Geotechnical
Instrumentation
NEWS

Geotechnical Instrumentation News

John Dunnicliff

Introduction

This is the forty-fifth episode of GIN. Three articles this time.

Recently Developed Technologies

I've been trying to find authors who are willing and able to write articles about recently developed technologies – it seems to me that one of the purposes of GIN should be to disseminate this kind of information. Within the last three years we've had the following:

- Measurement of pore water suction (negative pore water pressure). *December 2002, March and June 2003, September 2004 and March 2005.*
- Motorized total stations. *March 2003.*
- Time domain reflectometry. *March and June 2003.*
- Strain monitoring on geotextiles. *March 2004.*
- Landslide warning systems based on rainfall data. *September and December 2004.*
- Measurement of pore water pressure during earthquakes. *December 2004.*
- Acoustic emission. *September 2005.*

As part of this 'campaign', David Rutledge and Steven Meyerholtz agreed to write the following article on the global positioning system (GPS). It was certainly an eye-opener to me to realize how rapidly this technology has advanced, such that we can now make horizontal and vertical displacement measurements with an accuracy of +/- 1 millimeter.

The second article in this episode of GIN is about wireless tiltmeters, by Claus Ludwig and Etienne Constable – again a recently developed technology.

I have provisional agreements with some colleagues who I hope will be willing to write articles about fiber optic sensors, more on motorized total stations and more on time domain reflectometry. If you know of people with expertise in other recently developed technologies that are applicable to geotechnical monitoring, I hope you'll let me have contact information.

Earth Pressure Cell Readings

The third article, by Lyne Daigle, provides more information on the influence of temperature on earth pressure cell readings. There have been several articles on this subject in earlier episodes of GIN, and they are referenced in this one.

FMGM-2007

The next international symposium, *Field Measurements in Geomechanics (FMGM),* will be held in Boston in September 2007. When dates are finalized, details will be on *www.geoinstitute.org*. For more information about these symposia, please visit *www.fmgm.no*.

Cricket Yet Again

Did you read all that stuff about cricket in the previous episode of GIN? Ready for a bit more? No? Come on – have an open mind! The primary competition during the summer was a best-of-five series between England and Australia – the most prestigious series in international cricket, called "The Ashes". I won't bore you with an explanation of that! It's been going on since 1880, recently once every two years, alternately here and there. Australia had won all of the last nine series – as I said last time, they've been the undisputed World Champs. But their reign ended this summer. And what an end!

Each game can last up to five days (hard for USA folks to comprehend that, I know!). Four of the five were 'down to the wire' events, with grown men and women hiding behind the sofa because to watch any more on TV was too stressful! Generally acknowledged as the most exciting series ever. The score in one was England 589 runs, Australia 587. Now – don't think of this as akin to basketball, in which scoring often alternates between teams. It's like baseball, with two innings each, so such a close score is extraordinary. After the series victory the England team was driven through London in open-top double-decker busses, cheered by two million, thence to a celebration in Trafalgar Square and a visit to 10 Downing Street. Irene and I are suffering from withdrawal symptoms.

Closure

Please send contributions to this column, or an article for GIN, to me as an e-mail attachment in MSWord, to *johndunnicliff@attglobal.net, or by fax or mail: Little Leat, Whisselwell, Bovey Tracey, Devon TQ13 9LA, England.*
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Salute! (Italy)

Using the Global Positioning System (GPS) to Monitor the Performance of Dams

David R. Rutledge
Steven Z. Meyerholtz

Introduction

Global Positioning System (GPS) instruments are proving to be very useful for long-term performance monitoring of dams and other large structures. A growing number of these instruments are being deployed in differential GPS (DGPS) networks that take advantage of measurement-improvement information from an integral GPS reference station. Recent work at Libby Dam in Montana demonstrates that DGPS systems can very accurately track horizontal and vertical displacements at critical points along the crest of the dam. The horizontal and vertical accuracy of the displacement measurements at Libby Dam, for example, is +/- 1 millimeter for a daily mean solution based upon 17,280 measurements (Rutledge and Meyerholtz, 2005).

Engineers are increasingly drawn to GPS instrumentation for a variety of reasons. GPS receivers provide true three-dimensional measurements and have excellent long-term stability. The GPS sub-system (GPS hardware, wireless radio hardware, and photovoltaic hardware) includes solid-state electronic components that are reliable and well suited to automation. The signal coverage from the GPS satellites is “always on” which means that continuous measurements are readily available. Fixed GPS stations can be quickly installed, and have small footprints. These characteristics make DGPS systems cost-effective when compared with other monitoring techniques, and establish GPS overall as a valuable instrument for observation and surveillance of dams and other large structures.

The U.S. Army Corps of Engineers and Condor Earth Technologies, Inc. installed a DGPS monitoring system at Libby Dam in February of 2002. Six GPS monitoring stations are located along the crest of the dam to measure horizontal and vertical displacements, and a GPS reference station is located on each side of the dam to provide differential correction information. A processing sub-system collects raw measurements from all eight GPS stations and computes DGPS solutions in real-time. Four of the GPS monitoring stations on the crest of the dam were installed coincident with existing plumb lines in order to compare directly the readings of horizontal displacement from each measurement system. In this article we present the correlation between the DGPS data and the plumb line data, and discuss the implications for dam safety and risk management.

Instrumentation Background

Libby Dam is located on the Kootenai River in Northwest Montana. It is a straight axis concrete dam composed of 47 monoliths (ML). The U.S. Army Corps of Engineers owns and manages the dam and actively monitors its performance. This careful monitoring effort is managed by engineers who continually analyze readings from the instrumentation deployed on the dam. Besides the DGPS system, the instrumentation at Libby Dam includes plumb lines, joint meters, foundation deformation meters, extensometers, uplift pressure cells, inclinometers, concrete temperature meters, and leakage measurements.

The DGPS system was installed at Libby Dam to replace a laser alignment system. The laser equipment became increasingly difficult to maintain in the 1990s, and it became apparent that a replacement system was needed. The pilot installation of an automated DGPS alignment system was selected for various reasons. One of the major concerns with the laser alignment survey was that the end points of the dam were assumed to be stable, when in actuality this might not be the case. The U.S. Army Corps of Engineers concluded that a DGPS system could solve this problem by utilizing stable GPS reference stations located away from the dam. The DGPS system has the added benefit that the integrity of each reference station can be easily monitored. This is accomplished by periodically calculating the reference station positions vis-à-vis the global reference frame (International Terrestrial Reference Frame (ITRF)). This process is easy to do, does not require fieldwork, and provides a comprehensive quality assurance mechanism.

The Corps also decided to pursue a system that could provide continuous measurements at key monoliths. These continuous data were deemed to be more valuable for analysis than the twice-yearly laser survey, and would allow data to be collected for true peak

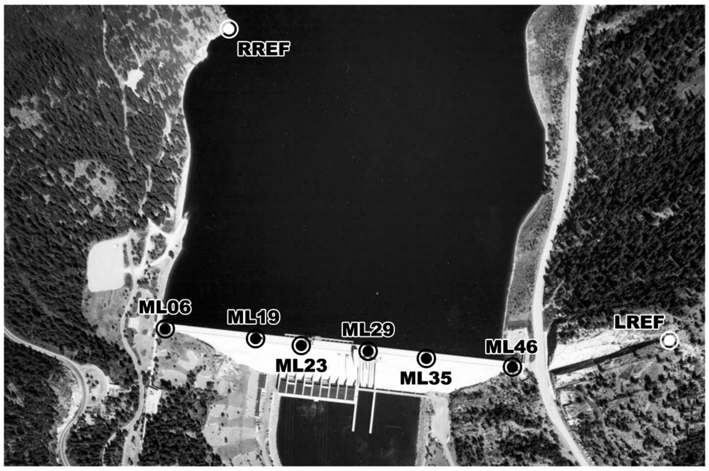

Figure 1. Plan view of Libby Dam DGPS System

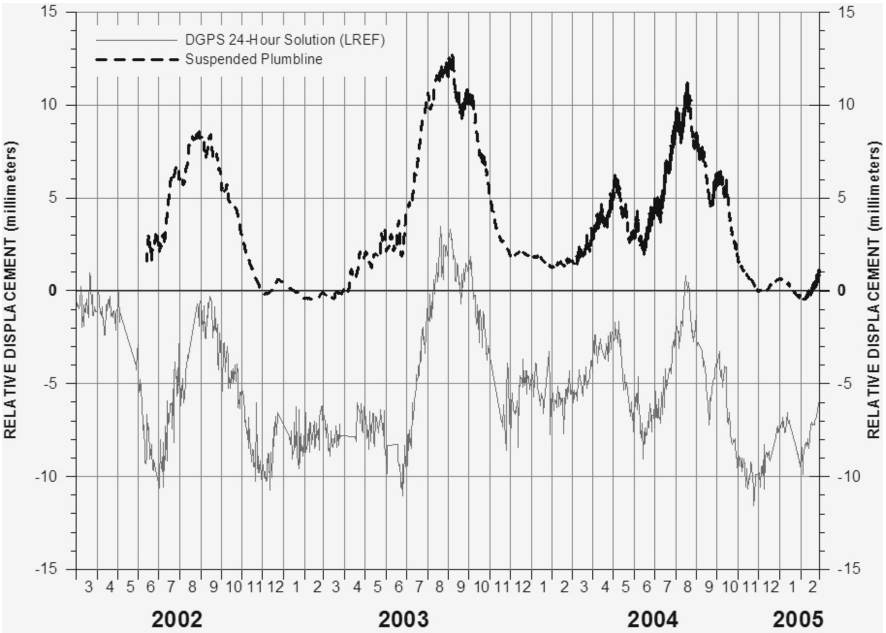

Figure 2. Upstream-Downstream Displacement at ML35 Plumb Line and DGPS (LREF)

loading conditions. The ability of GPS to operate in real-time fulfilled these requirements, and could even provide rapid feedback to Corps engineers and geologists in the event of a major flood or earthquake.

Installation of the DGPS System

Condor installed the DGPS system at Libby Dam during the winter of 2001-2002 with assistance from Corps personnel. The entire installation was completed in about three weeks at a cost of just under $150,000, including the GPS and radio hardware. All eight GPS stations are powered by photovoltaic equipment, and communicate to a central PC via a digital radio network. Each station is self-contained and autonomous of the existing electrical and mechanical systems at Libby Dam.

Six GPS monitoring stations were installed on the crest of the dam on carefully selected monoliths. A GPS reference station was installed on stable ground on each side of the dam (RREF and LREF). The GPS station locations are shown in Figure 1.

The DGPS system at Libby has proven to be reliable with reasonable operating and maintenance costs. Annual operating and maintenance costs have averaged roughly $20,000 per year since the system was installed (including the Corps' cost for maintaining a large database).

Correlation Between DGPS and Plumb Line Measurements

DGPS measurements and plumb line measurements collected at monolith 35 are presented alongside one another in Figures 2 through 4. The positive region of the graph represents upstream displacement, while the negative region represents downstream displacement. Three years of data are displayed. These figures clearly show the strong correlation between the DGPS data and the plumb line data.

Readers will notice the offsets between the DGPS data and the plumb line data. These offsets result from the installation of each measurement system at a different time, and come in two forms. The first involves the natural elastic cycle of deformation that occurs at Libby Dam. The DGPS system and the plumb line system were not installed at the same point in this cycle and therefore have separate and unique initial readings. This type of offset could have been mostly eliminated by installing each DGPS monitoring point at the same time of year as its corresponding plumb line was installed (a luxury not available because of the added installation cost). The second type of offset can result from the presence of inelastic deformation recorded by the plumb line system prior to the installation of the DGPS system.

Figure 2 shows the upstream-downstream displacement of Libby Dam at monolith 35 as measured by both the DGPS system and the plumb line system. The Corps of Engineers rotated the GPS frame such that the two horizontal axes were perpendicular and longitudinal to the axes of Libby Dam. This useful step allows us to track both upstream-downstream displacement and longitudinal displacement (the long axis of the dam). Plumb line data are displayed in black and DGPS data are displayed in gray. Plumb line 35 is read

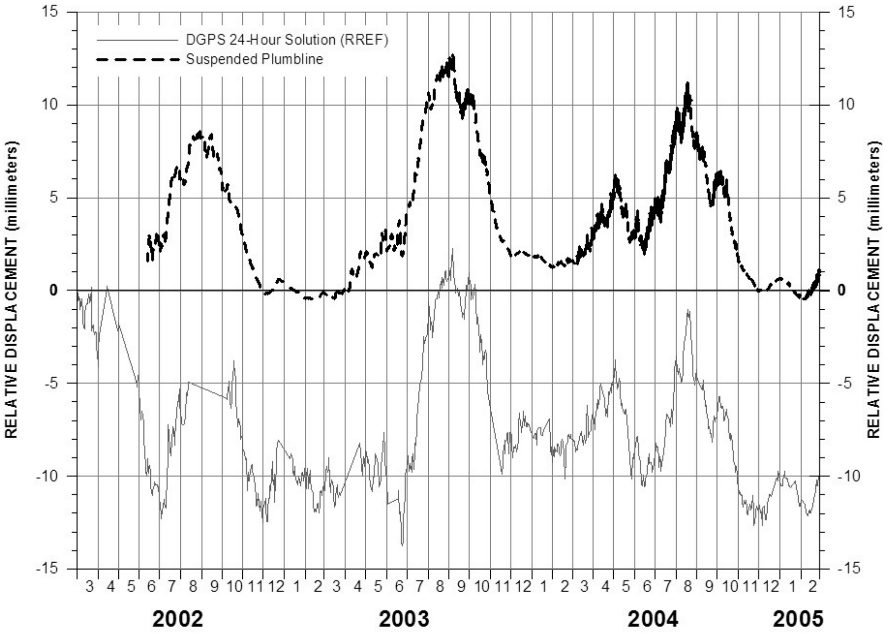

Figure 3. Upstream-Downstream Displacement at ML35 Plumb Line and DGPS (RREF)

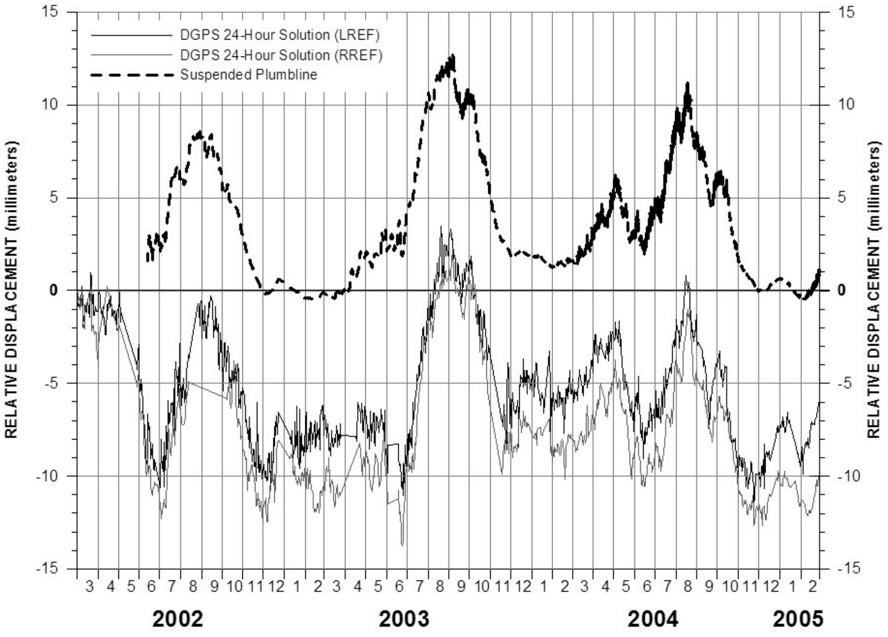

Figure 4. Upstream-Downstream Displacement at ML35 Plumb Line and DGPS (LREF and RREF)

automatically on a daily basis, whereas the DGPS station at monolith 35 computes a solution every 5 seconds. A daily average of the 5-second solutions is plotted in Figure 2 as a gray line. The time period between March 2002 and February 2005 is shown in Figures 2, 3, and 4.

All DGPS data shown in Figure 2 were computed by using the GPS reference station located near the left abutment of Libby Dam. We call this station LREF for left abutment reference station. DGPS Measurements computed using LREF show a high level of correlation with the plumb line data, and both show the same pattern of normal elastic deformation.

The same plumb line data are displayed in Figure 3, but this time alongside data derived by using the right abutment reference station, or RREF. When these measurements are plotted alongside the same monolith 35 plumb line data, the same strong correlation appears. This is expected because DGPS measurements do not drift, and are connected by a global reference frame (ITRF). Properly collected DGPS measurements will spatially agree in a relative sense, and will agree in an absolute sense.

Figure 4 is a composite of the data from both the LREF and RREF reference stations, and data from the monolith 35 plumb line. We present this figure to show the excellent agreement between DGPS data derived from two separate and independent GPS reference stations. This strong correlation between the LREF and RREF measurement sets adds another level of confidence in the accuracy of the DGPS data, and firmly establishes the validity of not just the DGPS system, but also the plumb line system.

The previous figures considered horizontal data only. Vertical data from monolith 35 is displayed in Figure 5. The installation of the DGPS network at Libby Dam marks the beginning of vertical displacement surveillance. This surveillance has revealed what appears to be a normal yearly displacement cycle of uplift and subsidence at the dam crest.

Final Comments

Correlating the DGPS data with the plumb line data demonstrates a high-level of agreement between these two vastly different measurement systems. Both systems are faithfully tracking the overall pattern of horizontal displacement, as well as its magnitude. Each system confirms that Libby Dam deforms in an elastic fashion, with very little long term inelastic deformation. The comparison between the two sys-

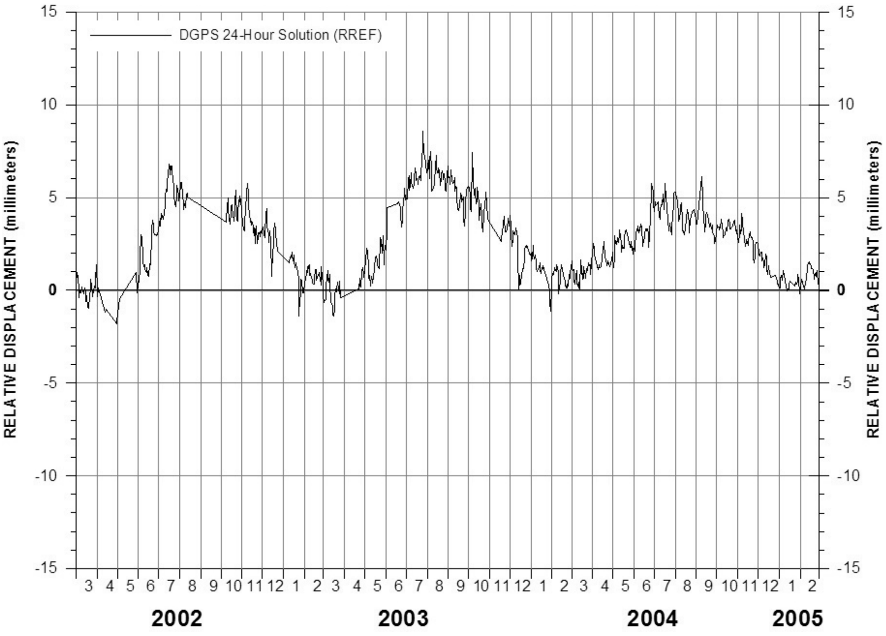

Figure 5. Vertical Displacement at ML35 (RREF)

tems provides compelling evidence that DGPS is well suited for long-term performance monitoring of dams.

A precise and modernized monitoring program is an important component of the U.S. Army Corps of Engineers' long-term risk-management plan for hydroelectric structures. The gathering of repeatable, high-accuracy horizontal and vertical measurements is part of a continuous feedback loop that verifies design assumptions and establishes normal deformation criteria. The DGPS system at Libby Dam has confirmed the horizontal deformation pattern reported by the plumb line, and is now being used to reveal the vertical deformation patterns as well. These data will be used for performance monitoring, and will be incorporated into risk-management programs.

The DGPS system at Libby Dam was installed with the hope that it would – at a reasonable cost – provide continuous surveillance and high accuracy measurements. It has. Equally important, the increase in performance transparency that DGPS can offer will create positive pressures to more efficiently allocate limited resources. The DGPS system at Libby represents an important technological advancement for long-term dam surveillance and performance monitoring, and provides an important window into the increasing role in risk management that DGPS systems will play by directly and accurately observing deformation in real-time.

Additional information on monitoring dams with DGPS is presented in Rutledge and Meyerholtz (2005). This paper is available from the US Society on Dams *(http://www.ussdams.org/).*

Acknowledgements

The authors would like to acknowledge United States Society on Dams (USSD) for allowing this material to be reproduced, and would like to thank Dr. Benjamin Remondi for his generous support.

Reference

Rutledge, D. R. and Meyerholtz, S. Z., (2005). "Performance Monitoring of Libby Dam with a Differential Global Positioning System", 25th Annual USSD Conference, Salt Lake City, USA

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Wireless Tiltmeters Monitor Stability during Trench Excavation for Reno Transportation Rail Access Corridor

Claus Ludwig
Etienne Constable

Figure 1. The ReTRAC rail trench is up to 33 feet deep, abutting sensitive buildings in downtown Reno, Nevada

Figure 2. The historic Amtrak Station and Men's Club were two of the structures underpinned along the trench alignment

Abstract

The new Reno ReTRAC rail channel, a trench 2.2 miles long and 54 ft wide, will carry two high-speed Union Pacific tracks through downtown Reno, NV, beginning in early 2006. Engineered support for eight "sensitive" buildings abutting the 33-ft-deep trench included continuous hand-dug piers, micropiles, vertical piling with tiebacks, and soil-nail wall shoring. The 42-month project benefited from wireless monitoring of structural stability using digital tiltmeters. Technicians interrogated the instruments remotely via laptop computer.

Introduction

For decades the city government of Reno debated relocating a pair of mainline Union Pacific Railroad tracks that congested the downtown area. In September 2002 the city issued its notice to proceed with the Reno Transportation Rail Access Corridor (ReTRAC) project, awarding the US$ 171 million design/build contract to joint venture partners Granite Construction Co. of Watsonville, CA and Parsons Transportation Group of Pasadena, CA.

ReTRAC will lower the on-grade, dual rail lines into a 33-ft-deep trench 2.2 miles long. This "U-channel" passes extremely close to eight buildings identified as sensitive. Several are historic structures, and at first the contractor expected that two of the three historic buildings would have to be moved. However, just prior to bidding it became apparent that they would barely clear the 54-ft-wide trench alignment. Cost analyses confirmed that it would be significantly cheaper to underpin the structures than to relocate them.

"We were concerned how excavation and construction of the U-channel might affect these buildings," noted Granite's ReTRAC project manager Ron Dukeshier. In addition to assuring safety, Granite sought to document the buildings' performance as a defense against possible damage claims.

Geotechnical design for the support scheme envisioned several sections of continuous underpinning piers doing double service as the new trench walls (Figure 2), and this approach proved to be effective. The rail channel now is nearly complete.

Early on, Granite identified the need for stability monitoring of the sensitive structures to warn of impending deformation or foundation movement. The contractor selected digital tiltmeters for data acquisition and designed an Ethernet wireless communications network for instrument interrogation and data recording.

Underpinning Sensitive Buildings

Over the first 20 months Granite crews built a temporary trackway, called a shoofly, alongside the alignment for Union Pacific to use during ReTRAC construction. Trench excavation began in May 2004 with removal of 700,000 cu yd of material. The 2.5-ft-thick channel would eventually comprise 100,000 cu yd of concrete.

Eight sensitive structures at the edge of the trench walls required extensive underpinning for safe construction of the U-channel. Schnabel Foundation Company of Walnut Creek, CA designed and constructed the underpinning for these structures using hand-dug piers and micropiles.

Trench walls were to be built directly below four of the sensitive structures. Here, continuous hand-dug piers, each nominally 5 ft by 3 ft in plan, were excavated and constructed in a checkerboard pattern to a depth ~10 ft below the construction groundwater table. These now form the new trench walls. The largest building underpinned in this manner was the seven-story Fitzgerald Hotel garage, which received continuous underpinning along two column lines, each 300 ft long, directly in the trench wall alignment. The table summarizes the installations of hand-dug piers.

Location	Wall length underpinned, lf	Maximum depth of excavation, ft	Key Factor
Freight House	56	33	Historic structure
Men's Club	158	33	Historic structure
Fitzgerald's Garage	600	37	Garage spans trench
Rainbow Bridge	69	37	Footbridge spans trench

At the remaining four sensitive structures along the trench, horizontal clearance was sufficient to allow use of micropiles for underpinning in lieu of hand-dug piers. These are the National Bowling Stadium, the historic Amtrak station, the center pier of the Rainbow Bridge, and the Ice House. Three smaller structures also were supported with micropiles.

In all, the various forms of excavation support included soil-nail wall shoring (200,000 sq ft), vertical piling with tiebacks, micropile underpinning, and conventional underpinning. The choice of support technology depended on right-of-way constraints, proximity of the buildings and shoofly, and continuance of street traffic parallel to and across the project during construction. Conventional surveying using transits and laser targets recorded horizontal and vertical displacements of all underpinned structures.

The excavation extended below the groundwater table in a significant portion of the trench. Jet grouting of the soil between the vertical piles created a vertical impermeable cutoff wall in wet areas. The vertical piles installation and jet grouting between the piles were performed by Condon Johnson & Associates directly for Granite. Where Schnabel installed conventional hand-dug underpinning piers, permeation grouting from the original ground surface produced an impermeable soil mass below the groundwater table. This ensured safe access for workers hand-digging and constructing the piers below the water table. ACT of Toronto, ON performed the permeation grouting.

With the underpinning piers all in place, an unreinforced seal slab then was poured at the bottom of the excavation, spanning the trench width and completing the nearly watertight "bathtub." This allowed Granite to build ReTRAC's reinforced concrete U-channel in the dry.

Precast concrete tension bridges now in place provide 11 at-grade crossings. When the channel details are finished, Union Pacific will lay its permanent 60-mph rail line and begin testing the two mainline tracks. Granite will then remove the shoofly and regrade the crossings, completing the project in late spring 2006.

Observing Structural Response

Stability monitoring of sensitive buildings included Ethernet "Wi-Fi" tiltmeter installations on the landmark National Bowling Stadium, Fitzgerald's Garage, and Fitzgerald's Hotel-Casino Rainbow Bridge spanning the trench (Figure 3). The instruments also recorded the excavation's effects on three historic buildings that abut ReTRAC: the Amtrak station, where carloads of tourists arrive and depart Reno each week; the Men's Club, a natural-stone structure which recently housed a cabaret; and the two-story Freight House with its associated warehouse.

In April 2004 Granite directed Applied Geomechanics Inc. of Santa Cruz, CA (AGI) to install 36 Wi-Fi-equipped tiltmeters on the eight buildings identified as sensitive. In order to establish response baselines for each structure, the instruments had to be on-line several weeks prior to the start of excavation. (It would have been preferable to have baseline data over several seasons, but the project schedule precluded this.) The 36 digital tiltmeters have remained fully functional since construction began in May 2004, providing a record of

Figure 3. Typical ReTRAC instrument installation; tiltmeter is located on column above weatherproof enclosure containing step-down transformer and Wi-Fi transmitter.

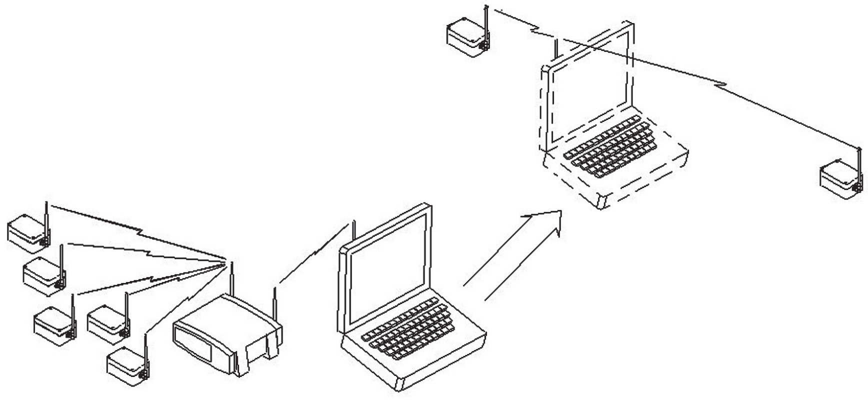

Figure 4. At Granite's request, AGI designed a drive-by communication and data download system for line-of-sight access to each tiltmeter via laptop computer.

building performance over the life of the project.

"We did extensive underpinning to ensure that these buildings remained stable," ReTRAC project manager Dukeshier said. "The tiltmeters helped us monitor their stability and, fortunately, no notable changes were recorded."

Wireless Capability

Granite's Wi-Fi requirement necessitated an upgrade of the digital tiltmeter's data-output design to incorporate wireless capability. Modifying its standard MD900 by adding a clock for synchronization and time-stamping of each data point, and mating each instrument to an outdoor-rated 2.4GHz Ethernet radio transmitter, AGI proposed to install:

- A step-down transformer (to 12/24VDC) for each tiltmeter, connected to line power
- Weatherproof utility boxes containing a Wi-Fi radio transmitter, transformer, and RS232 serial cable and connector
- A 20-watt (DC) solar panel and storage battery on each of the three historic buildings, where no AC line power was available
- ZAGI software, which enables control/communications by laptop or central computer, and TBASEII software for managing, displaying, and analyzing the data.

In this system as originally specified, each tiltmeter would communicate directly with the ReTRAC Wi-Fi network. However, broadcast frequency restrictions prevented Granite from completing the project-wide network, so AGI developed an alternative: "drive-by" data downloading (Figure 4). In the drive-by arrangement, from any line-of-sight location within several hundred feet of a tiltmeter, a field technician with Wi-Fi-equipped laptop computer can connect to the instrument, confirm its functional operation, and acquire the recent data. Where line-of-sight to tiltmeters was restricted by their remote locations, two weatherproof routers with high-gain antennas were placed such that each could serve as a hub for nearby clusters of the instruments.

Technical Issues

Although tilt monitoring is an established technology for observing the effects of large excavations on nearby structures, each project presents unique technical challenges. Costs of instrumentation, ease of interrogation and maintenance, and data quality all depend on how effectively the technical issues are addressed. Environmental conditions proved to be one such concern for the ReTRAC project team: Reno experiences 100°F temperature swings through the seasons, as well as strongly gusting winds. The winter of 2004-2005 added record snowfalls; nonetheless all of the instruments and peripherals survived and continue to function.

The most critical problem that arose was the unanticipated absence of a total Wi-Fi network. As originally planned, a project headquarters computer would automatically initiate data queries and relay them to the tiltmeters via this network. Data downloads were to be scheduled frequently enough not to fill up each unit's on-board flash memory capacity. When instead drive-by downloading was implemented, a consistent, once-every-six-days schedule had to be followed.

Operational Benefits

With the successful installation for ReTRAC, the first geotechnical project in which digital tiltmeters were used in an all-Wi-Fi configuration, this stability-assurance monitoring approach is field proven. Wireless tiltmeters may be considered a developed technology, offering several operational benefits:

- *Reduced costs*. A typical Wi-Fi system requires less cabling and no data loggers, less labor to install, and generally less power.
- *Easier equipment moves*. Wireless systems have fewer components to

relocate if the instruments must be moved as construction proceeds.

- *Limited need for surge protection*. In lightning-prone areas, cable-based monitoring systems normally employ expensive, dual-ended surge protection, whereas a wireless system needs only a single surge protector at each antenna.
- *Data digitized at the measurement site*. This improves data reliability by precluding the possibility of information loss during transmission of analog signals.

Conclusions

Structural stability assurance for the Reno ReTRAC project required a combination of complex underpinning design and careful construction, along with wireless monitoring of the response of sensitive structures. Based on the "lessons learned" at ReTRAC, digital tiltmeter technology is being upgraded to include (a) on-board Wi-Fi transmitters to shrink the instrument's footprint, and (b) expanded memory to allow greater flexibility in the downloading schedule.

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Temperature Influence on Earth Pressure Cell Readings

Lyne Daigle

Introduction

Temperature variation is one of the factors mentioned by Dunnicliff (1988, 1993) that may affect pressure cell measurements. He recognised that temperature calibration of cells in an unloaded condition was not likely to give the same results as a temperature calibration of a confined cell. He pointed out that the influence of temperature was potentially greater for a contact pressure cell than an embedded cell, due to a possibly larger temperature variation. In the Canadian climate, totally embedded cells can also be subjected to temperature variations, since the depth of zero annual temperature variation can be as much as 10 m to 15 m (Smith 1996) depending on soil type and geographical location. Temperature effects on earth pressure cells were also thoroughly discussed by Sellers (2000) and Yang et al. (2001). Based on some assumptions and approximations, Sellers proposed a thermal correction factor for embedded and contact pressure cells, respectively as follows:

$CT = 1.5\ EKt / R$ (embedded) [1a]

$CT = 3.0\ EKt / R$ (contact) [1b]

where CT is the temperature factor (kPa/°C), E is the soil elastic modulus (GPa), K is the coefficient of thermal expansion of the liquid inside the cell (10^{-6}/°C), t is the thickness of the liquid inside the cell (mm) and R is the radius of the cell (mm). Yang et al. (2001) discussed the results obtained from contact pressure cells installed on the roof of a cast-in-place concrete box culvert. Even though the temperature correction recommended by the manufacturer was applied, the pressure data collected over a four-year period still showed a very strong relationship with the seasonal temperature variations. They used the theoretical correction factor, [eq.1b], proposed by Sellers (2000), which reduced the temperature-induced variation but only by one order of magnitude less than the correction factor obtained by the empirical approach. The empirical approach involves finding the relationship between the recorded temperature and measured pressure assuming the vertical soil pressure remains constant over the range of observed temperatures.

The objective of this article is to give a summary of the calibration and testing program carried out at the National Research Council laboratories to determine adequate temperature factors or equations that could be used for eighteen 76-mm diameter pressure cells, which were already installed in the field in the Ottawa region (Daigle and Zhao, 2001). These cells were subjected to large temperature variations. The testing program was later broadened to include some more commonly used 228-mm diameter pressure cells. Some general recommendations are formulated to minimize the effects of temperature on earth pressure cell readings based on the results of this calibration and testing program.

Earth Pressure Cells

Earth pressure cells tested in this study were hydraulic cells with vibrating-wire transducers. Five cells with a diameter of 76 mm, measuring range of 200 kPa and aspect ratio (cell dia./thickness) of 7.6 were tested. The recommended value for aspect ratio should be above 10 (Dunnicliff 1988, 1993). In addition, eleven 228-mm diameter cells were tested, with measuring ranges of 173 kPa (2 cells), 200 kPa (3 cells), 750 kPa (1 cell), 1000 kPa (2 cells) and 1500 kPa (3 cells) and aspect ratios of 38.3 or 23.2, depending on the manufacturer. The equation used to convert frequency readings to pressure readings has the following general form:

$$\Delta P = CF\left(F_1^{\,2} - F_0^{\,2}\right) - CT\left(T_1 - T_0\right) - \left(B_1 - B_0\right) \qquad [2]$$

where ΔP is the pressure variation (kPa), CF is the calibration factor (kPa/Hertz^2) and CT is the thermal correction factor (kPa/°C). F, T and B are the frequency readings (Hz), temperature (°C) and barometric pressure (kPa). Subscripts 0 and 1 stand for initial and current readings. The CF and CT values, measured for each cell by the manufacturer, are given on the calibration sheet along with the temperature and barometric pressure at which the initial calibration was performed. Most of the time, there is no clear indication on the datasheet that the temperature factor does not apply to the whole pressure cell unit but only to the transducer (Dunnicliff 1997), in this case, the vibrating-wire.

Experimental Work

A testing program was established to determine the effect of temperature variations in unloaded and loaded conditions and to examine whether the magnitude of pressure acting on a cell would modify or amplify the temperature effects on the cell readings. Cells were tested at temperatures ranging between -10°C and 30°C, representative of field conditions in the Ottawa region.

Testing equipment

An environmental chamber was used to provide a temperature-controlled environment. The data acquisition system consisted of a Campbell Scientific CR10X measurement and control module, and associated multiplexer and vibrating-wire interface module for both frequency and temperature measurements of the pressure cells.

For the loaded condition, a pressure chamber was used to apply load on the cell. This steel chamber had an inside diameter of 380 mm and was designed to accommodate a 76-mm diameter cell and fit inside the environmental chamber. Loading on the cell was adjusted with an air pressure control valve. Other details concerning the pressure chamber and complete set up are shown on Fig. 1 and presented elsewhere (Daigle and Zhao, 2004).

Temperature readings

For the unloaded condition, the temperature of pressure cells was measured by the thermistor built in the sensor. For the loaded condition, the cell thermistor would not provide a representative measurement since it is located in the cell handle outside the pressure chamber. The temperature of the pressure cell was measured by a thermocouple installed on the surface of the pad (Fig. 1).

Temperature calibration of unloaded cells

The five temperature set points were 30°C, 20°C, 10°C, 0°C and -10°C. For each set point, a 3-hour plateau was sufficient to achieve temperature equilibrium of the unloaded cells since they were in direct contact with the air circulating inside the chamber.

Temperature calibration of loaded cells

Only one cell at a time could be tested with the pressure chamber. Fifteen hours were needed for the cell, surrounded by sand, to reach temperature equilibrium at each set point. Time limitations only permitted the use of four temperature set points. Calibrations of five 76-mm pressure cells with 3 or 4 levels of applied pressures ranging from 1.1 kPa to 132.6 kPa were carried out. Four of the eleven 228-mm pressure cells were also tested in loaded condition. However, since the pressure chamber was not designed for this size of cells, these test results are only preliminary.

Results and Discussions

In the subsequent text, the term “apparent pressure” represents the change in pressure cell reading that was caused solely by temperature variations, while the loading conditions remained the same.

Unloaded cells – 76-mm diameter

Figure 2 shows a typical curve obtained for the temperature calibration. A datasheet temperature correction factor of 0.0336 kPa/°C would cause an apparent pressure variation of 1.3 kPa (=0.0336 x 40°C) for the studied temperature range. An apparent pressure variation of 59.2 kPa was measured for the same temperature range. This variation represents 30.3% of the full-scale reading of the pressure cell. For the group of five cells, the ratio of the thermal factor (RCT) calculated from laboratory data to the one taken from the datasheet varies from 11 to 85. The percentage of the apparent pressure variation over the full-scale range due to a temperature difference of 40°C (PVFS$_{40}$) varies from 23.7% to 45.1%. In all cases, the degree of correlation between laboratory data and a second-degree polynomial was higher than with a linear model.

Such a high temperature effect on pressure measurement is critical. When

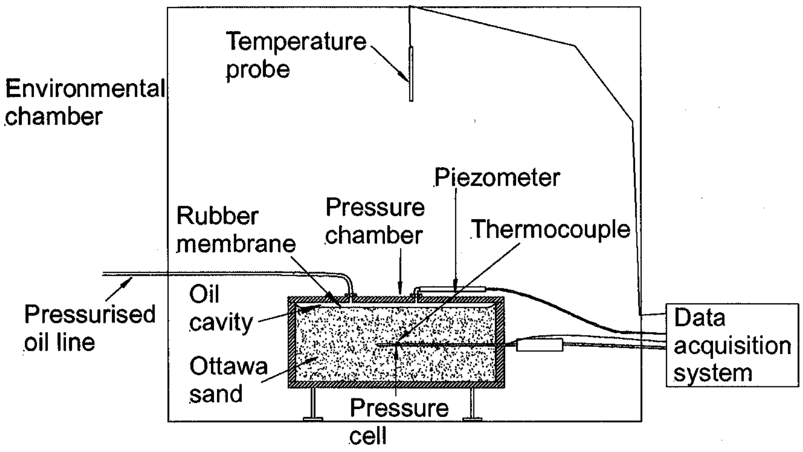

Figure 1. Schematic of the test set up for cell calibration under pressure.

the cells are subjected to temperature variations, the apparent pressure caused by temperature variations could be as high as the physical pressure acting on the cell, which is undesirable for any type of sensor. Thermal factors of the whole pressure cell assembly are sometimes assumed to be in close agreement with those of the transducer. For these 76 mm pressure cells, this was clearly not the case.

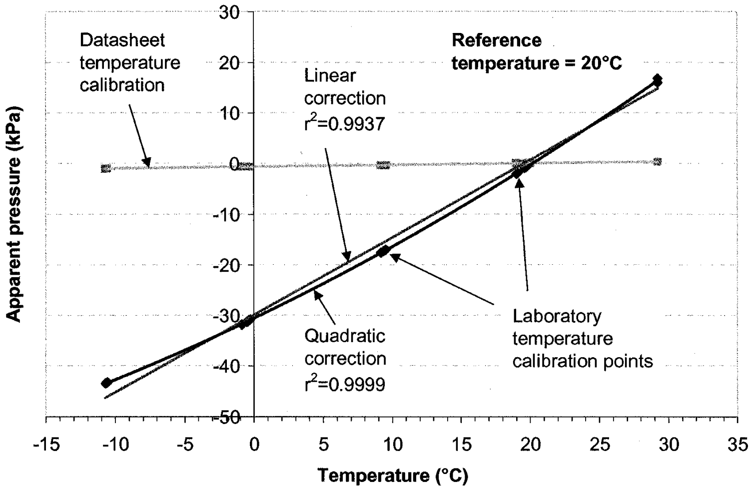

Figure 2. Typical temperature calibration curve of an unloaded 76-mm cell.

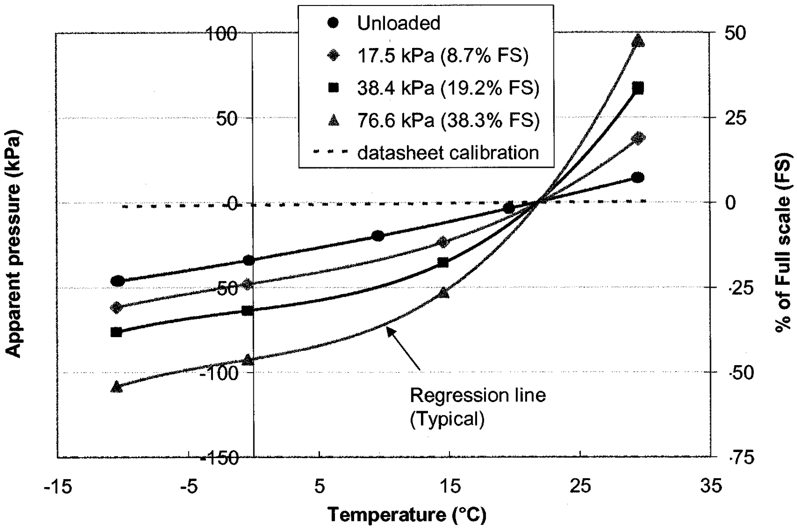

Figure 3. Loaded temperature calibration of a 76-mm cell.

Cell #	Applied pressure (kPa)				Apparent pressure variation (kPa) for a temperature variation of 40°C			
	P#1	P#2	P#3	P#4	P#1 (% FS)	P#2 (% FS)	P#3 (% FS)	P#4 (% FS)
1	-	17.5	38.4	76.7	-	99 (50)	143 (71)	203 (101)
2	-	63.7	71.7	75.1	-	136 (68)	144 (72)	150 (75)
3	-	16.1	38.5	41.0	-	128 (64)	171 (85)	184 (92)
4	16.9	46.7	67.5	132.6	68 (34)	91 (45)	106 (53)	180 (90)
5	1.1	21.9	36.5	82.3	75 (37)	116 (58)	139 (69)	220 (110)

Table 1. Summary of loaded temperature calibration of 76-mm pressure cells.

Unloaded cells – 228-mm diameter

Readings were corrected for temperature variation according to the CT from the datasheet to obtain the apparent pressure variation. The $PVFS_{40}$ values for the cells with 750, 1000 and 1500 kPa measuring ranges were all below 0.5%. A $PVFS_{40}$ of 1% or less was judged adequate. For the lower measuring range cells (173 and 200 kPa), the $PVFS_{40}$ were between 0.89% and 6.8%. The RCT, calculated only for cells with an apparent pressure variation larger than 1%, varied from 1.25 to 5.61. The difference between a linear and second degree correction for the 228-mm cells was not significant considering the reduced effect of temperature variation on the cell readings. Two of the five low range cells provided high apparent pressure variations of 6.8% and 5.3%.

Loaded cells – 76-mm diameter

The effects of the loads applied on the cells were subtracted from the pressure readings to obtain the apparent pressure variation and adjusted to zero at 22°C (the temperature of the datasheet calibration). Figure 3 shows the temperature calibration of one 76-mm cell. As the applied load increased, so did the absolute value of the apparent pressure due to temperature effect. For a 77 kPa pressure applied on the cell, an additional apparent pressure variation of more than 150 kPa was caused by a temperature variation of 40°C. This apparent pressure variation represented 75% of the full-scale reading and was larger than the applied pressure. The dashed line in Fig. 3 shows the thermal correction using the datasheet CT. In addition, the curvature of the correction equation for temperature effects increased with

Cell # (range in kPa)	Applied pressure (kPa)				Apparent pressure variation (kPa) for a temperature variation of 40°C			
	P#1	P#2	P#3	P#4	P#1 (% FS)	P#2 (% FS)	P#3 (% FS)	P#4 (% FS)
3-A (200)	17.9	36.9	68.3	124.7	28 (14)	40 (20)	60 (30)	85 (42)
4-A (750)	-	52.0	213.1	-	-	38 (5)	84 (11)	-
10-B (173)	12.6	19.1	92	-	16.1 (9)	19 (11)	34 (20)	-
11-B (173)	14.7	20.7	78.6	-	5.5 (3)	6 (4)	33 (19)	-

Table 2. Summary of loaded temperature calibration of 228-mm pressure cells.

applied pressure. Table 1 presents a summary of the loaded temperature calibration results for the five 76-mm cells. With the data collected from the five similar 76-mm cells, a relationship between the applied pressure and the 2nd degree polynomial approximation, which characterised the cell variation of pressure with temperature changes, could not be established. The temperature sensitivity of the cells seemed to be related to one or more parameter(s) that were cell dependent. One possible factor that still has to be verified is the initial oil pressure inside the pad.

Loaded cells – 228-mm diameter

The temperature calibration was also carried out for four 228-mm loaded cells. Results are summarised in Table 2. Figure 4 shows the results of the four different pressures applied on cell # 3-A, the cell amongst the eleven tested that was the most sensitive to temperature variations in the unloaded condition.

The influence of temperature variation on loaded cells was larger on the 76-mm cells than on the low range 228-mm ones. For the 76-mm cells, the apparent pressure variation was at least twice the applied pressure in almost all cases. For the 228-mm cells, the apparent pressure variation ranged from 30% to 155% of the applied pressure, which was still not negligible. Although the pressure chamber dimensions were designed for the 76-mm cells, the results obtained for some 228-mm cells showed that the temperature effect was considerable when the load was increased.

Obviously, the design of the 76-mm cell used in this experiment was not optimal, as revealed by its low aspect ratio. Calibration of these cells nevertheless permitted the uncovering of temperature effects that were also observed, to a lesser extent, in some low range (173 and 200 kPa) larger diameter cells (228 mm).

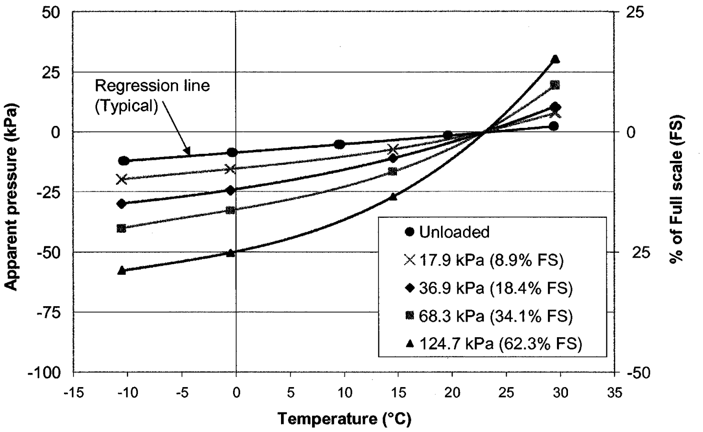

Figure 4. Loaded temperature calibration of 228-mm cell 3-A.

Thermal correction factors for the 76-mm cells were calculated with Sellers' equations [1a] and [1b]. Using an approximated soil elastic modulus of 345 MPa (coarse sand as in a field site) and an oil thermal expansion coefficient of 700 x 10^{-6}/°C as suggested by Sellers (2000), the thermal correction factors were 66.7 kPa/°C for embedded cells and 133.4 kPa/°C for contact cells. Such high values may indicate that Sellers equations are not applicable for these small diameter cells.

Empirical values obtained from the eighteen 76-mm cells installed in the field varied between 0.6 kPa/°C and 2.9 kPa/°C for contact pressure cells and between 0.8 kPa/°C and 3.0 kPa/°C for embedded cells. Considering the difficulty of obtaining a good approximation for the elastic modulus of the soil and that this value varies with soil confinement, equations given by Sellers (2000) do not yield accurate thermal correction factors. Moreover, Sellers' equations do not account for the fact that the thermal correction becomes non-linear with increasing load and that the sensitivity to temperature is not uniform amongst a group of similar cells.

Conclusions

Laboratory work has shown that temperature calibration is dependent on the pressure applied to an earth pressure cell. Cells that show a strong temperature effect in unloaded conditions are likely to show an even stronger temperature effect under load, especially as the applied pressure increases. Furthermore, as load increases, the thermal correction factor becomes non-linear.

Unloaded temperature calibration revealed that the thermal correction factors (CT) were 5 to 85 times larger than the datasheet CT for the smaller diameter cells, and up to 5.6 times larger than the datasheet CT for the 228-mm cells with low measurement range. Temperature effects were negligible on the higher range larger cells in the unloaded condition.

In a group of pressure cells of the same model, under the same temperature and pressure conditions (loaded and unloaded), some cells are much more sensitive to temperature effects than others.

The following recommendations will help minimize the undesirable effects of temperature on pressure cell readings:

- If you are not equipped to calibrate the cells in temperature, ask the manufacturer, before you buy the cells, to perform a temperature calibration of each pressure cell instead of a temperature calibration of the transducer
- In a group of cells, select the ones that are the least sensitive to temperature effect in unloaded calibration to install in locations where the temperature variation is expected to be greater.
- When planning an instrumented site, tend to select higher measuring range cells, and locate them where the temperature variation is less pronounced, if possible.
- Pressure cells with a diameter smaller than 228 mm seem to be more sensitive to temperature effects. Try to keep the cell diameter to a minimum of 228 mm.

A complete report on this calibration/testing project is available at *http://irc.nrc.gc.ca/fulltext/rr131*.

A better understanding of temperature effects on earth pressure cells will lead to a more confident use of pressure cells under field conditions which, in many cases, include significant temperature variations.

References

Dunnicliff, J. 1988, 1993. Geotechnical Instrumentation for Monitoring Field Performance. John Wiley & Sons, New York, 577pp

Dunnicliff, J. 1997. Temperature sensitivity of earth pressure cells. Geotechnical News, 15(2): 42.

Daigle, L. and Zhao, J.Q. 2004. The influence of temperature on earth pressure cell readings, Can. Geotech. J. **41**:551-559

Sellers, B. 2000. Temperature effects on earth pressure and concrete stress cells – Some theoretical consideration. Geotechnical News, 18(1): 23-24.

Smith, D.W. 1996. Cold Regions Utilities Monograph. ASCE, New York.

Yang, M.Z., Drumm, E.C., Bennett, R.E. and Mauldon, M. 2001. Temperature effects on contact earth pressure cells: inferences from long term field instrumentation. Geotechnical News, 19(2): 25-28.

Zhao, J.Q. and Daigle, L. 2003. Concrete pipe bedding alternatives to OPS – Analysis of first two–year data from monitored concrete culvert. Client Report, IRC, National Research Council Canada, B-5116.3 pp. 33.

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