Instrumentation

John Dunnicliff

Introduction

This is the nineteenth episode of GIN. There is only a brief column this time, but there are two accompanying articles. In GIN-18 I said that in this episode there would be a case history about misbehaving liquid level settlement gages on a project in Florida. However, publication of this article has been delayed while the various parties involved come to a meeting of minds, as I don't want to publish it without including recommendations for the future. In the next episode there will be (no broken promise this time, as I already have a semi-final draft!) an article about lightning protection, written by colleagues at Roctest, which sheds light on something that is often categorized as black box magic. (No, that has nothing to do with English chocolates!).

It could be argued that the following two articles are not strictly about **geotechnical** instrumentation. I solicited them both because they are examples of exciting new technologies which add to the toolbox of the geotechnical engineer, hence they are consistent with my goals for GIN.

International Flavor of Instrumentation Course in Florida

The next instrumentation course at Cocoa Beach, Florida, on November 1-4, 1999, will have an international flavo(u)r. Lecturers will include Helmut Bock, who until recently was President of Interfels GmbH in Germany, a world leader in providing geotechnical instrumentation and field services, with emphasis on applications in rock. He will talk about instrumentation of tunnels, with particular reference to European practice. Lecturers will also include Jean-Ghislain La Fonta, Managing Director of Sol Data S.A. in France, who also provide instrumentation and field services, and who is the author of one of the following articles. He will talk about automatic survey monitoring and also his experiences with automatic monitoring with in-place inclinometers.

Seven North American instrumentation manufacturers will have displays of their products and will also be presenting lectures:

- Applied Geomechanics - Using Tilt Measurements to Measure Performance
- Campbell Scientific - Automated Data Acquisition System Design and Implementation
- Geokon - Vibrating Wire Tiltmeters, Recent Developments and Experiences
- Geomation - Real-time Monitoring of Pipeline Stress, and Automatic Slurry Level Control During Cut-off Wall Excavation
- Roctest - Fiber Optic Sensors for Geotechnical Monitoring Applications
- RST - Measurements of Negative Pore Water Pressure in Unsaturated Soils
- Slope Indicator - Case Histories of the Application of Electrolevel Sensors and Other Instrumentation to Large-scale Projects

For technical content please contact me or visit the following web-site: *http://www.doce.ufl.edu/conf&sem.*

For registration, price, and other issues, please visit the web-site or contact *Ole Nelson at the University of Florida, tel: (352) 392-1701, ext. 244; fax: (352) 392-6950; email:*onelson@doce.ufl.edu.

I hope to see you there. If you all come, we will move out of the lecture room on to the beach!

North American Versus European Practice

Note that, as is the case for most European companies, Interfels and Sol Data, referred to above, provide 'the whole package', rather than providing only the hardware, as is the usual practice in North America. It is my understanding that North American practice is driven by concerns about competing with customers (typically the consulting firms and construction contractors who provide field services) and about professional liability. In my view the European practice has a great deal to recommend it, because it more readily satisfies Wally Baker's dictum *"The party with the greatest vested interest in the data should be given direct line responsibility for producing the data accurately".* How about this as a topic for a North American conference session?

I can't mention Wally in this column without expressing sadness about his death on February 9, 1999, from complications resulting from treatment of leukemia. For many years he controlled Hayward Baker, and made the company name a synonym for quality in the grouting and soil improvement industry. As a specialty contractor, he often initiated and managed the use of geotechnical instrumentation as a tool to monitor performance, always with *a great vested interest in the data.* We will miss him.

Pore Water Pressure Measurements with a Piezocone

I haven't had any responses to the alarm bell that I sounded in GIN-18:

During some recent installations of push-in piezometers in desiccated clay, the temperature sensors within the piezometers showed temperatures up to 85 degrees C, created by friction between soil and piezometer during the push. ***This experience rings an alarm bell.*** *In such a situation the piezometer is subject to 'temperature transients' (see Geotechnical News Vol. 14, No. 3, September 1996, page 27), such that the pressure measurements are incorrect.* ***What does this do to piezocone data? Any comments?***

Any comments from those of you who make measurements with the piezocone?

Change of Address

I will be changing my address on June 25, 1999. I dont yet know the mailing address, but after that date you can send material for GIN to me by *e-mail,* johndunnicliff@ibm.net (send as an attachment in msword please), or by *fax +44-1626-832919.*

Tchin-tchin! (international)

Puerto Rico
Real-Time Control of Compensation Grouting with the Cyclops System

Jean-Ghislain La Fonta
Thierry Person

Abstract

Ground movements induced by underground excavation are always of critical concern, particularly in urban areas.

In San Juan, Puerto Rico, the planned Tren-Urbano project involves underground works directly beneath historic buildings, which must be protected.

Compensation grouting works, under the control of an efficient automatic monitoring system, reduce the settlement induced by these excavations.

This article describes the automatic monitoring system that is presently employed on this project.

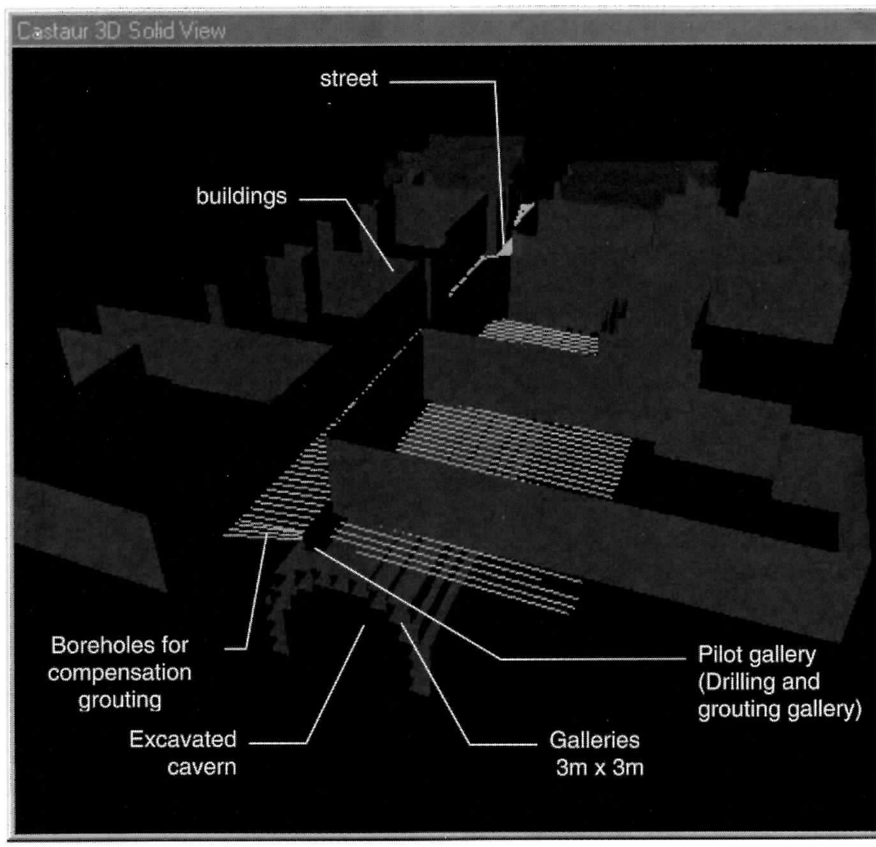


Figure 1. 3D view of site

Introduction

Puerto Rico is an island in the Greater Antilles group between the Dominican Republic and the Virgin Islands. As a US dependent territory with commonwealth status it has enjoyed continuous development of the economy since the end of the second world war.

It has a population of 4 million and a land area of 8500 km^2. The capital, San Juan, dominates the country's economic activity. The San Juan metropolitan area comprises 13 municipalities covering a total area of some 1000 km^2 with a population of 1.2 million. It has four major districts: the historic city centre, Hato Rey business district, Rio Piedra with its university, and Santurce on the coast, with its tourist hotels. The island's road network is nearly saturated, especially between these four districts. Traffic congestion also has a negative impact on the use of public transport. Under these circumstances and faced with an expected 20% rise in population by 2010, it was decided to build an underground railway line to relieve pressure on urban travel. This is the *Tren Urbano* Project.

Predicting and controlling soil movements caused by excavation is one of the most difficult problems in tunnelling. Whatever tunnelling method is used, it is always accompanied by surface settlement. It is extremely difficult to predict accurately and tunnelling techniques rarely offer any scope for controlling settlement. If a critical settlement value is reached there are few options except to grout the surrounding ground or install additional support. However successful or otherwise, this always has a negative impact on progress of works and project economics.

Modern methods of compensation and jet grouting provide effective solutions for minimising the effects of underground engineering projects on the nearby environment.

These methods are versatile enough to adapt to many different configurations, and are able to keep pace with the increasingly high speeds of tunnel driving. Effective control of grouting operations calls for real-time monitoring of settlement and heave especially when structures and buildings are involved.

This real-time monitoring capability was provided on the *Tren Urbano* project in Puerto Rico. Building movements caused by the tunnelling operations were monitored using the automated optical measurement system CYCLOPS (CYCLic OPtical Surveyor).

Rio Piedras Station and Compensation Grouting

The most critical section of the new line on the San Juan underground railway in Puerto Rico was Rio Piedras Station, an underground chamber measuring 140 metres long by 18 metres high and 23 metres wide, directly beneath a busy shopping quarter of the historic town centre.

The major challenge was the limited ground cover of only 3 metres above the roof of the excavated chamber. This 3 metre band of ground was subject to the compensation grouting.

The station was excavated in stages, as follows (see figure 1) :

i) Drive 2.5-metre square pilot gallery between a pair of access shafts.
ii) Drill fan arrays of horizontal and sub-horizontal compensation grouting holes from the pilot gallery.
iii) Drive fifteen 3-metre square galleries by standard methods around the station excavation line under cover of an umbrella of compensation grouting.
iv) Excavate the remainder of the station below.

Compensation grouting was used to control the settlement associated with the excavation. The grouting plan was based on a combination of settlement predictions from the design calculations and real settlements measured in the course of the work (see figure 2). This required rapid and accurate monitoring of actual ground movements

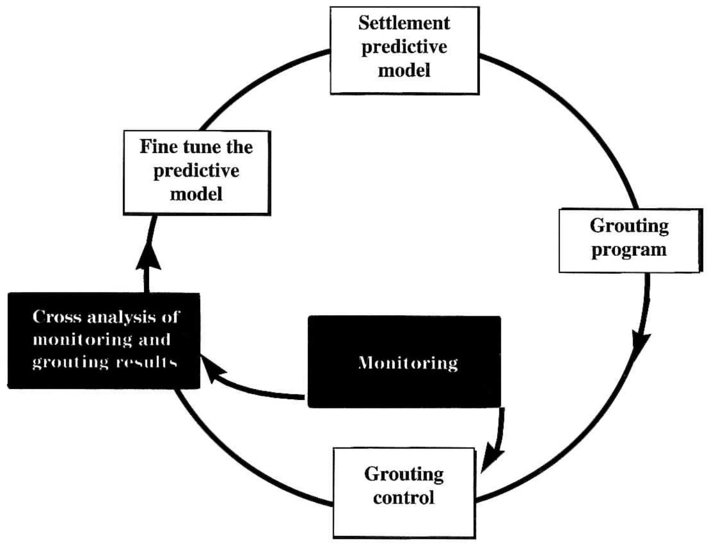


Figure 2. Schematic of cyclic process by which grouting is controlled by ground movements

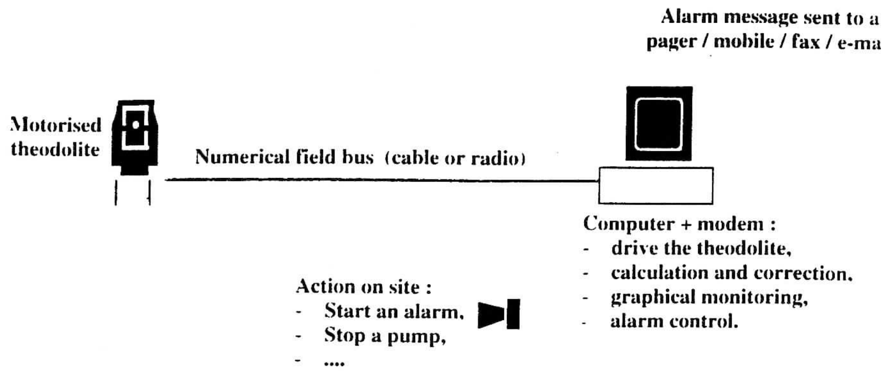


Figure 3. CYCLOPS : real-time optical ground movement monitor

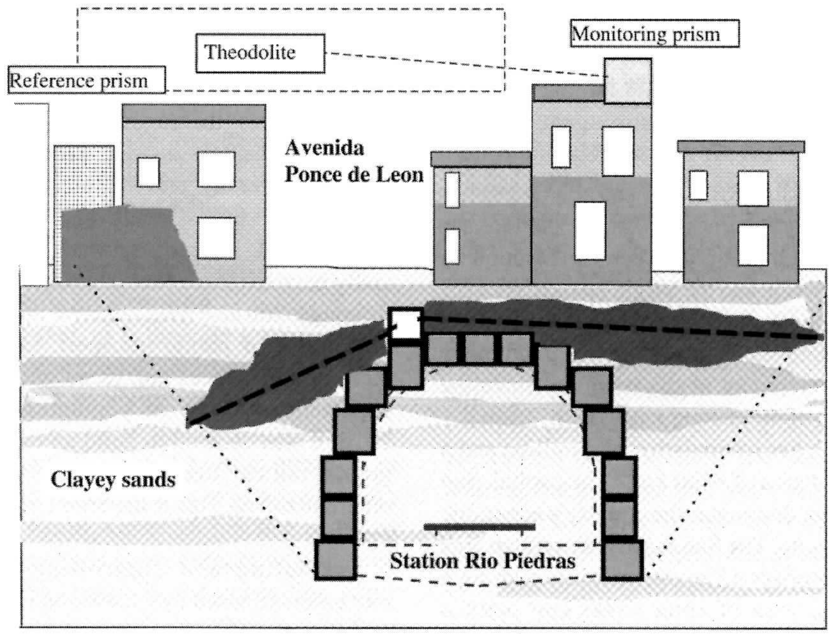


Figure 4. Sketch of site and installation

Figure 5. Motorised theodolite on building roof

Figure 6. Prism (monitoring) on building roof

Automated Control of Movements

It was originally planned to have manual levelling surveys on a close grid covering the whole site, plus a few point measurements on structures. Because of the difficult access to parts of city centre and the time delay involved in processing the survey data, it was found that this approach, which would at best provide one or two sets of readings per day, was inadequate for controlling the grouting works. It was therefore decided to install the CYCLOPS system (see figure 3), keeping a reduced frequency of ground precise levelling survey as a cross check.

THE SYSTEM AND ITS INSTALLATION

The system consists of a motorised total station under computer control linked to SolData's in-house software SMACS (Soil Monitoring And Control System). The system measures the 3 dimensional coordinates of reflective prisms set up around the site at various spacing intervals. There are two classes of prism: 'reference', assumed to be a fixed point from which the system may detect any self-movement, and 'monitoring', giving the movement of the structure, calculated each time the total station completes a measurement cycle.

Since many parameters may affect the measurements taken on prisms between different cycles, e.g. atmospheric conditions at each cycle, the software automatically applies corrections to produce rigorous, reliable data.

At Rio Piedras the system continuously monitors 22 buildings above the critical zone over a linear distance of some 150 metres.

Properly setting up the components is vital for a successful installation. Considerations include visibility, radius of action of the theodolite (which has a direct relationship with the required final precision), and judicious siting of the reference prisms at points assumed to be unaffected by movement. As schematised on figure 4, the theodolite (figure 5) is set on the roof of a high building to the west of the station mid-point, with full view of the site and some 50 prisms (figure 6) installed on top of the monitored buildings. Nine reference prisms outside the zone directly affected by the excavation work are used by the system to determine its true position and correct the data for the monitoring prisms.

The total station is connected by digital field bus cable to the control computer in the engineer's office some 200 metres away. The system converts angular and distance measurements obtained during the predetermined cycles into X, Y and Z movements with a 1 mm accuracy at a distance of 120 metres.

ACCURACY

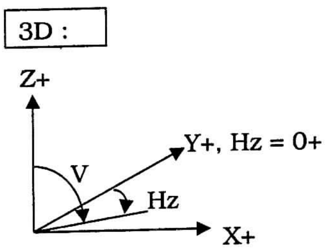
The accuracy depends on three parameters linked to the quality of the total station. In Puerto Rico we use a LEICA TCA 2003 with the following manufacturer's specifications :

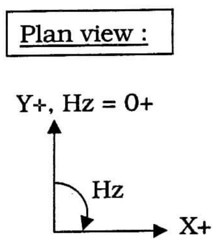
- Accuracy of angle measurement = 0.15 mgon = 0.5 arc second,
- Accuracy of distance measurement system = 1mm + 1 ppm (part per million)
- Accuracy of the localisation system = 1 mm at 200 m

Relative measurements and software allow for improvements to these accuracies. For instance, repetitive measurements carried out for each point give the standard deviations for angles and for the distance immediately after the point has been measured.

X, Y, Z approaching coordinates are calculated as follows for a right-handed coordinate system :

Xo, Yo, Zo = Total station coordinates
X, Y, Z = Target coordinates





Hz : Horizontal angle
V : Vertical angle
SLOPE : Distance between the station and the target
Dist : Horizontal distance between the station and the target
Dist = SLOPE * sin V
Z-Zo = SLOPE * cos V
Y-Yo = Dist * cos Hz
X-Xo = Dist * sin Hz

Actually, using reference targets, the total station position is calculated using a Helmert transformation providing the following information: rotation and translation corrections for the total station position and after which the "monitoring" targets are calculated. These operations are carried out after each cycle to provide real movements of the area.

MONITORING TEST RESULTS

The full cycle of the prism measurements takes less than 15 minutes and the result is displayed on the monitor screen using a graphic interface to provide clear and concise information both to the engineer in charge of the work and the client.

The system is regularly connected via modem from France, both by SolData and IGN, to verify the data quality and, if necessary, fine tune the system parameters to refine the accuracy of the measurements.

Roof mounting was necessary for reasons of visibility. At first, there was concern that displacements recorded at the tops of buildings might not be a true reflection of foundation movements but, in practice, it has been found that these correlate well with ground movements on this site.

Figures 7 and 8 show the positions of the targets mounted on the building roofs and the ground level survey points.

Figure 9 shows differences in settlement measurements made by a surveyor at street level and by CYCLOPS at roof level. It clearly shows good correlation between the two sources of information and thus confirms the accuracy of measurements made by the automatic system.

Figure 10 shows that CYCLOPS measures movements almost impossible to detect with a precise levelling survey. This building is not affected by settlement but by a twist - highlighted by the X movement curve.

Thanks to the data management software, data is processed and analysed very quickly and presented in readily assimilated format (see figure 11), providing the engineer

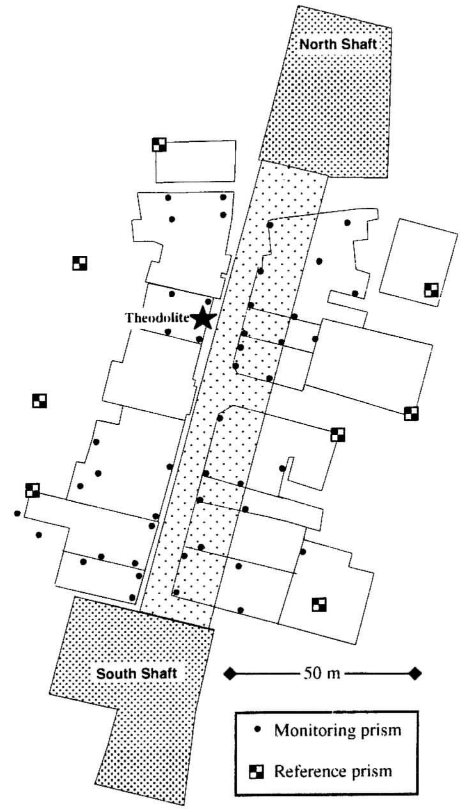


Figure 7. Position of Cyclops elements on building roofs

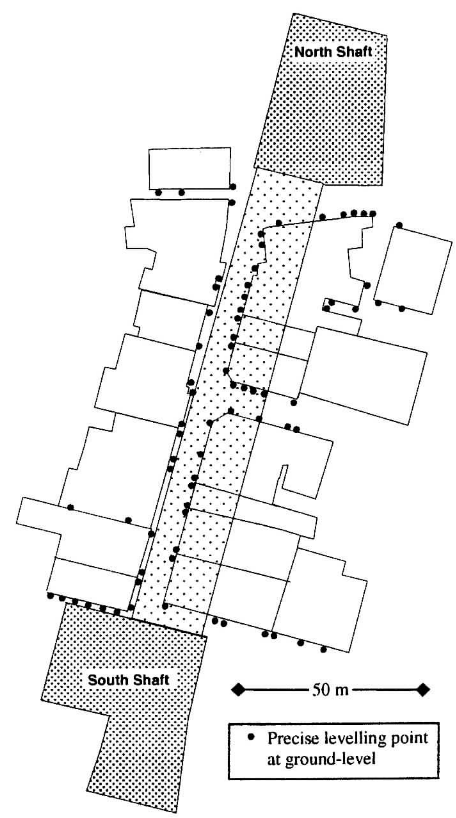


Figure 8. Position of levelling survey points at ground level

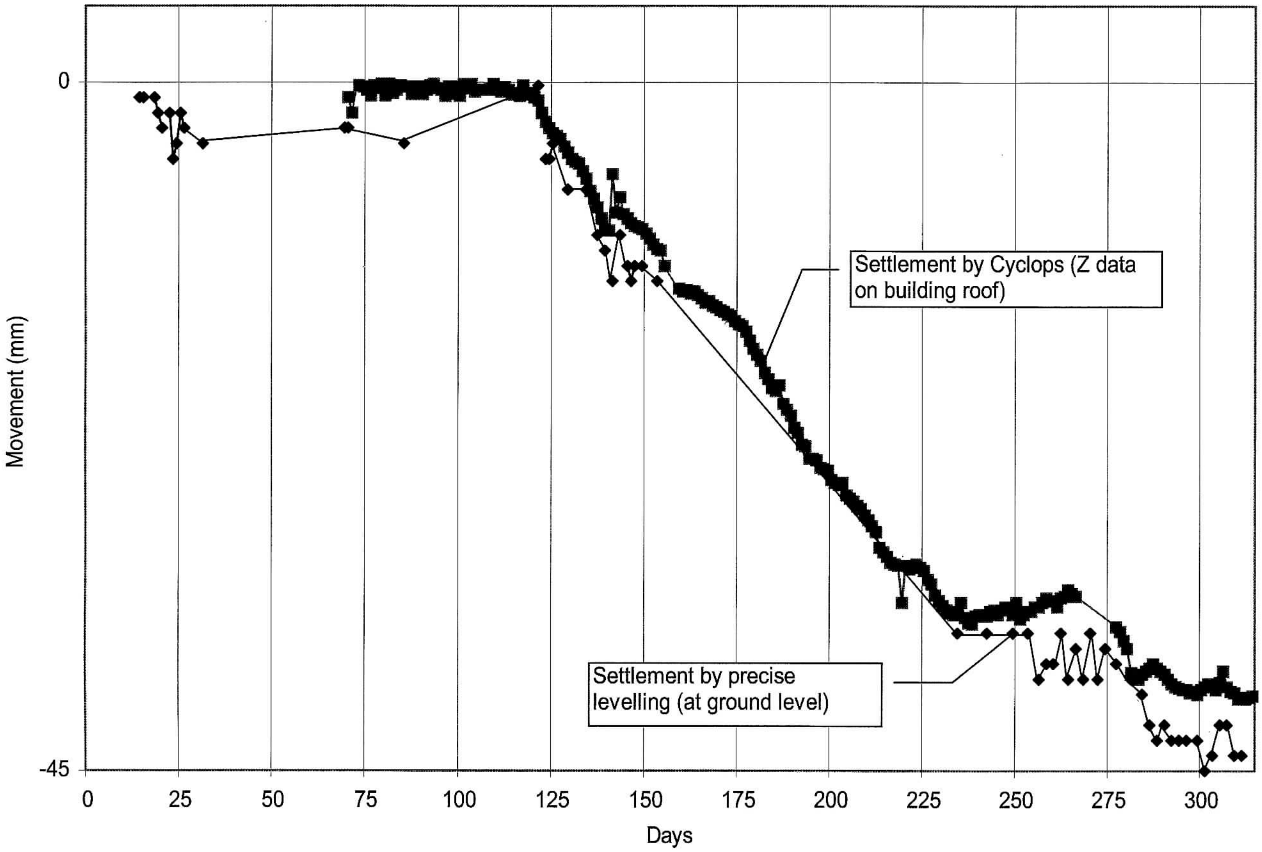


Figure 9. Correlation between levelling survey and CYCLOPS results

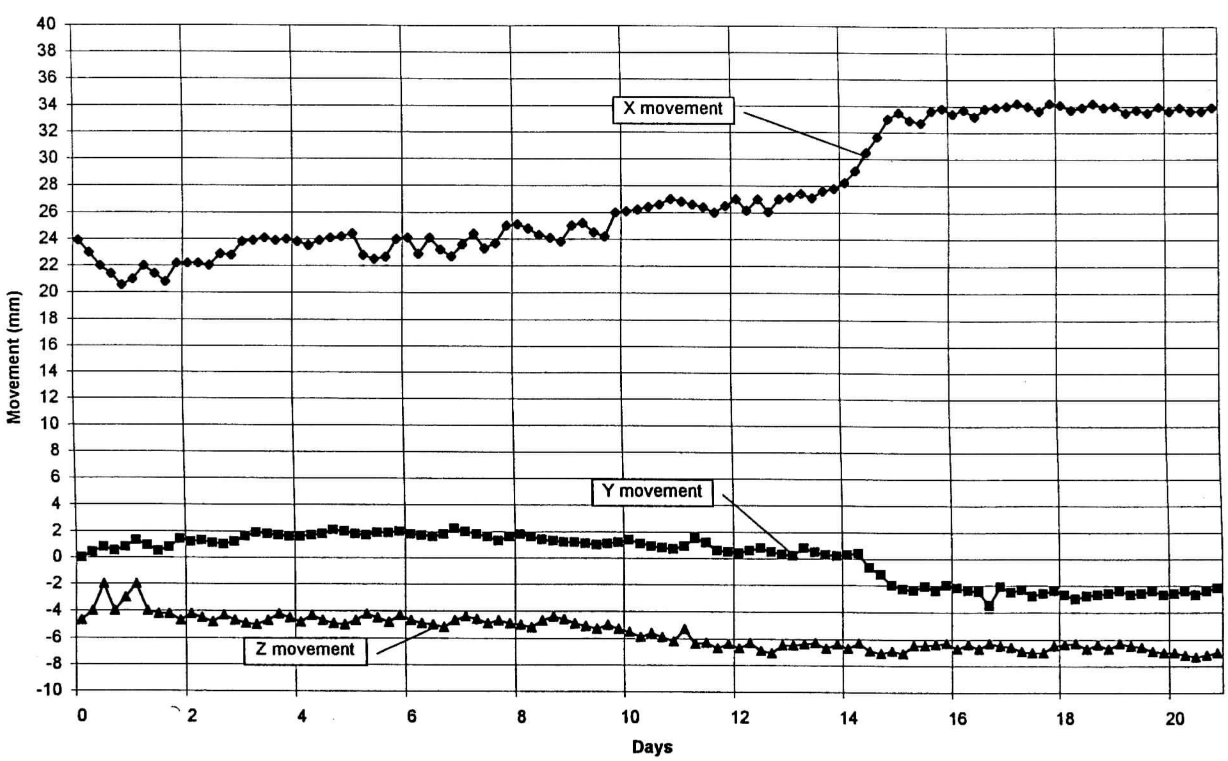


Figure 10. 3-D movements monitored by CYCLOPS

with an efficient monitoring tool and decision-making aid.

The day's results are analysed each evening. Grouting data is correlated with monitoring readings as a cross-check on prediction methods and to recalibrate the grouting model.

Data acquired is stored in the database. It is always available, at a moments notice, for tracing the full history of any monitoring point and relating this to details of the grouting and/or excavation taking place in this area.

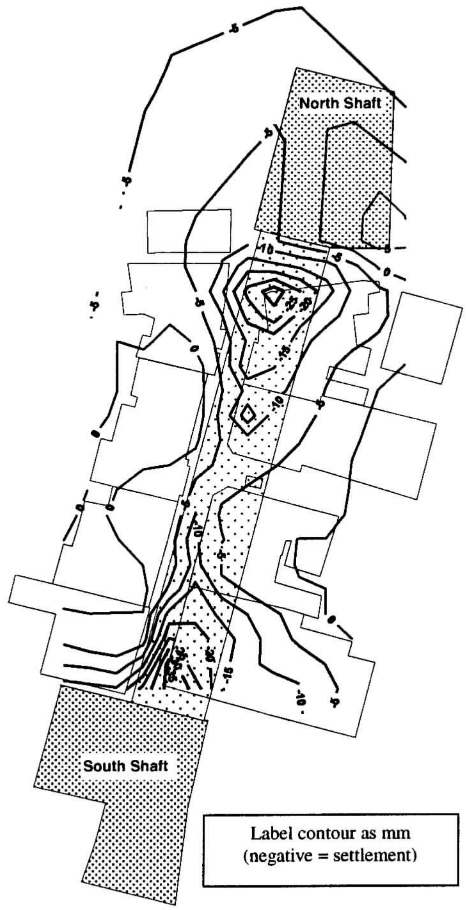


Figure 11. Contour lines of settlement

Lessons Learned

Based on experience at this and other projects over the past three years we have learned the following key points:

- An installation needs a few days of background data collection before all parameters are fully adjusted to ensure the base readings are fully representative for the site.
- This equipment is very reliable even under difficult site conditions (heavy rain, extreme temperatures, dust). However, as always it is important to think about a backup system when carrying out critical works. If necessary the total station or computer can be replaced within an hour provided a spare is available and the fundamental data was properly backed up.
- One of the greatest risks is theft and vandalism. It is very important to install the equipment as securely as possible e.g. at height, and locked inside a special steel protective box.
- An automatic system does not completely eliminate manual reading. Most importantly an initial survey must be taken in order to allow continued monitoring in case of the failure of the automatic system. On sensitive sites, regular manual surveys to check reference points and to confirm automatic measurements provide additional reassurance to the client.

Conclusion

The automated monitoring system described is an effective tool for monitoring ground movements caused by underground excavation and controlling the compensation grouting designed to minimise these movements.

This system is quickly set up on site and provides a valuable monitoring tool:

- It offers real-time monitoring with a cycle time of less than 15 minutes (for 50 locations).
- It provides round-the-clock monitoring (including week-ends and holidays) and can be connected to an automatic alarm system, pagers or fax, to give warnings to key staff when movements exceed a preset trigger value.
- It yields reliable, accurate data.
- Instrumented points can be chosen, if necessary, to detect differential transverse or tilting movements.

The ground cover at Puerto Rico is too thin for instruments to be installed in the ground, but under other circumstances, this automated surface monitoring could be coupled with sub-surface instrumentation in the grouting area to provide advance warning of movements approaching the surface (permitting faster and even more effective compensation grouting).

The system has operated continuously since it was installed in January 1998 despite several tropical storms and hurricane George in September 1998. It is not scheduled to be de-commissioned until mid-1999.

Bibliography

JG La Fonta & S Carayol, Settlement Monitoring and Compensation Grouting (in French), *Tunnels et Ouvrages Souterrains* No. 140, March/Apr 1997

S Carayol, Injection de Compensation (in French), *Travaux* May 1997

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New Instrumentation Technology Offers Reduced Life-Cycle Cost for Maintaining Geotechnical Structures and Other Infrastructure

Paul E. Grayson
William Law

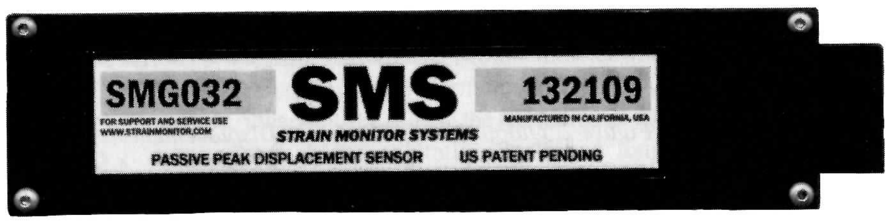

Figure 1. SMG-032 Passive Peak Displacement Sensor

Introduction

The world's infrastructure is deteriorating rapidly, yet little information is available to determine the integrity or safety of existing structures. To cite one of the most dramatic examples, the U. S. government reports that nearly 40% of the 575,000 bridges in the nation are structurally deficient or functionally obsolete. Reducing the backlog of obsolete and deficient bridges is a challenge whose cost is estimated at $78 billion.

Earthquakes seriously damage nearly 100,000 American buildings annually and wind, floods, and earth-failures destroy or damage even more. It is commonly recognized that owners of these structures face an enormous problem - how to manage the risks and costs associated with sudden or inevitable structural deterioration. The technology described here offers to provide the required information necessary to mitigate this problem and to optimize plans for repairing or replacing these structures.

Structures of all kinds normally operate in their "elastic" regimes of deformation; they are designed to bend and then return to their original configurations. Bridges are good examples. When a bridge is loaded beyond its normal limits into the "plastic" regime, it becomes permanently deformed and weakened. Often this damage is invisible, but as strains in the bridge structure increase so the bridge edges closer to structural failure. Changes in girder strains, joint rotations and crack growth are all key indicators of impending structural failure. By monitoring such changes closely, engineers would be capable of adding quantitative clarity to the often-murky picture of a bridge's structural health.

This article describes a new and unique technology for the safety and damage assessment of materials. The technology provides a simple, reliable, and inexpensive means of assessing structural damage. The developed system provides the ability to quickly and quantitatively discern the level of damage (and the potential for failure) within a structure. Such information will improve the process of repairing or retrofitting a damaged structure as well as provide a means for the quick and accurate determination of a structure's safety.

Smart Sensors

A family of peak displacement sensors has been developed, along with a digital networking approach, for this monitoring capability. The goals of the development were to produce a sensor that could be adapted to a variety of measurement applications, that would be easy to install and calibrate, and that would be durable and long-lived. The devices sense the peak displacement and passively retain that value for later interrogation. A system comprised of these sensors is able to immediately assess the structural condition of its host and provide quantitative information on this to the user. Most importantly, this information can be obtained remotely without actually visiting the installation site. These sensors require **no electrical power** except to read out the stored peak-displacement values. Such quantitative information greatly improves structural safety inspections and provides valuable information for directing timely maintenance relief to those areas of the structure most in need of repair. Structural maintenance engineers now have a tool that will provide the information they need to extend the structural lives of the bridges, buildings, dams, tunnels, landfills, and other structures that we the public rely on daily.

The approach presently is based on two totally different technologies working in different ways. However, both are *passive peak strain sensor systems.* The systems are ideal for most structural monitoring because it is crucial to know the cumulative effects of damage, and to know them at the very moment they exceed a threshold of danger. The initial development covers a family of high-performance metal alloys that are "smart," meaning that they can "remember" the peak strain to which they have been subjected. Here's how they work. When subjected to strain, the material instantly transforms from a nonmagnetic to a magnetic state. This change is permanent and can be measured electronically. The more the strain, the more pronounced the transformation; the correlation between stress and resulting ferromagnetism is precise and remarkably proportional. The degree of strain is permanently recorded in the properties of the metal and is easily readable at any time; the alloy always remembers its maximum strain. For common civil engineering applications we fabricate a small tensile specimen and place it inside a protective housing along with some simple circuitry to measure these changed magnetic properties. Output is a stable direct current and is proportional to applied strain.

The second approach has resulted in a family of SMG-03X peak reading passive strain sensors as shown in figure 1, which involves the use of linear potentiometers. These are inexpensive, off-the-shelf devices that have gone unrecognized for their capabilities as structural sensors.

The sensor uses a change in resistance across a strip of conductive plastic to produce a voltage change proportional to any relative displacement between its attachment points. This movement is then internally mechanically restricted, giving the sensor its "peak retention" capability. The sensor, which can measure both tensile and compressive peak strains and can be reset for repeated use, has a ratiometric output, a total stroke of 18 mm and an accuracy over full scale of ±10 µm. These sensors are simple enough to be read with a handheld voltmeter yet accurate enough to detect the onset of damage in civil structures. Figure 2 shows a typical calibration test curve for a sensor.

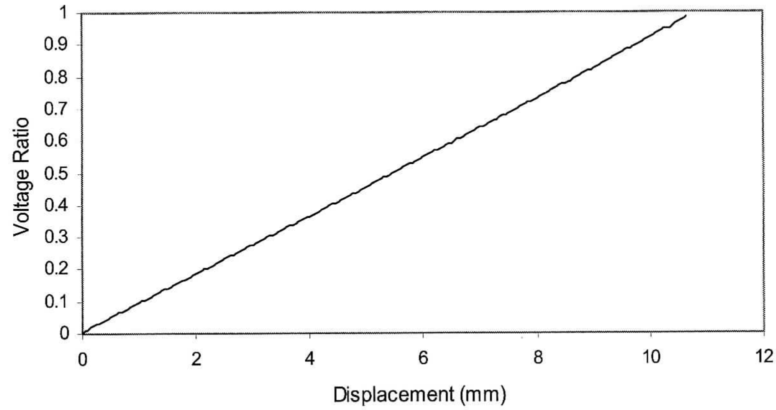

Figure 2. Output Voltage Ratio vs. Displacement

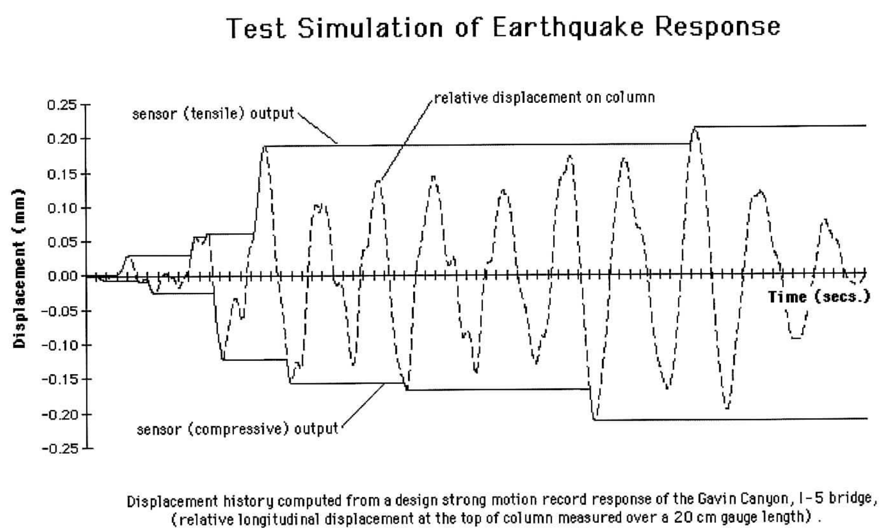

Figure 3. Measured Response of Gauge (Both Directions) for an Earthquake History Excitation

The response is linear within an accuracy of 0.4% of full-scale. If a full nonlinear calibration curve is applied, the overall accuracy is less that 0.1% of full-scale. The error as established using a motion control table with a certifiable accuracy of 0.5 microns, is typically less that 10 microns. The use of ratiometric changes in the potentiometer means that temperature changes are immediately compensated for. The accuracy quoted is valid for temperatures from -40°C to 65°C.

Both technology approaches produce sensors that have intrinsic memory capabilities that eliminate the need for constant power and constant monitoring. At any time the sensor can report the peak strain to which it has been exposed. The state of deterioration in a structure shows up as stretching or bending and finally as cracking. Small cracks are followed by large cracks. The gauges of either design simply measure and remember the maximum amount of such deformation that has occurred. Since engineers can calculate with a very high degree of confidence which components of a structure will break first, each gauge is carefully located on just those components and in just such a way that it can watch the entire damage process from beginning to end. Both types of sensor systems can be configured to monitor tensile, compressive, and torsional strains and can be reset for repeated use.

Current Technology

Traditionally, there have been two fundamental approaches to assessing structural strain: By measuring either acceleration (velocity), or local strain (relative deflection). The former uses accelerometers to measure motion at key structural locations. The latter uses strain gauges and displacement transducers to measure local deformation, and is generally preferred as the more accurate of the two. The new patented technology falls in the strain-gauge category, but utterly redefines it in terms of cost, simplicity and safety.

The traditional strain-gauge devices - such as bonded and vibrating wire gauges, LVDTs, DCDTs and fiberoptic sensors - are active, which means that three factors limit their use.

The first of these factors is that active sensors measure tiny changes in physical parameters and, with the exception of vibrating wire gauges, are complex and require significant signal processing to produce a useful digital output. Secondly they are expensive, mostly due to the equipment required to read them. But their third and most serious drawback is that they require constant power and constant data logging since they lack intrinsic memory.

Consider an active gauge that measures racking of a primary column in a building or bridge. To capture peak deflection that lasts for fractions of a second, the gauge is read at 100 Hz (100 time a second). For five years nothing happens; then an earthquake strikes for 15 seconds. Up to that point, the gauge has taken approximately 15 trillion readings! Not even an engineer wants to see trillions of confirmations that nothing has happened. By contrast, the new device can be left unattended for any length of time, relied on to permanently trap the worst deflection, however transient it may be and then trusted to report that reading when queried at a later date.

Sensor Performance

A laboratory simulation of the sensor operation was performed on a tensile testing machine with a sensor inserted. A simulated time history of a calculated bridge response (from a Caltrans design earthquake) was used as the input for the gauge loading. Figure 3 shows the results of such a typical test.

The gauge output was the peak displacement in either direction. In a passive mode of use, the sensors two outputs, when measured at any time after the earthquake, would indicate the maximum displacements (or strains) that occurred during the excitation, even though the excitation itself had long since ceased.

Applications and System Design

For civil infrastructure applications, engineers can place the devices in highly stressed areas of bridges, buildings, pipelines, dams and tunnels. Placement is simple and nondestructive; epoxy glue bonds the sensor to the structure. Various degrees of complexity in monitoring schemes are available. In the simplest scheme, they can be mounted at critical locations within a structure, without any power or datalogging equipment in place, and interrogated manually at the site when required. With this approach the sensors are wired into a central junction box, to which a portable data logger can be connected for quickly downloading data. This monitoring scheme is especially well suited to monitoring bridge support columns and elevated roadways after seismic activity, in cases where the number of columns and the relative infrequency of events do not warrant a remote access system.

A more extensive system approach, employing large numbers of sensors, spaced at large distances, can be interfaced via a serial, digital EIA RS-485 network, as shown in figure 4. The sensors are locally connected to analog-to-digital converter units that have digital addresses on the RS-485 line.

Up to 256 junctions can be placed onto a single twisted-pair wire in this manner and cable lengths of up to 1,200 meters can be used. The fully automatic sites consist of a microprocessor and cellular phone with modem that allows communication with the monitoring software. Solar panels and batteries are used to supply power to the monitoring system in remote locations.

A further development provides desktop software, which can remotely interrogate a suite of sites from an engineer's office and then store, calibrate and present the data. The software operates autonomously and requires no additional input once set up. This system is called the Remote Cellular Interrogation System (RCI), the main screen as shown in figure 5. The program is thorough, It:

- routinely dials up the remote sites,
- collects the data from the sensors,
- performs the engineering units calibration on this output,
- stores the data in a spreadsheet,
- outputs the data onto a website,
- prepares time history charts of each sensor, and
- e-mails specific users if the values should exceed specific alarm levels.

Clicking on the "view a chart of sensor output" button on the front panel of the RCI brings up the charting tool, whose front panel is shown below in figure 6.

Once open, it is active and running. The "site" selector pull-down menu will offer a choice of all the available sites.

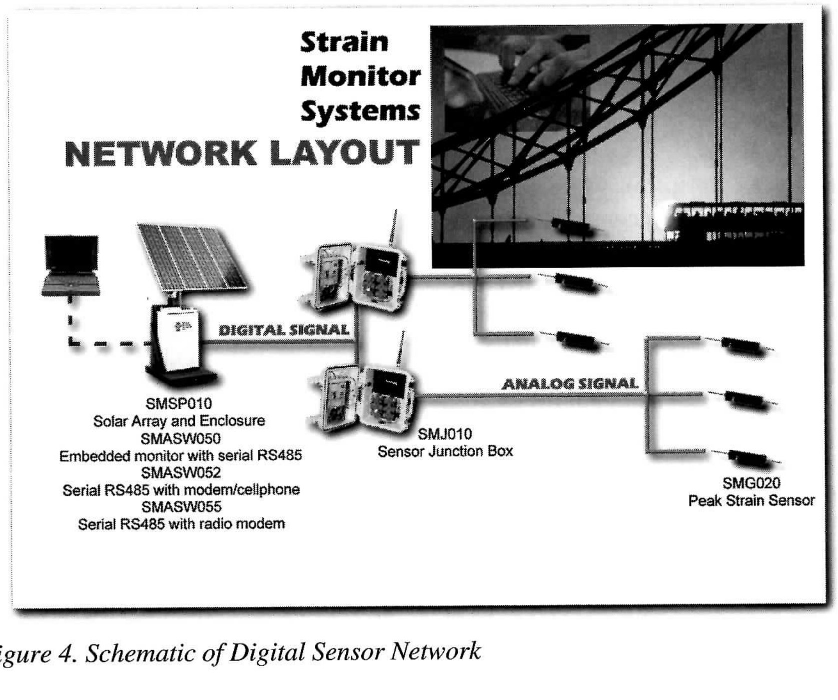

Figure 4. Schematic of Digital Sensor Network

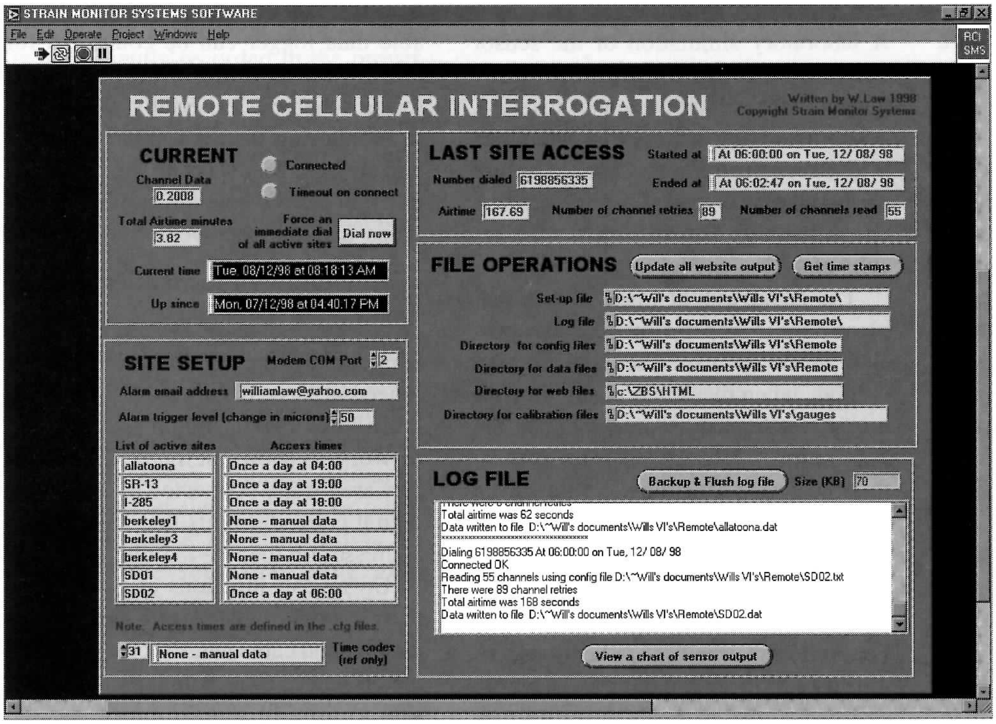

Figure 5. Remote Cellular Interrogation - Main Screen

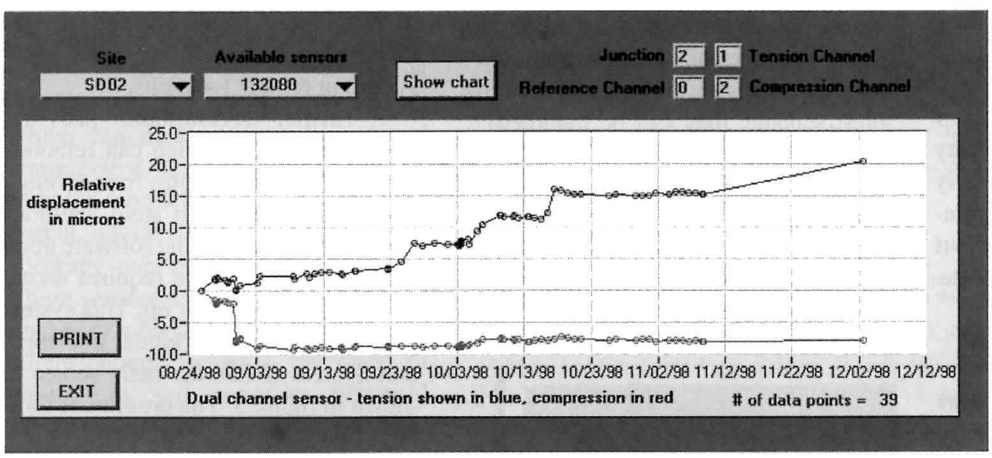

Figure 6. Sensor Output History

Once a site is selected by clicking on it, the list of "Available Sensors" pull down menu will automatically change to list all the sensors installed on that site. Once a particular sensor is selected, and the "show Chart" button is clicked, the chart display will update to show a plot of displacement versus time. The displacement is relative to the first reading taken for that sensor. The display windows will also automatically update to show the junction and channels to which that particular sensor is connected. For SMG032 sensors, tensile displacement is considered positive and is shown as a blue trace (top trace), while compressive displacement is considered a negative and is shown as a red trace (bottom trace). For SMG034 (hybrid active/passive sensors), the peak tensile displacement is shown as a blue trace and the active diplacement as a red trace. Clicking on the "print" button will cause the current chart to be printed.

Summary

The authors do not advocate the replacement of a visual inspection with a monitoring system. A computer and sensor system can detect only what it has been set up to find. The purpose of the monitoring system is to relieve inspectors of the mundane and time-consuming task of looking for evidence of failure, thereby freeing them to do what they do best - searching for the unexpected. Peak strain measurements are not the be-all and end-all of monitoring.

We believe a mix of active and passive sensors is the best way to monitor. Active sensors are well suited to an intensive, short-term, in-depth analysis of a problem. Once an in-depth analysis has been made, the engineer can withdraw the active sensors, leaving behind a passive long-term monitoring system. We design interfaces to our network for popular active sensors, such as linear variable differential transducers (LVDTs), vibrating wires and bonded resistive strain gauges. These may be easily integrated into the system should the situation warrant an active phase of investigation.

With the development of this new gauge, a new toolbox has been opened for those designing and maintaining civil infrastructure. Peak passive strain sensors, simple networks and remote interrogation are making the transition from high technology to applied technology. The concrete and steel monoliths of our world are far from inert. They have strains, stresses and movements that can provide vital insight into their condition. It is time we started listening.

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