Instrumentation

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Introduction

This is the ninth episode of GIN. One article and four "column" topics this time.

More on Metallic Time Domain Reflectometry (TDR)

The last issue of Geotechnical News (June 1996) included an article by Kevin O'Connor on metallic TDR. O'Connor indicated various applications, including volumetric water content, rock and soil deformation, water level monitoring, and contaminant transport. The September 1994 issue of Geotechnical News included an article by McKenna et al, which referred to experience with metallic and optical TDR for monitoring slope stability at the Syncrude Canada Ltd Oil Sands Mine. McKenna et al reported:

> *Through laboratory and field experiments, it was found that the system, while good at indicating a movement zone, was difficult to calibrate to shear movements. Also, the direction of movement could not be determined. TDR is an emerging technology with a great deal of potential but its current limitations make it technically unsuitable as a highwall monitoring sensor. One potential application for the existing technology is a warning system where a coaxial cable would be grouted in a hole alongside an SI [inclinometer casing] and would trigger an alarm immediately if a certain displacement or velocity is reached and thus allow timely reading of the SI.*

The following article by Kane and Beck (oh, the joys of receiving an **unsolicited** article!) reports on more experience with metallic TDR for monitoring slope stability, and makes a strong case for using the technology. I would welcome discussions from readers on Kane and Beck's point:

> *In most cases, the depth to the failure plane is the most important information derived from the inclinometer data. Once it is determined, it is possible to estimate the shear strength of the slide mass from back-analysis and develop a repair strategy. The magnitude, rate, and direction of slide movement can usually be determined from surficial features such as development of a head or side scarp, and a slide toe.*

I quibbled with the authors on their use of the world "alternative" in the title of the article, suggesting that we usually need information on:

- Depth of horizontal deformation
- Direction of horizontal deformation
- Magnitude of horizontal deformation
- Time rate of horizontal deformation
- Information throughout any shearing zone

They replied:

> *We do feel that the use of "alternative" is very appropriate. We see MTDR as a time-saving and economic replacement for inclinometers* ***in appropriate situations.***

Any views out there?

New Corps of Engineers Technical Center for Automated Performance Monitoring of Dams

The Corps of Engineers has established the Technical Center of Expertise for the Automated Performance Monitoring of Dams (TCX APMD). The Center will provide Corps-wide technical support for automated data acquisition systems (ADAS) for the performance monitoring of dams and appurtenant structures. The Center will maintain state-of-the-art expertise, provide advisory assistance and design services in the planning, design, layout, system integration, transmission and management of data, as well as assist in the procurement, training and maintenance of ADAS for new and existing projects.

The Center is located in the St. Louis District. It is managed by James C. Brown, telephone 314-331-8410.

Pre-Installation Acceptance Tests for Vibrating Wire Piezometers

Recognizing that if an instrument isn't working perfectly before installation, it isn't likely to work well after installation, pre-installation acceptance tests should always be made. I was asked recently to recommend pre-installation acceptance tests for vibrating wire piezometers that were to be installed in boreholes. I contacted several manufacturers of vibrating wire piezometers to ask for their recommendations, and the following points were made:

1. Temperature transients cause false readings. "Temperature transient" refers to different parts of the instrument being at different temperatures, such that strains occur through the instrument until an equilibrium temperature is reached. To observe this effect, hang a vibrating wire piezometer outside the window on a cold or a hot day, and take a reading every minute. If a vibrating wire piezometer is lowered, on a hot or a cold day, down a water-filled borehole, it will take between 20 minutes and 2 hours, depending on manufacturer, to achieve a uniform temperature and hence to give a correct reading. Gripping a piezometer in the hand can also cause temperature transients. Temperature transient errors cannot be eliminated by using the manufacturer's temperature correction factors, because these assume uniform temperature. Almost all sensors are affected by temperature transients - this issue is by no means limited to vibrating wire piezometers.

2. When a vibrating wire piezometer is in air, it measures atmospheric pressure, just like a barometer. When the

piezometer is submerged in water that is open to the atmosphere, it measures both water pressure and atmospheric pressure. The pre-installation reading therefore depends on barometric pressure. Manufacturers provide a pre-shipment reading and corresponding barometric pressure with each piezometer, and also a temperature correction factor. A pre-installation reading should be established, and this should be compared with the manufacturer's pre-shipment value, correcting for barometric pressure and temperature. If the two differ significantly, the manufacturer should be contacted.

3. If changes **have** occurred between factory and site, they are much more likely to be changes in "zero" reading rather than changes in slope of the calibration plot.

4. Although changes in slope of the calibration plot are unlikely, some users choose to verify that this has not occurred. Three methods are possible, in priority order:
   - Connect the piezometer to a known air pressure source, and check a few points within the range. This can be done in a laboratory. Alternatively some manufacturers provide a small portable pressure chamber with a precise electrical pressure transducer for this purpose.
   - Lower the piezometer within a water-filled pipe, and check that a few readings agree with the level of water in the pipe. If an installed inclinometer casing is available, this can be used. Remember that the water level varies as the piezometer is lowered or raised, because of the volume of the cable below the water level.
   - Lower the piezometer down the borehole in which it is to be installed, and check as above, again remembering the changing water level. Also, an allowance must be made for the likelihood of borehole water not being clean, hence having a specific gravity greater than one.

   In all three methods, time must be allowed for thermal equilibrium.

5. In general, it is difficult to duplicate factory conditions in the field. Pre-installation acceptance tests should be regarded more as function checks rather than check calibrations.

6. If a piezometer with a dry filter is placed in water, surface tension in the filter will affect the reading. Hence, for checking, either the filter should be removed or the filter and cavity should be completely saturated.

7. The same problem can arise if the piezometer is placed in a sand-filled bag.

The above seven points are an attempt to summarize the views of the several manufacturers. However, on several issues there were differing views, and the editor used his casting vote. I'll welcome additions, comments or other inputs, for inclusion in a later issue of GIN.

Software for Predicting and Analyzing Ground Movements

While in England recently I was taken, by Mott MacDonald engineers, on an exciting site visit to two large construction projects in London: a 180 foot diameter cofferdam at Heathrow Airport and an extension of London's Underground (subway) line through the City of Westminster. Both projects have very large instrumentation programs for monitoring ground movements and groundwater pressures, and associated real-time hardware and software. Mott MacDonald has provided the following brief summary of the software:

> *Assessing and controlling ground movements induced by large-scale excavations and tunnels may require extensive monitoring instrumentation, which can generate massive amounts of data. PASS (Prediction and Analysis of Structural Settlement) is a 3-D software package, developed by Mott MacDonald. PASS can manage these large data sets efficiently, to provide predictions and analysis of structural ground movement associated with tunnelling in urban areas, thus minimizing the risks of serious building damage.*
>
> *PASS provides an economical way of analyzing and modelling entire ground engineering projects in 3-D. It offers integrated data and software management, a virtually real-time human/machine interface and tailor-made system for the review, risk assessment and control of structural movement.*
>
> *A model can be created quickly in PASS to represent construction works in an urban area, including existing structures, soil and geotechnical parameters and other data such as the construction program. The way the overlying ground and structures respond to deformation generated by excavation is assessed by PASS, which automatically flags areas where there is potential risk of damage.*
>
> *Provided with this information, engineers can design preventative works, appropriate monitoring systems and also evaluate the need for route alignment changes. For example, the tunnel elements in the model automatically determine where they clash with other known objects in the ground, such as piles, or other tunnels, and alert the user to this fact. The model is also immediately ready to collect data from instruments and to receive excavation progress data. PASS automatically assesses the data and provides early warning of potential problems or trends. Proactive reassessment of the original design assumptions can readily be undertaken.*
>
> *PASS hosts all the software tools necessary for such complex analyses. This makes it ideal for helping engineers to implement the observational method, a technique which uses the results from*

monitoring to modify the way in which construction proceeds, and minimize both risk and cost. In addition, PASS is able to review design assumptions against actual site conditions using whole project data, thus furthering state-of-the-art of analysis and design procedures.

For more information, contact Mick Latham, Mott MacDonald, Foundations and Geotechnics, St. Anne House, 20-26 Wellesley Road, Croydon, CR9 2UL, England, Tel: +44-181-686-5041, Fax: +44-181-681-5706.

Closure

Please send contributions to this column, or a separate article for GIN, to me: 16 Whitridge Road, South Natick, MA 01760. Tel. (508) 655-1775, fax (508) 655-1840.

Isten èltesse! (Hungary)

An Alternative Monitoring System For Unstable Slopes

William F. Kane and Timothy J. Beck

Introduction

Inclinometers are the most common means of monitoring unstable slopes. The method measures the offset over time of an aligned slotted pipe casing 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 are then entered into a computer and analyzed to determine the pipe deflection. The casing offset provides an indication of the failure depth, magnitude and rate of movement, and direction of sliding.

In most cases, the depth to the failure plane is the most important information derived from the inclinometer data. Once it is determined, it is possible to estimate the shear strength of the slide mass from back-analysis and develop a repair strategy. The magnitude, rate, and direction of slide movement can usually be determined from surficial features such as development of a head or side scarp, and a slide toe.

Recently, a time-saving and less costly alternative to inclinometers has been developed. This alternative monitoring system consists of a coaxial cable inserted in a borehole or trench, and a cable tester to determine faults or breaks in the cable. It is based on pioneering research by the U.S. Bureau of Mines. This technology with additional equipment such as a datalogger, cellular phone, and modem permits real time slope monitoring from any location [1,2].

Metallic Time Domain Reflectometry (MTDR)

The California Department of Transportation (Caltrans) has successfully used coaxial cables installed in landslides to determine slide depths. This method is called metallic time domain reflectometry (MTDR).

MTDR was originally developed by the power and communications industries to find breaks in cables. In MTDR, a voltage pulse waveform 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. Should the cable have a change of impedance, 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 measured pulses are known, the distance to any impedance change (cable deformation) can be determined.

Coaxial cables are composed of a central metallic conductor surrounded by an insulating material, a metallic outer conductor surrounding the insulation, and a protective jacket. The cables have a characteristic impedance determined by the thickness and type of insulating material between the cables. 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 even air. If the cable is deformed, the distance between the inner and outer conductors changes as does the impedance at that point. The MTDR cable tester can then determine the location of the deformation.

Data consist of a series of MTDR signatures. Wave reflections are received for cable deformations. The length and amplitude of the reflection indicate the severity of the damage to the cable. MTDR for determining ground movement 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 impedance. This change can be used to determine the position of failure. The change in impedance with time will correspond qualitatively to the rate of ground movement.

Caltrans Installations

Caltrans has begun using MTDR cables in conjunction with their inclinometer monitoring program. Described below are installations in which Caltrans has used the cables.

Last Chance Grade Landslide, U. S. Highway 101

U.S. Highway 101 in Del Norte County has been damaged by the Last Chance Grade landslide in Redwood National Park. This is the main coastal highway between the Oregon border and the San Francisco Bay area. It carries a significant amount of vehicular traffic including many logging trucks. To learn the depth of the slide plane before recommending a repair/rerouting strategy, Caltrans installed two inclinometers in the winter of 1994. One inclinometer was installed in the southbound traffic lane. Attached to the outside of the inclinometer casing was a length of small-diameter, flexible coaxial cable for MTDR measurements. A groove was cut in the pavement and the cable extended off the shoulder of the roadway to a location behind the adjacent concrete guard rail. The borehole was approximately 80 meters deep and was backfilled with coarse aquarium sand. The inclinometer showed a shear plane at a depth of approximately 40 meters. A spike also developed in the MTDR signature at that depth, indicating deformation of the cable due to ground movement.

The advantage of the MTDR installation was that the cable could be read in a matter of minutes by a single technician safely behind the barrier without any interruption in traffic flow. However, reading the inclinometer required a crew of three to four people to reroute traffic to a single lane on a very heavily traveled roadway. The asphaltic concrete (AC) then was removed from above the casing, the inclinometer read, and the AC patch replaced. This process required several hours

Grapevine Grade Landslide, Interstate 5

The Grapevine Landslide is in Kern County next to Interstate Highway 5, the major transportation route between the Mexican border and Oregon. The toe of the slide daylights in the northbound truck lane. The head scarp already was 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 inclinometers to monitor movement, and piezometers to monitor groundwater levels. In addition three MTDR cables were installed with the other geotechnical instrumentation in three boreholes drilled at the site. Two were attached to inclinometers and one was attached to a piezometer.

The inclinometers can only be read by a technician actually visiting the site. The Grapevine location is in a steep and remote area. To read the inclinometers, two technicians travel two hours in one direction from Fresno. In addition the slope is a difficult and dangerous climb. Since each inclinometer is approximately 90 meters deep, the entire process takes a full day.

A MTDR remote data acquisition system was installed to monitor the cable. The remote data acquisition system includes a cable tester, data logger, multiplexer, solar panel, cellular phone and modem. When fully operational, the system will enable movement to be monitored via phone from any computer.

Cloverdale Landslide, U. S. Highway 101

Caltrans installed four inclinometers, with two MTDR coaxial cables attached to them, above a cut slope failure along U.S. Highway 101 in Sonoma County. The inclinometers and cables function as a warning system for homes near the slide scarp. It takes about one hour to read the inclinometers. The MTDR cables can be read in ten minutes and any movement can be detected immediately from the signatures without any further data processing.

Willets Landslide, State Highway 20

An inclinometer casing can only undergo a certain amount of curvature before the probe will no longer pass through it. After that the inclinometer cannot be used, and any shear planes developing below that point cannot be detected. Sticking and losing the inclinometer in a deformed casing is also possible — a significant financial risk.

A small landslide damaged Highway 20 in Mendocino County during the winter of 1996. The failure also affected a private road below the highway. Inclinometers, with MTDR coaxial cables attached to the casings, were installed in the private road and next to Highway 20. Soon after installation one inclinometer in the private road experienced too much deformation to insert the inclinometer probe. The MTDR cable attached to the casing, however, was still operational and showed a severe deformation at the location where the casing showed movement. Although the inclinometer is no longer functional, the MTDR cable continues to provide information on the depth to the failure plane(s) and a qualitative feel for the rate of movement.

Devil's Slide, State Highway 1

Devil's Slide, on California Highway 1 in San Mateo County, is as much a sensitive political problem as an engineering problem. The slide has a long history of movement, but in the winter of 1995, it damaged the road causing it to be closed for several months. Caltrans repaired the slide and installed a large-scale movement warning system that trips an alarm, turns on an electric sign board, and pages maintenance supervisors. To monitor small-scale slide movement an inclinometer and two MTDR coaxial cables were installed in the winter of 1996. One cable is stronger and thicker than the other. It is believed that it will survive more movement than the inclinometer and the thinner cable. This will allow monitoring to continue over a longer period of time.

Slopes that are undergoing rapid movement, such as Devil's Slide did, may expose the technician to landslide or rockfall danger. Since moving slopes are of the most interest to the geotechnical engineer, this prevents real-time monitoring of the slide potential. Using MTDR in such a situation allows data collection and monitoring to be done safely away from the slide. It also is possible that MTDR, with the correct software, can serve as an early warning system. MTDR can help determine if catastrophic movement is impending rather than "after-the-fact" as with the present warning system at Devil's Slide.

Comparison with Inclinometers

In many circumstances, there are clear advantages to using MTDR over inclinometers. Listed below are comparisons between the two technologies:

1. Cost

Cable has a significant cost advantage vs. casing. Some cables can be purchased for as little as $0.17/foot as opposed to $6 to $10/foot for inclinometer casing. The cost of the electronic equipment is approximately the same: roughly $8000 per unit. For remote installations, dataloggers and cellular phone equipment run another $2000. The cost of drilling is the same. With MTDR there is no risk of losing an expensive probe due to a kink in the inclinometer casing, only expendable cable is lost.

When MTDR is installed in highways, traffic control is not necessary. Cables can be run under the pavement.

2. Time

Besides the cost savings in equipment, the rapid reading of MTDR cables means that more holes can be read in less time — an additional savings in personnel time. A single cable can be read in about 5 minutes or less as opposed to ½ hour to an hour to read an inclinometer. Multiple cables at a site can be run to an easily-accessible central location and all cables read at the same time.

3. Remote Access

Telemetry using a datalogger and cellular phone can be installed for real-time readings and/or difficult access areas without the need to visit the slope. In-place inclinometers are available, but they are expensive and must be considered sacrificial.

4. Safety

With MTDR data collection can be done from a safe location, even from an office with remote data acquisition equipment. It is not necessary to expose a technician to dangerous traffic, or to landslide and rockfall hazards on moving slopes.

5. Data

In most unstable slope situations, the questions that need to be answered are: is it moving?; where is it moving?; and how fast is it moving? MTDR provides this information quickly. It is not necessary to download data from a readout box into a computer and then plot the results. The screen on the cable tester shows the cable signature immediately. By comparing cable signatures over time, the location of any slip and changes in the rate of movement can be determined. Different cable testers are available that can locate a deformation in the cable accurately to 0.3 mm along 600 m, or within 0.3 m along 15,000 m of cable. Rates of deformation can be determined by plotting the magnitude of the spike in the cable with time.

In some instances, the direction and magnitude of slope movement must be determined. At present MTDR cannot provide this information. Research is currently being done in these areas, and there is great potential in optical time domain reflectometry (OTDR) in this respect [3].

Conclusion

Experience with MTDR shows that it is a cost-effective alternative to inclinometers in many instances. It provides quick and easy monitoring of slope movement. It can accurately locate a shear plane and provide an indication of changes in the rate of movement.

MTDR is not suitable for every situation. It cannot provide the shape of the cable, and relating cable measurements with an amount of movement is very difficult at this time. However, most landslide monitoring programs require only that the location and rate of movement be known. In these cases, MTDR is a very attractive alternative.

In the future, MTDR will be installed in horizontal trenches along slope crests to locate scarps and provide early warning systems for movement. MTDR cables have the potential to be installed in small diameter boreholes or casings that have deformed too much for inserting an inclinometer probe.

Cable applications are being developed that will measure both groundwater levels and deformation. The technology already exists to create satellite uplinks for very remote locations.

Computer systems will monitor telemetry stations and provide warning of changes, all tied-in with GPS/GIS to provide quick real-time monitoring of moving areas.

References

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2. O'Connor, K., "Geotechnical, Environmental, and Infrastructure Applications of Metallic TDR," Geotechnical News, June 1996.
3. Tsang, C.M., and England, G.L., "Potential of Fibre Optic Sensing in Geotechnical Applications," Geotechnical News, December 1995.

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