Geotechnical Instrumentation NEWS

Geotechnical Instrumentation News

John Dunnicliff

Introduction

This is the sixty-fourth episode of GIN. Two articles this time.

Web-based Data Management Software

In the previous GIN I told of a request from a colleague for information about web-based data management software and responded with, " What an excellent suggestion!" Here's an article by David Cook that identifies *things to consider*, intended to assist a person who needs instrumentation geotechnical database management in determining what is important, before committing to a particular system.

A few weeks ago I sent the article to several firms who supply web-based data management software, inviting each to respond with a one-page "Ours will do this" article. I've had positive responses from seven firms and plan to include their contributions in the next GIN, March 2011.

More on Fiber-Optic Sensing Systems

Earlier GINs have included:

- From Switzerland: "Overview of Fiber Optic Sensing Technologies for Geotechnical Instrumentation and Monitoring", and "Distributed Fiber Optic Sensors: Novel Tools for the Monitoring of Large Structures", both by Daniele Inaudi and Branko Glisic, September 2007.
- From England: "Distributed Optical Fibre Strain Measurements in Civil Engineering", by Peter Bennett, December 2008.

Here's another article about distributed fiber-optic sensing by colleagues from the Institute for Geotechnical Engineering, ETH Zürich - Swiss Federal Institute of Technology, who appear to be playing a leading role in developing this technology. Because I expect that you'd like to have information on commercial sources, I asked the authors to include this but, being a professional institute, they preferred not to do so. At the end of the article I've therefore included an *Editor's Note* with eight commercial sources - if you know of others, please let me know, and I'll update the list in a later GIN.

Next Instrumentation Course in Florida

Since my previous GIN column, the dates of the next course have been changed. Dates are now April 3-5, 2011 at Cocoa Beach. Details are on page 33 and on www.conferences.dce.ufl.edu/geotech.

Next International Symposium on Field Measurements in Geomechanics (FMGM)

As many of you will know, FMGM symposia are organized every four years, the previous one being in Boston in September 2007. They are "the places to be" for folks in our club. The next FMGM will be in Berlin, Germany on September 12-16, 2011. Information is on www.fmgm2011.og. The deadline for submission of abstracts is December 31, 2010.

Alex Feldman

Alex Feldman.

The following has been sent to me by Alex's colleagues at Shannon & Wilson, Inc., Seattle, Washington.

> Alexander I. Feldman, an internationally known structural and instrumentation engineer, passed away on August 14, 2010. Alex came to the US in the late 1970s following a meeting with Stan Wilson, one of Shannon & Wilson's co-founders, at a conference in Russia. Stan was impressed and later sponsored Alex and his family to emigrate to the U.S.
>
> Alex had a brilliant mind, particularly for instrumentation, and never backed down from a challenge. Among his other accomplishments, he pioneered the use of open-channel liquid level systems to monitor vertical displacements of sensitive structures such as tunnels and dams. Alex was a long-time member of Shannon & Wilson. Ever the innovator, he secured patents for

a "Tensional Bellows Pressure Transducer" and, with three co-workers, a patent for a "Method and Apparatus for Measuring *in situ* Strain and Stress of Concrete." After retiring, Alex often returned to Shannon & Wilson to help with projects that needed his special expertise.

Alex was an accomplished amateur photographer, an avid reader, and enjoyed a lively discussion. Once you met Alex, you did not forget him.

I worked with Alex on several projects, and can echo "ever the innovator" and "brilliant mind". Our instrumentation community will miss him.

The editor with new friends.

A Breathtaking Experience

Have you seen the movie *The Bucket List?* I started my list, with *Safari* as Item One. The Masai Mara in Kenya. A most extraordinary experience, beating Taj Mahal, Giza pyramids, Grand Canyon, Niagara Falls et al at al. Lions, elephants, cheetahs, buffalos, giraffes (and many more) galore, often as close as 15 feet from the 4WD. And those idiotic wildebeests, crossing the Mara River as part of the annual migration of 1.3 million of their brethren. Large numbers don't make it – they either drown or become dinner for the crocodiles. Spectacular! Go gotta go! If you'd like specific suggestions, please let me know.

Enjoy the wonderful Kenya welcome song "Jambo Bwana" (Hello sir) on www.youtube.com/watch?v=fK0wPpLryc4, and learn some Swahili too!

Closure

Please send contributions to this column, or an article for GIN, to me as an e-mail attachment in MSWord, to john@dunnicliff.eclipse.co.uk, or by mail: Little Leat, Whisselwell, Bovey Tracey, Devon TQ13 9LA, England. Tel. +44-1626-832919.

Maisha marefu! (Swahili, "Long life" – Kenya of course!)

Fundamentals of Instrumentation Geotechnical Database Management – Things to Consider

David Cook

Introduction

The purpose of this article is to identify elements of geotechnical monitoring databases: collection, verification, storage, visualisation and dissemination of monitoring data, which need to be considered. This should allow users to make more informed decisions early in the procurement process. There are no right or wrong answers, only a determination of need related to specific project requirements.

This is not a checklist, but it discusses instrumentation, software and hardware elements to be considered. Inevitably it is not a discussion of how to achieve these results technically, but indicates the outcomes required. It is a personal list, and others' experience may identify different considerations which are more important for their situation.

Why Do I Feel Able to Write This Article?

Readers may ask why my comments might assist others in their decision making. I have been involved in monitoring and the use of custom interfaces to allow interpretation of the results since the late 1980s, commencing with the Docklands Light Railway Extension into the City of London (which included 3D-spatial survey, displayed via AutoCAD) through Heathrow Express, Channel Tunnel Rail Link, Heathrow Terminal 5 and Amsterdam Noord/Zuidlijn, an EPSRC study examining the benefits of 3D presentation of monitoring results and as a Member of the British Tunnelling Society Subcommittee producing "Monitoring Underground Construction: a best practice guide."

Historic Context

At the outset, virtually all monitoring software was custom-made for each project, with Excel a favoured data visualisation tool. Since then proprietary software has become more commonplace. However, some clients will require monitoring visualisation software to be incorporated with their own systems, and that increasingly means within a corporate Geographic Information System (GIS).

Client Decisions

Data handling responsibilities must be clearly determined at an early stage. For example, does the monitoring contractor merely provide the data, with responsibility only for verifying that it is correct, or do they also provide a visualisation package and analysis services? If a client chooses to split these roles, does the client have the capability of ensuring that mitigation actions can be directed accordingly? This decision will fundamentally direct what is required.

Table 1 indicates some fundamental decisions which need to be made.

Interface

How comprehensive an interface is required? Is 3D visualisation required and the added complexity this can involve appreciated?

Systems are usually graphical, indicating the locations being considered, for easy assimilation.

Is a comparison of different instrument types within the same graphical output possible, for example comparisons between borehole extensometer readings at surface and related precise levelling can be instructive in determining where problems lie?

Is the system sufficiently flexible to allow selection of particular locations for comparison purposes, which have not been pre-determined?

Can the data be viewed in different graphing formats? For example inclinometer readings are often displayed in a "tail-wagging" form but for examining data against time, but it may be more useful to determine trends on a movement versus time graph, at a particular level.

Response Times

What is the time delay from collection, through import, to use being made within the visualisation software? This may be a project-wide standard frequency, but more frequent at focused locations (if required) without compromising more global frequencies elsewhere.

Does an increase in the data held slow down response times, which then make ease of archiving and re-import (if required) a consideration? Timescale issues are covered in Tables 2 & 3.

Alarm Raising Functionality

Assuming that the monitoring office will not be staffed 24/7, the system will need to provide notification of trigger limit (response level) breaches or potential trigger level breaches to an on-call monitoring engineer. This could be provided by SMS text, e-mail (Blackberry), or a digitised voice over a mobile phone. Consider how reliable each of these communication routes is at the project location, before fixing on one. There need to be escalation capabilities if the initial contact does not respond within the requisite time scale. How does the software escalate the alarm raising? The alarm message is more meaningful if it gives specific location where the breach is taking place, the breach level which is occurring (Red/Amber) (or predicted to occur within a certain time), the current value and the previous value plus the times at which these details were recorded.

Instrumentation Types

Does the system handle all the instrumentation systems envisaged and is there the capability to incorporate additional instrumentation types or at

Table 1. Access requirements to monitoring data

Category	Considerations
Viewing	Who needs to view the data and for what purpose? Is only local access (from within one office or network) needed or is remote access, possibly via the Internet, also required?
	Are multiple or limited simultaneous accesses by the various parties required? There may be a performance hit in terms of system response from multiple simultaneous accesses.
Access Limitations	Consider the access limitations to be put in place and related security considerations for each user. This could be from a Full Administrator Read and Write capabilities (including ability to add or remove access to/from others) through to Read Only which, in itself, could be Read Only full access to data for the main project team or partial access only for third parties.
Maintenance	Is it possible for an on-call engineer to access remotely and respond to alarms raised, without needing to attend the monitoring office? It should be possible for limited provision, even if general viewing of results by the team is not planned.

Table 2. Project/data timescale issues - generic	
Category	Considerations
Timescale	Over what timescales are the pre-construction, construction and close-out monitoring to be performed, and what use is to be made of that data after close-out monitoring is completed?
Software	Updates for operating systems/monitoring software etc. are likely to take place within a project timescale and recognition taken of this need. For example, if monitoring software is based on a proprietary GIS, updates on the base GIS software may result in custom routines needing to re-written.
Computer Hardware	Developments may prevent use of earlier software. Whilst old software may run very fast on newer operating systems, it may not work at all.
File Format and Storage Media	The data file format and means to read it over time are important if long-term use is to be made. An example is the NASA 1960 space shots where there are warehouses of punched cards which no longer have the necessary reading equipment. The AGS Data Format may prove to the way forward, but be wary of proprietary formats which may not be supported in future. What storage media is to be used and will it need updating over time? Over the last 20 years there have been 8", 5.25" & 3.5" [720kb, 1.44Mb, 120Mb] floppy disks, Bernoulli drives, Zip drives, CD, DVD [+R/-R/RW], as relatively common examples. Many organisations would now have trouble reading a 5 ¼" floppy. What provision (if any) is to be made for the project data longer term?
Time/Date Format Convention	A very simple point to indicate the importance of convention is that the Time/Date format (as expressed in output) should not be capable of confusion between different countries. An example is date/month/year as indicated in UK v US systems and in countries where there is an hour change, from example Greenwich Mean Time (GMT) to British Summer Time (BST) in the UK: is it clear what is being viewed? How are the 23:00, 00:00 and 01:00 GMT readings indicated in a system which shows BST readings?

least store output from other packages within the monitoring database? For example railway track monitoring vehicles may be used as part of a monitoring system and derivation of data from such a specialist system may be beyond generic monitoring software systems, but the ability to make a link to the data at relevant site locations is all part of the necessary data assimilation/review process.

Other Functionality

In addition to viewing monitoring results for trigger limit (response value) breaches, there should be clear demonstration of both instrument and reading availability (where these fundamentally differ) to allow effective maintenance targeting. For example, a robotic total station (RTS) takes readings from a number of monitored prisms. The loss of an RTS will result in a total loss of readings for all those prisms. Alternatively local line-of-sight issues (RTS to prism) will result in some prisms not being read. The database software should be capable of this discrimination, thereby assisting in maintenance operations.

There should be an ability to annotate the information held. For example maintenance work may affect readings at a certain location. Whilst the team may be aware of the reason at that time, two years later researching the history becomes more difficult if that information is not readily available.

The capability to include other relevant information, such as reference photographs and details of construction progress may be required.

Ability to compare information between primary and secondary instrumentation systems may be required.

Is the ability to be able to compensate for pre-construction movements important?

How is the software segmented operationally? Does a problem with data collection overspill onto visualisation, effectively locking the system up?

Is the system sufficiently scaleable to encompass requirements at all monitoring stages? A monitoring database sufficient to provide access to data during pre-construction monitoring may not meet the full project-wide system requirements during the construction phase. This could be in terms of locations being monitored, instruments being used or user access requirements. Any such limitations should be appreciated at commencement of pre-construction monitoring, and not discovered part-way though construction. Some specific data management considerations are covered in Table 4.

Output

Generally outputs are graphical in order to aid review, but data in a numeric form often needs to be available for evaluation outside the main monitoring package. This can be provided with an export facility to Excel and other statistical and analysis packages.

Conclusions

My apologies for the inevitable number of questions rather than answers in this

Table 3. Project/data timescale issues - specific

Category	Considerations
Customisation	For custom software, what customisation services are available? As an example, are simple predictive capabilities needed/available?
Response Time (General	Does the software process the data and then draw from a database of that processed data, or does it process on the fly for each query? What is the typical response time from time of query to delivery of results? Do the numbers of system users affect it at the time?
Response Time (Data/Volume)	Maintain access to data. Data quantity may require archiving if magnitude slows system down too much, but base information needs to be retained. Historic (archived) data may need to be accessed - how is this accomplished?

article. But, as indicated at the beginning, there is not a "right" answer for what is required. My intention is to assist a person who needs instrumentation geotechnical database management in determining what is important, before committing to a particular system. If it assists in that aim it will have served its purpose.

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Table 4. Data management

Category	Description
Collection	How secure is data input to the system? For example is data placed on an FTP site which the software then imports, or does the software dial-up individual logger boxes to collect the data? How is access managed? It is important that both raw and processed data are collected and stored, even though is unlikely that raw data would need to be accessed unless a dispute arises. Is Manual Data Capture information readily input and if Remote Data Capture (RDC) communication links are temporarily unavailable can manually collected data from RDC instruments be readily imported to the system?
Verification	It is important that data verification checks are carried out before the data is used. If imported monitoring data is subsequently determined to be incorrect, the ability to re-import/reprocess is an important consideration, without overwriting data determined to be incorrect, but being able to flag it as not for use. Consideration must be given to storing both raw and processed data.
Processing	Is time to process the data within the visualisation software affected by the import system used? Can the system handle/process the quantity of data envisaged, and can it be more focussed when the situation demands it?
Replication/ Archiving	In some systems, whilst backing-up is taking place, access to the monitoring data may not be possible. In this eventuality a form of data replication will be required to allow ongoing access to data. It should go without saying there needs to be a disaster recovery system in place.

Advanced Geotechnical Applications of Distributed Fiber-Optic Sensing

Alexander M. Puzrin
Michael Iten
Dominik Hauswirth

Introduction

Distributed fiber-optic (FO) strain sensors are offering new possibilities in the field of geotechnical monitoring. By integrating a single FO cable into soil or structure, an unprecedented amount of accurate, spatially resolved data can be obtained. Current commercially available technology allows for strain measurements in the microstrain (με) range (0.0001%) with a spatial resolution of 1m along a 30km long fiber.

In this article we describe recent novel geotechnical FO technology applications in the laboratory and field. The emphasis is to sketch the FO cable layout, integration and the monitoring results, with details of the projects given elsewhere (Iten et al., 2009a; Hauswirth et al., 2010; Iten & Puzrin, 2010).

For locating landslide boundaries, a soil-embedded sensor system, a road-embedded sensor and the reactivation of an old inclinometer are described. In addition, a new monitoring ground anchor is presented. Finally, laboratory testing of a novel sensor technology offering spatial resolution below 5cm indicates the direction where FO sensor technology is heading: substitution of hundreds of individual local strain gauges with one single FO cable.

Distributed Fiber-Optic Sensing

Measurement Technology

Continuous strain can be measured along optical fibers by several techniques based on the Brillouin scattering effect: spontaneous Brillouin Optical Time Domain Reflectometry (BOTDR) occurs when a light pulse guided through a silica fiber is backscattered by a nonlinear interaction with thermally excited acoustic waves. In the more refined Brillouin Optical Time Domain Analysis (BOTDA), two counter-propagating light waves (pump and probe) at different frequencies interact via stimulated acoustic waves.

The scattered light undergoes a frequency shift, which is directly related to the strain and temperature in the medium. Thus, in addition to the strained FO cable, a loose fiber must be placed for temperature compensation. The backscatter is recorded in the time domain to obtain information of the scattering location along the fiber and the frequency shift of the signal is analyzed and converted into strain and temperature data. The strain measured is the average value over the spatial resolution (typically >1m), which corresponds directly to the length of the light pulse sent down the fiber. Remote control and automatic measurement mode is possible.

Recently, a significant breakthrough was achieved in narrowing the spatial resolution down to 5cm with extremely short pulse durations in the Brillouin Echo Distributed Sensing (BEDS) setup. The BEDS concept is based on observing a "negative" gain created by a very short-time phase shift applied on the pump that interferes destructively with the reflected light. BEDS is not commercially available yet, but first testing in soil has shown its potential for future applications.

Table 1 gives an overview of the listed technologies (see also Thévenaz, 2010).

Fiber-Optic Cables

FO cables used for integration into different environments have to comply with several requirements, such as being strong enough to withstand harsh installation conditions, transmitting strain applied on the jacket without loss to the fiber core, allowing unproblematic handling and offering flexible adjustment to project modifications. The quality of the FO cable and its fixations strongly influences the overall measurement accuracy of the sensing system.

Increasingly, specialty FO cables for strain sensing are available from cable manufacturers. Most important for the user is to focus on the quality

Table 1. Comparison of distributed FO strain sensing technologies, according to manufacturer information

	BOTDR	BOTDA	BEDS
	Brillouin Optical Time Domain Reflectometry	Brillouin Optical Time Domain Analysis	Brillouin Echo Distributed Sensing
Measurement accuracy	20με to 40με	2με to 10με	10με to 20με
Spatial resolution	1m	1m	0.05m
Max. distance	30km	30km	More than 5km
Availability	Commercially	Commercially	Lab prototype
Comment	Single fiber	Loop required	Loop required

Table 2: FO cables used						
BSM	TSM	S06	S08	P07	S09	M07
Bare fiber	Tight buffered fiber	Heat shrink tube protected TSM	Polyurethane protected cable	Polyamide protected cable	Polyamide & metal protected cable	Metal protected cable
0.25mm diameter	0.9mm diameter	2mm by 3mm	2.8mm diameter	1.6mm diameter	3.2mm diameter	0.9mm diameter
EA = 0.9kN	EA = 0.9kN	EA = 2kN	EA = 2.5kN	EA = 3kN	EA = 50kN	EA = 70kN
Commercial product	Commercial product	Custom produced	Prototype	Prototype	Prototype	Prototype

and quantity of the strain transfer from the jacket to the fiber, as by far not all commercially advertised "FO strain sensing cables" do fulfill this requirement sufficiently. In addition, the FO cable design needs to allow for stripping of the protection layers down to the fiber itself in order to repair (splice) the broken fiber.

Several single mode FO cables were used in this study, ranging from bare fibers to well-protected prototypes of tight buffered FO strain sensing cables. Special attention was given to include only easy repairable FO cables in our research. Table 2 gives a brief overview of these FO cables.

Defining and Monitoring of Landslide Boundaries

Motivation

Differential soil displacements initiated by creeping landslides can cause immense problems by damaging infrastructure and buildings in the sliding area. Moreover, special construction and reinforcement requirements, or even total halt of construction within a landslide area may be demanded by local construction laws. In some cases it is therefore of crucial importance to determine the exact position of the boundary between the landslide and the stable part of the slope. Geodetic measurements can identify the boundary on the surface, but not necessarily with high accuracy. Inclinometers serve for detection of the sliding surface, but once an inclinometer casing is excessively distorted, a conventional inclinometer probe can not be inserted and the inclinometer will no longer produce results.

New landslide monitoring techniques by means of distributed FO technology can offer an unprecedented amount of high quality data at reasonably low costs. By performing optical strain measurements along the FO cable, the transition zone between the sliding and the stable parts can be identified. Several systems to determine this boundary have been successfully implemented in field projects on creeping landslides in the area of St. Moritz, Switzerland, as described below.

Asphalt Road-Embedded FO Cable

The first system, an asphalt road-embedded FO cable, serves for the evaluation of such a boundary in an urban area. An instrumented road, which intersects this boundary, can be seen as a large-scale strain gauge. The FO cable (of longitudinal stiffness EA between S06 and P07 in Table 2) was glued at 1m intervals inside a trench (about 10mm wide by 70mm deep) cut into asphalt, with a temperature sensor placed on top of it. Subsequently, the whole trench was filled with an elastic cold sealing compound.

Since 2006 three such road-embedded systems have been integrated and tested in the field. The differential strain along a 90m long FO cable accumulated in a 7 months period is shown in Figure 1. The transition zone has been identified as a 15m long section and the landslide movement estimated at about 20mm (by multiplying the measured strain by the length of the transition zone and assuming that the FO cable crosses the boundary at 45° angle). This was later independently verified by geodetical data. Good repeatability of measurements was confirmed by installing another FO cable at the same location.

Soil-Embedded " Micro-Anchor" -FO Cable System

For the boundary identification in an area where no road or other infrastructure exists, to which the FO cable could be attached, a soil-embedded " micro-anchor" -FO cable

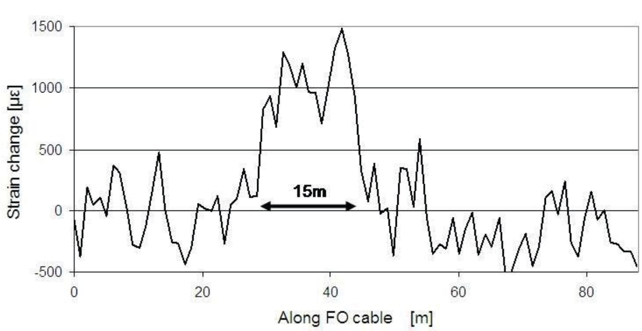

Figure 1. Strain data along a road-embedded FO cable.

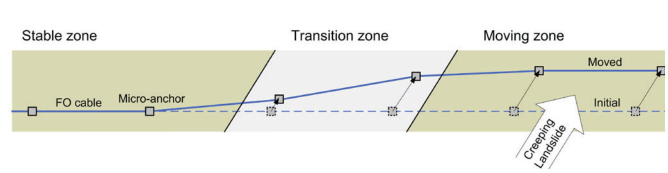

Figure 2. The "micro-anchor" - FO cable system.

system has been developed (Figure 2). The principle of this second system is that a FO cable fixed to "micro-anchors" buried in soil experiences the same movement than the soil around it. The "micro-anchor" (Figure 3) consists of three perpendicular planes in order to provide bearing resistance in all directions and to act as a three dimensional "dead" anchor. The anchor size (side length of 40mm, 60mm or 80mm, respectively) is chosen as a function of the anchor depth and the stiffness of the chosen FO cable (preferably S08 and S09, Table 2).

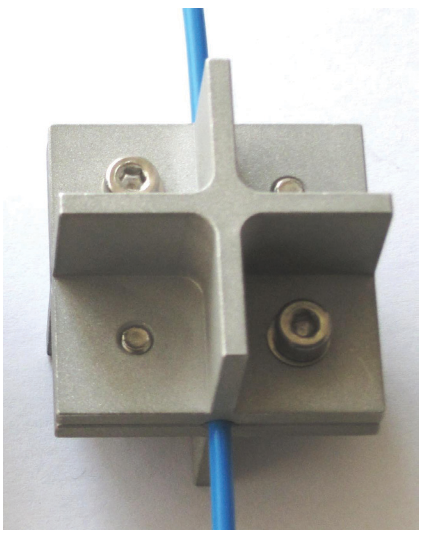

Figure 3. The "micro-anchor".

Large scale laboratory testing of the system in a 9m long shear box proved the system to be very efficient. Compared with data obtained by FO cables buried without anchors and FO cables embedded into geotextiles, this system is significantly more sensitive. Figure 4 shows data from such a test of a FO cable without anchors and a FO cable with anchors. Additionally to the laboratory testing, an 80m long system has been successfully installed in a field project in St. Moritz. The temporal change in the measured strain increments correlates well with the independent geodetical and inclinometer measurements in this location.

Reactivation of Old Inclinometer Casings

The third monitoring system takes advantage of old, out-of-service, inclinometer casings. In order to continue using such casings, a FO cable (P07 or S08, Table 2) is placed inside and the casing is filled with cement-bentonite grout. The current sliding surface can then be identified and displacements on this surface back-calculated. Installation of such a system on site in 2008 allowed for the sliding surface to be detected within three months.

Applications in Ground Anchors

Motivation

The determination and monitoring of the stress distribution along the grouted section of a loaded ground anchor tendon is essential for the understanding of its bearing behavior. Strain along anchor tendons is normally measured at distinctive points by various sensors, such as conventional strain gauges and more recently, fiber Bragg gratings. Other approaches are based on elongation measurements in a very limited amount of tendon sections, such as the regularly-used commercially available monitoring anchors that offer strain readings in up to four sections.

A novel monitoring ground anchor using embedded FO cables allows for continuous strain assessment along the anchor tendon, and thus provide a powerful tool for calculating the load distribution in the anchor tendon, which is of interest to the geotechnical community, as other reliable methods are rare.

Design and Installation

The monitoring anchor is built of a tendon consisting of a hollow steel bar with a threaded outer surface of 35mm diameter. As the integration of FO cables is one of the key factors, two different integration methods were tested: integration in grooves machined on the outside of the tendon at 180 degrees to each other and internally in the hollow of the tendon. In the groove (1mm wide, 2mm deep), the FO cables (BSM, TSM & P07) are directly glued to the tendon. In internal integration, the FO cables (P07, S08 & M07) are placed inside the hollow center of the tendon later filled with a low viscosity injection resin. In 2009, such an 8m long monitoring anchor has been installed in a drillhole with a fixed anchor length of 5.75m (grouted). The anchor was integrated into a sheet pile wall supporting an excavation pit.

Monitoring

During anchor pullout testing, the anchor was loaded in stages up to 470kN, almost reaching its ultimate bearing capacity. BOTDA measurements were taken at each loading stage recording

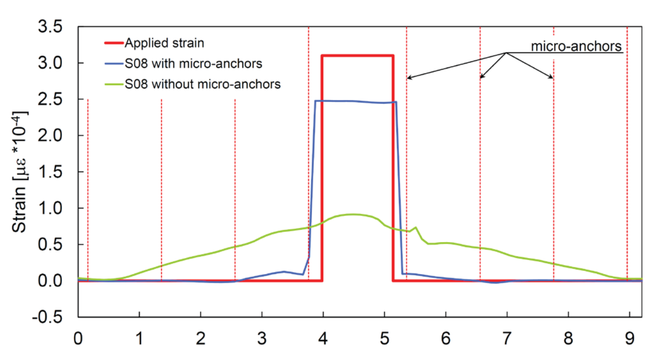

Figure 4. Strain measurements in a shear box obtained by a FO cable only and the "micro-anchor" - FO cable system.

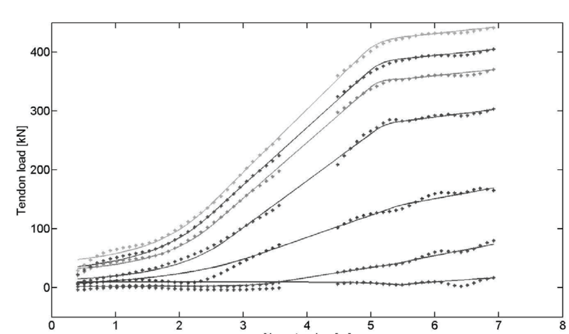

Figure 5. Monitoring ground anchor: load distribution from FO measurements for selected load steps.

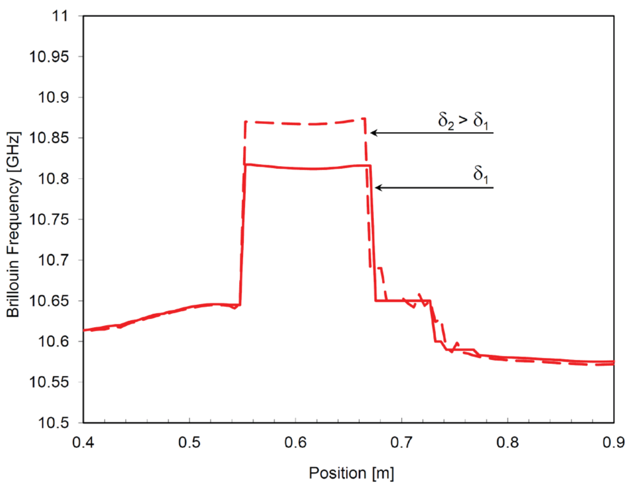

Figure 6 Monitoring of single crack opening with 5cm resolution (in collaboration with Foaleng Mafang S. and Thévenaz L, EPF Lausanne, Switzerland).tif

the load distribution along the tendon (Figure 5). This provides a better understanding of the real strength mobilization and progressive failure than some currently commercially available monitoring anchors.

Applications Requiring High Spatial Resolution

The novel BEDS technology, allowing for measurements with a spatial resolution of 5cm, is likely to expand the applications for FO sensing in geotechnical monitoring. It becomes possible to detect single cracks in structures affected by ground movements, and gives a comprehensive strain profile along geotechnical structures such as the monitoring anchor or a pile. At the laboratory scale, two applications have been explored. In the first one, the strain profile evolution in a 2m long FO cable pulled out of sand was successfully monitored (Iten et al., 2009b). In the second application a crack monitoring was performed by fixing a FO cable at both sides of the "crack" leaving 10cm of the free cable length and moving one fixation point by 0.1mm (simulating a crack opening). The BEDS data clearly detects the crack opening (Figure 6). With this technology becoming commercially available during the next years, hundreds of individual cracks can be monitored with one single FO cable.

Conclusions and Outlook

In contrast to structural health monitoring, FO geotechnical monitoring applications are not yet very common. However, their ability to provide enormous amounts of data at low cost per reading (in spite of the relatively expensive measurement units) is a convincing fact. The issues that have to be handled with care are (a) FO cable selection, (b) FO cable integration and (c) data interpretation. FO cables of a broad range of stiffness and protection are now available. The FO cable integration is project-specific and methods have been outlined in the references. The data interpretation requires background knowledge of FO technology. The authors are convinced that for the applications described in this article, FO technology is a valuable alternative to conventional methods.

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Editor's Note

Some readers may want to know the commercial sources of FO sensing systems. Here's a partial list. If you know of others, please let me know, and I'll update the list in a later GIN.

Company Name and Country	Website
FOS&S, Belgium	www.fos-s.be
Inventec, The Netherlands	www.inventec.nl
Micron Optics, USA	www.micronoptics.com
Omnisens, Switzerland	www.omnisens.ch
OpSens, Canada	www.opsens.com
Sensornet, England	www.sensornet.co.uk
Smartec, Switzerland	www.smartec.ch
Tencate, The Netherlands	www.tencate.com