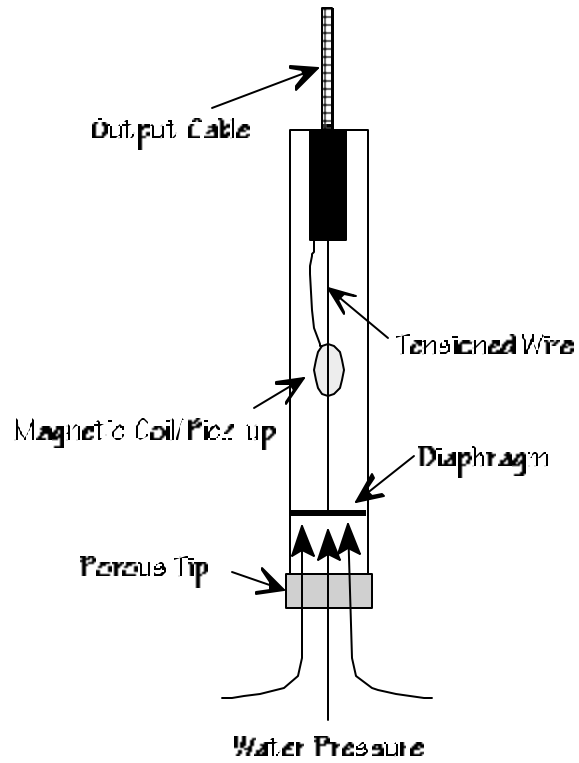


Figure 1. Schematic of vibrating wire piezometer.

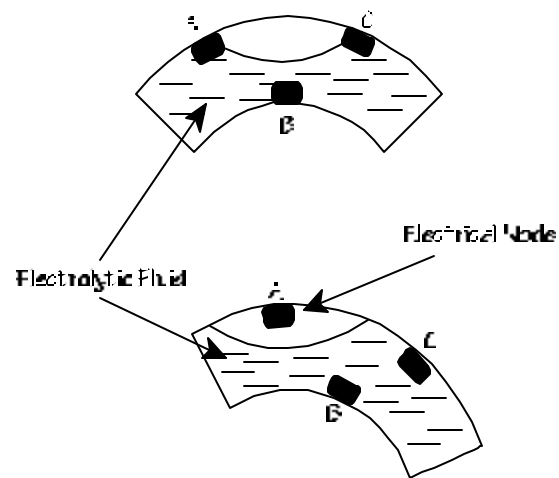


Figure 2. Schematic of electrolytic bubble. See text for explanation.

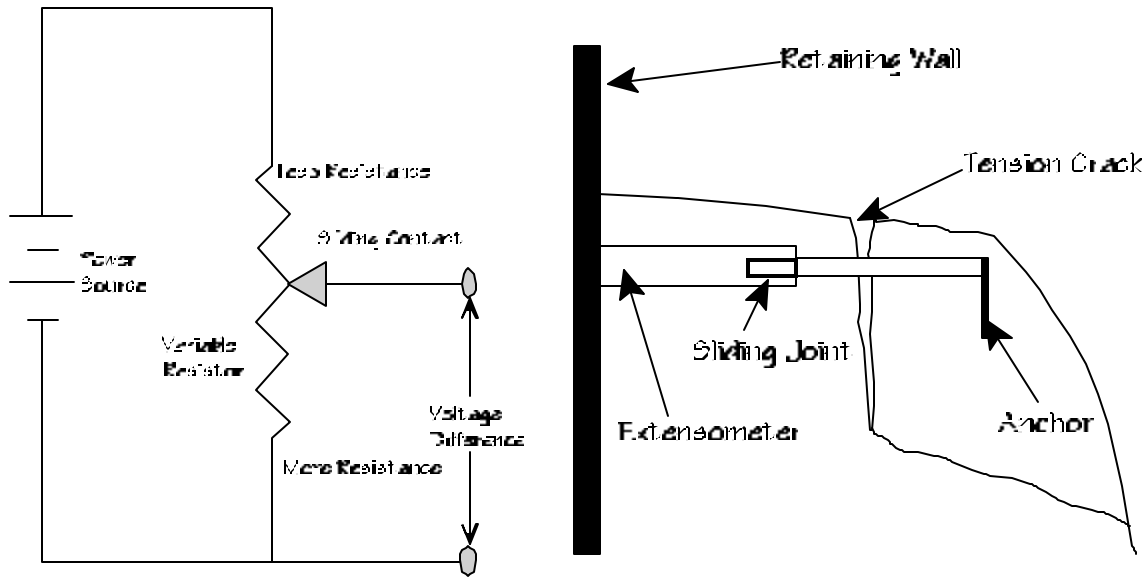


Figure 3a

Figure 3b.

Figure 3. Schematic diagram (Figure 3a) of variable resistance potentiometer used in a slope to monitor movement (Figure 3b). Sliding contact moves within joint to change voltage output of extensometer as slope moves.

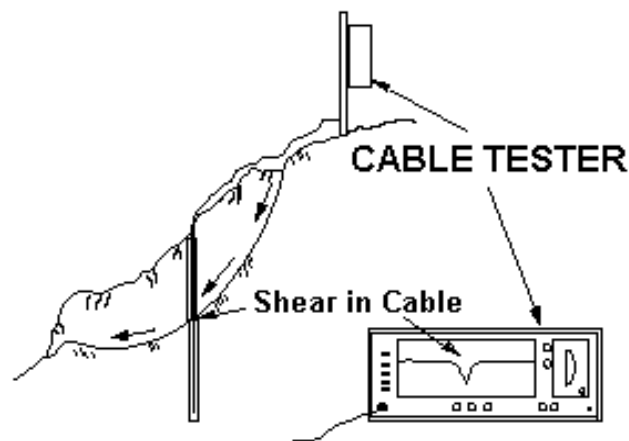


Figure 4. Deformed cable resulting in signature "spike" on cable tester screen.

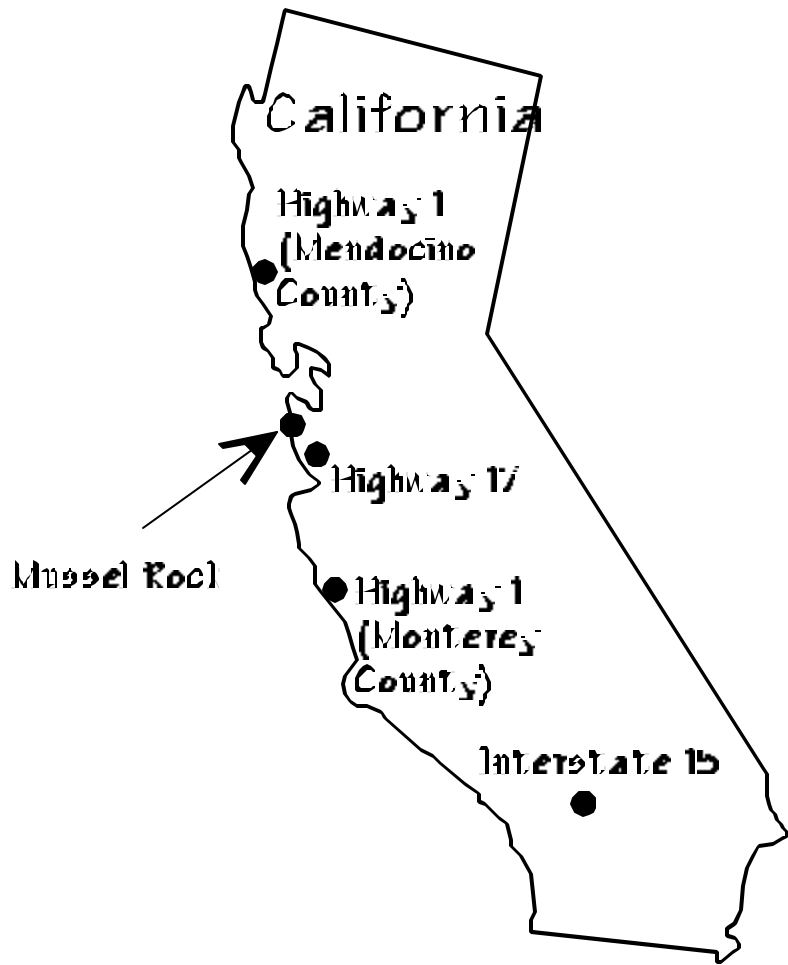


Figure 5. Location map showing case studies.

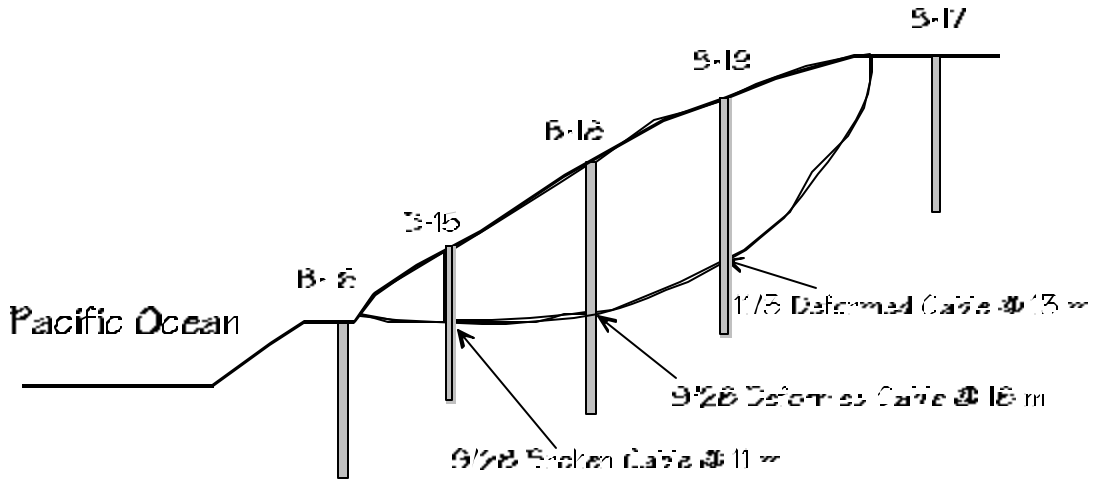


Figure 6. Relative location of TDR boreholes in Mussel Rock Landslide, San Mateo County.

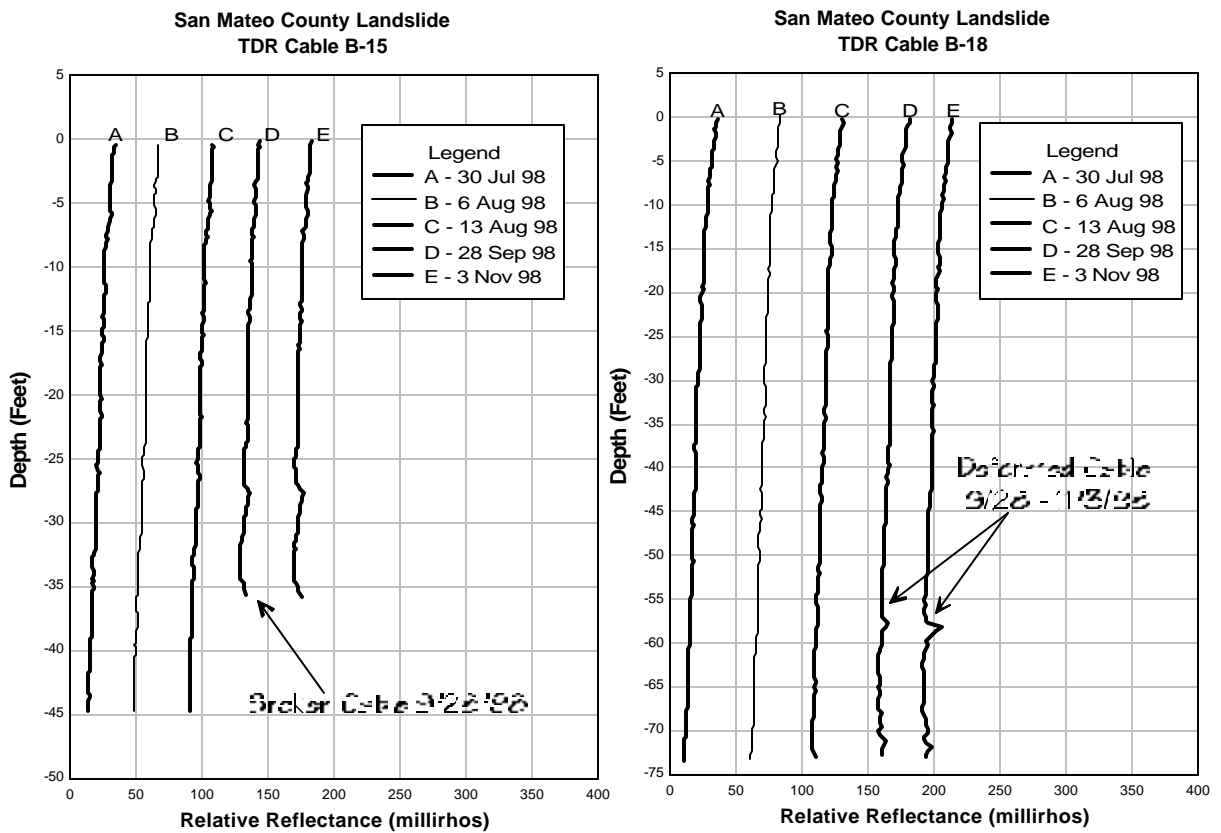


Figure 7. TDR cable signatures from Mussel Rock Landslide.

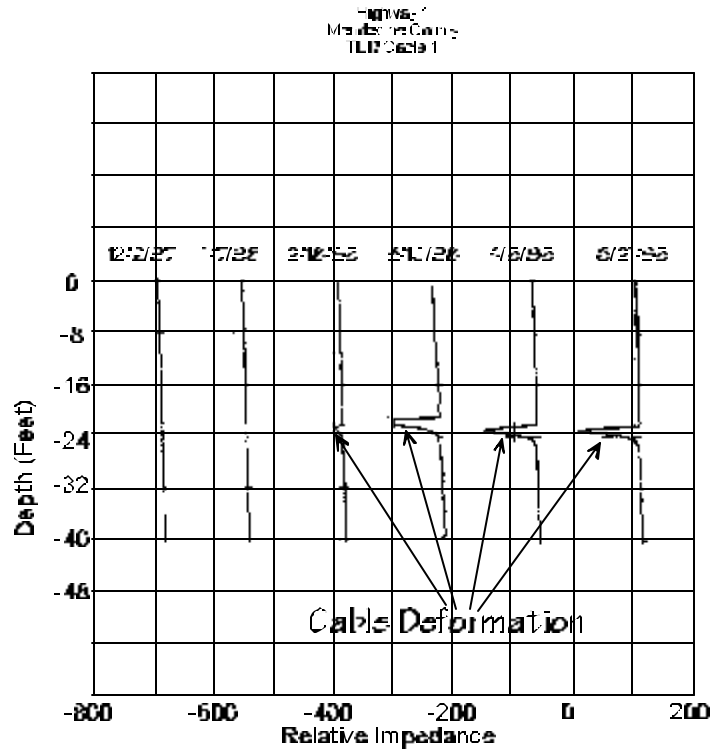


Figure 8. TDR cable signatures from Mendocino County.

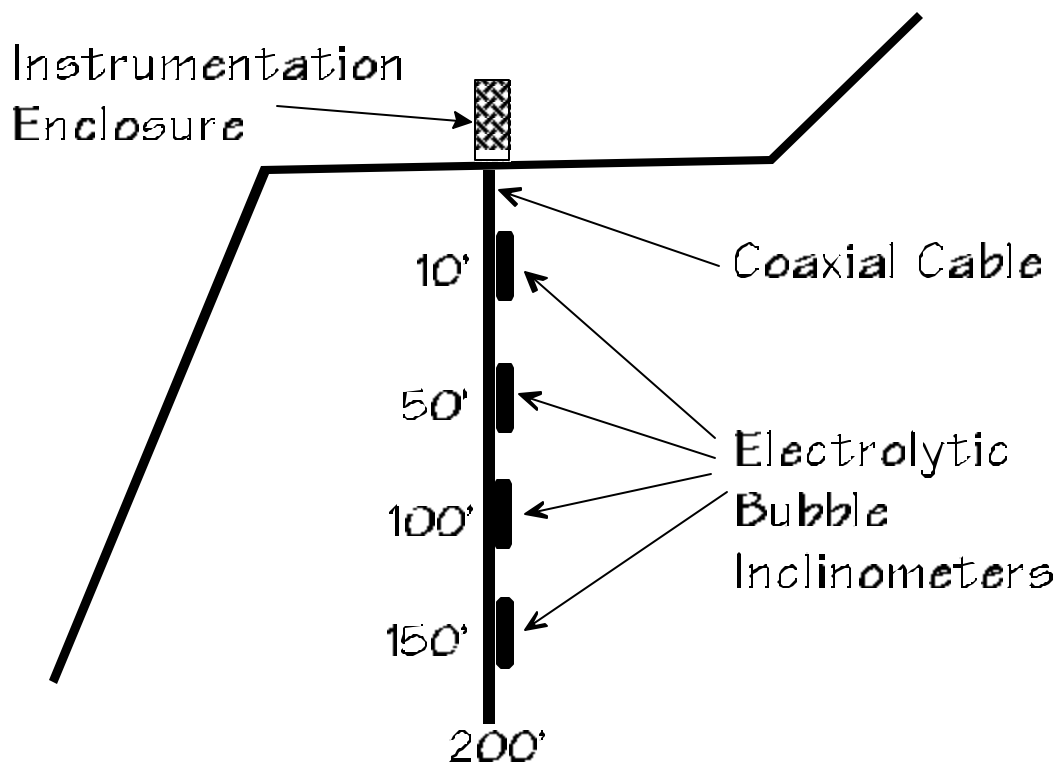


Figure 9. Schematic showing positions of electrolytic bubble inclinometers attached to coaxial cable.

California Highway 1
Grandpa's Elbow Landslide

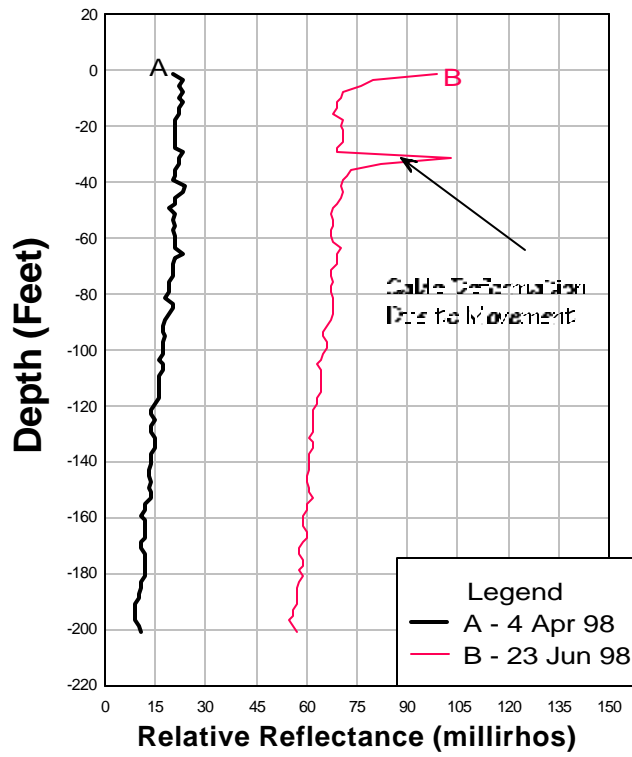


Figure 10. TDR cable signatures showing deformation which activated alarm circuit.