Advances in Slope Instrumentation: TDR and Remote Data Acquisition Systems

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Advances in slope instrumentation: TDR and remote data acquisition systems

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ABSTRACT: Many options are available for monitoring unstable slopes. 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 a failure. Advances in electronic instrumentation, such as time domain reflectometry (TDR), can be combined with electrolytic (EL) bubble inclinometers, vibrating wire piezometers, and extensometers. Telecommunications make it possible to monitor these slopes economically and provide warning of any movement.

1 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 locating the 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. Time domain reflectometry (TDR) can locate 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 probe 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 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.

2 INSTRUMENTATION FOR LANDSLIDE MONITORING

The critical data 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 available, ranging from simple, mechanical devices to sophisticated electronic equipment.

2.1 *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 including vibrating wire piezometers.

2.1.1 *Vibrating Wire Piezometers*

A vibrating wire piezometer, Figure 1, works on the same principle as tuning a guitar or piano. A steel wire is stretched over a distance. The wire is vibrated 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 is output to a readout device.

One end of the wire is attached to a diaphragm that is deformed 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 should read atmospheric pressure and the other downhole pressure. By subtracting the atmospheric from the downhole pressure, the true water level can be obtained.

2.2 *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). Probe inclinometers require manual operation. Electrolytic (EL) bubbles are often used in "in-place" tiltmeters and inclinometers. EL instruments, when coupled with a datalogger, can be used for continuous monitoring. It is also possible to string several EL bubble inclinometers together in a casing to make an "in-place" inclinometer.

2.2.1 *Electrolytic Bubble "In-place" Inclinometers 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. An electric current is applied to the nodes and the resistance through the fluid is measured. As the vial tilts, the resistance between nodes changes. The change in resistance can be measured, and is directly proportional to the angle of tilt.

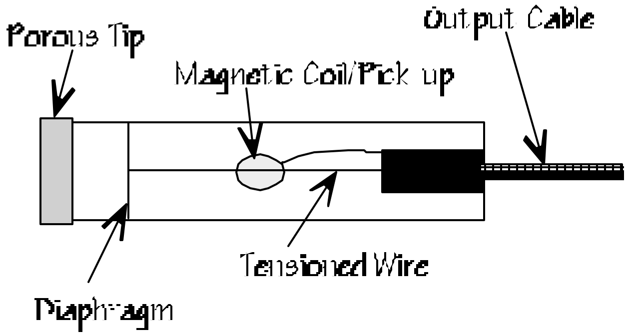

Figure 1. Schematic of vibrating wire piezometer.

2.2.2 *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 2. 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.

2.2.2 *Time Domain Reflectometry (TDR)*

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

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 3. 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

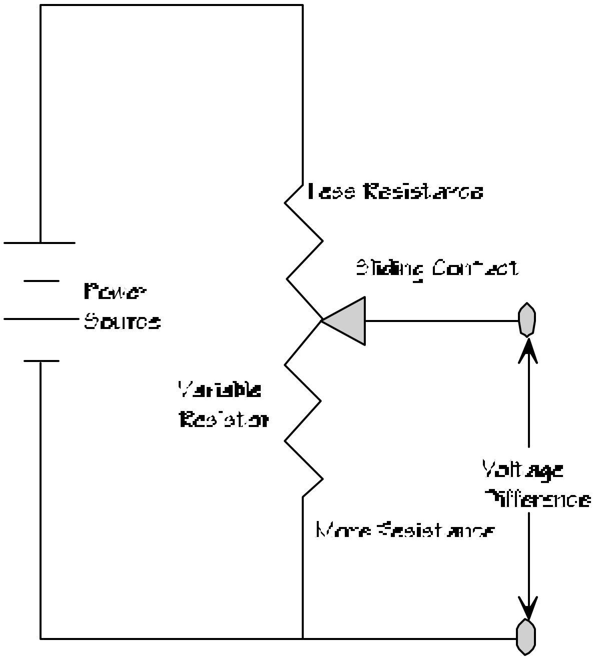

Figure 2. Schematic diagram of variable resistance potentiometer as used in an extensometer.

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.

3 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.

3.1 *Datalogger*

A datalogger is a essentially a small computer CPU/voltmeter with memory. It is programmed to do certain tasks. The datalogger is programmed to output specified voltages over certain durations, read voltages, and store values. It can also be programmed to do calculations and store the results such as converting the readings of a piezometer to meters 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.

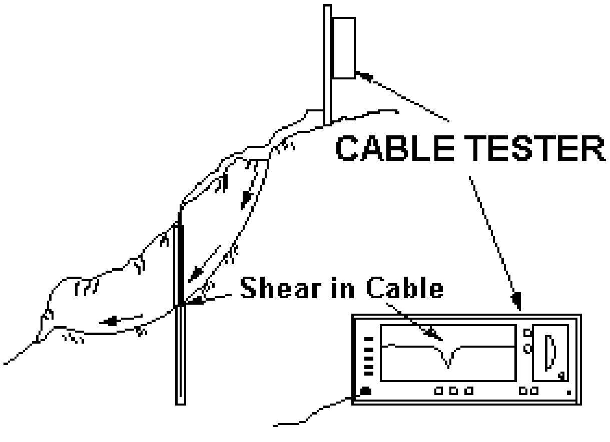

Figure 3. Deformed cable resulting in signature "spike" on cable tester screen.

3.2 *Multiplexer*

A multiplexer 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. 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.

3.3 *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.

3.4 *Power*

Power requirements vary depending on the number of instruments and the communications device. Ideally, power is available at the site but that is not always 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.

3.5 *Software*

Specialized software is required to process the raw data. When TDR cables are read, signatures are digitized using available software and downloaded to a laptop computer. Several TDR signatures taken at different points in time are plotted and compared using a spreadsheet or use a commercially available program (Kane & Parkinson, 1998). Data from piezometers and EL bubble tiltmeters and inclinometers can be plotted with spreadsheets or specialized laboratory plotting software.

In order to program and communicate with the datalogger, software specific to the manufacturer is necessary. These programs allow the user to write code for datalogger control; contact the remote station, either automatically or manually; monitor instrument readings; and download data.

4 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 4.

4.1 *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 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 required 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 the base station computer about 350 km away dialed the cell phone number and downloaded the data. The piezometer and TDR data were plotted. Data was collected for over a year before the system was removed for installation at another site.

4.2 *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 4. Map of California showing locations of case studies.

4.3 *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. One slide, known as 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 61 m borehole. The inclinometers were placed at the 46 m, 31 m, 15 m, and 3 m. 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 indicating movement, Figure 5. Observation of tension cracks in the ground surface verified the fact that movement had taken place.

4.4 *Orange County, California*

The developer of a coastal property was cautioned by its attorneys that slope movements adjacent to the property could pose a concern. The nearby city of Laguna Niguel, in particular, experienced severe damage from El Niño storms. This included a spectacular failure of a 38m slope which destroyed several condominium buildings at the base and caused a number of homes at the crest to plummet down the head scarp (CDMG, 1998).

The site under development contained some weak colluvial material as well as a remnant landslide. Construction plans called for removal of the weak material and construction of an engineered fill shear key. This meant the use of a temporary excavation with steep slopes.

To alleviate fears of litigation by adjacent property owners, and to protect workers and property during construction, an ambitious remote monitoring plan was established. This included the installation of six conventional cased inclinometer borings, eight TDR cables, and ten EL bubble tiltmeters to mount on a retaining wall. In addition, each of the six inclinometer casings had a removable EL bubble inclinometer installed to monitor for movement between readings. Data was acquired daily and stored by a datalogger attached to cellular phone for communications. Alarms were set for each instrument to warn of movement between scheduled automatic readings.

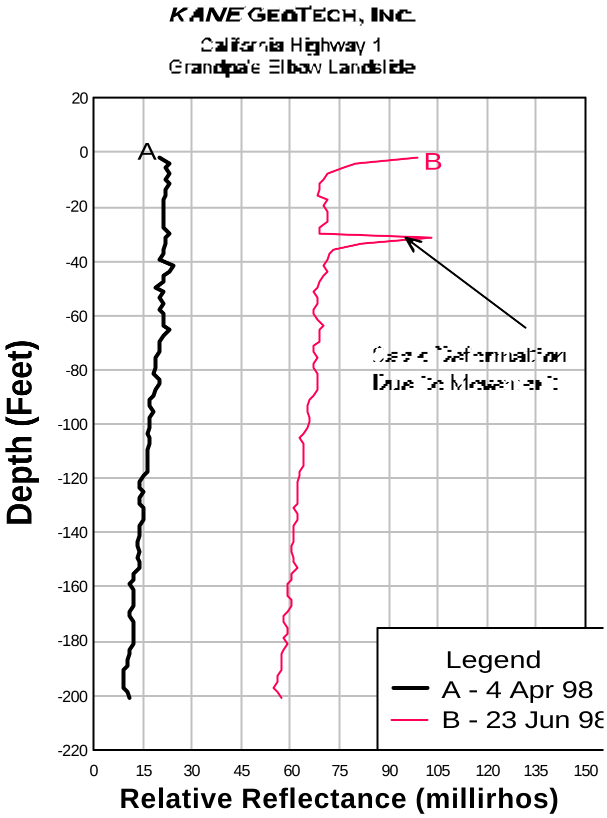

Figure 5. TDR cable signatures showing deformation which activated alarm circuit (1 ft = 0.3048 m).

5 CONCLUSIONS AND REFERENCES

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 eliminates the costly necessity of field visits to acquire data.

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