Geotechnical Instrumentation News

John Dunnicliff

Introduction

This is the fifty-seventh episode of GIN. Three articles this time, all following up on previous GIN topics.

Fiber Optic Sensing

In GIN- 52 (September 2007) we had a two-part article by Daniele Inaudi and Branko Glisic about this subject, in which they described the basics and told us about the four main types: point sensors, multiplexed sensors, long-base sensors and distributed sensors. The current article by Peter Bennett tells us more about distributed sensors—these are clearly powerful tools to have in our tool box.

GIN can be accessed on BiTech's website www.bitech.ca

Monitoring by Manual and Automated Optical Survey

We've had five previous articles on this subject, which are listed at the beginning of the current article by Joel Volterra. There's a very strong consensus that this technology is not being used to our full benefit, primarily because of poor specifications and the fact that the field work is awarded on a low bid basis. Read and learn!

MEMS

In GIN-54 (March 2008) we had four articles about MEMS (Micro-Electrical-Mechanical Systems), two of which told us about the ShapeAccelArray (SAA). Erik Mikkelsen and I have put together some of our views on this instrument.

GIN Available on the Web

Starting with GIN-55 (June 2008), episodes of GIN can be accessed on BiTech's website www.bitech.ca. Click on the link "Geotechnical News".

Next Instrumentation Course in Florida

The next course will be on 15-17 March, 2009 at Cocoa Beach Florida. See page 30 for more information. Details are on http://conferences.dce.ufl.edu/geotech/

Soil Profile for December 25

The figure on this page depicts a classic soil profile. There's a hard white desiccated crust overlying a yellow-orange stiff silty clay, and below this a compact and heterogeneous mix of cobbles and boulders in a matrix of dark brown CL material.

When sampled, the matrix clearly lacks an essential property, but this can be overcome by a form of jet grouting. Open boreholes are drilled throughout the profile at close centers. There's no need for casing to support the boreholes, and drilling mud would be environmentally unacceptable. A brown volatile and aromatic liquid is then poured into the boreholes and allowed to permeate the matrix under a falling head. This ground treatment is repeated until saturation takes place.

(If you don't know what this is all about, ask someone from the Mother Country, perhaps the boss of the jet grouting crew, Irene Dunnicliff).

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 fax or mail: Little Leat, Whisselwell, Bovey Tracey, Devon TQ13 9LA, England. Tel. and fax +44-1626-832919.

Ooogy Wawa! (Zulu drinking toast)

Distributed Optical Fibre Strain Measurements in Civil Engineering

Peter Bennett

Two articles in the fifty-second episode of GIN (Vol. 25, No. 3, September 2007) by Inaudi and Glisic gave an introduction to optical fibre strain sensors, particularly distributed strain sensors. Unlike conventional strain gauges which can be used to measure the strain only at a single point, distributed strain sensors allow strain measurement continuously along a cable. A suitably installed optical fibre cable can give the full strain profile of a structure. This article describes some of the applications of this technology.

Introduction – When to Use Distributed Optical Fibre Strain Sensors

Since the range over which the strain profile can be measured is very large, potentially up to tens of kilometres, this technique is attractive for large scale structures such as dams and pipes, as described in the previous GIN articles. However there is growing interest in using this technique on all structures where a high density of measurement points is required. This is particularly the case in geotechnical applications, because soil loading is non-uniformly distributed and can change its magnitude in short distance due to soil layering. This technology is also of interest for increasingly complex structures because soil loading patterns are more difficult to predict. A continuous strain profile can be easier for field engineers to interpret, and has the advantage that local features, e.g. cracks, can be detected.

It is important for readers to appreciate that the BOTDR optical technique should not be confused with time domain reflectometry (TDR) techniques that are based on detecting changes in electrical impedance by deformation of a coaxial cable.

Table 1 shows a comparison of the performance among distributed optical fibre strain sensors based on Brillouin optical time domain reflectometry (BOTDR), conventional vibrating wire strain gauges (VWSG) and fibre Bragg grating sensors (FBG). VWSGs are typically preferred to resistance gauges in most civil engineering applications because they have a much better long term performance. The FBG sensors are also point sensors, but allow more than one sensor per cable. They are described in more detail in the previous GIN articles.

When a large number of measurements are required, the high cost of individual point sensors can be prohibitive. In contrast, the cost of the optical fibre can be very low. The cost of the analyser is higher than for VWSGs and FBGs, but the analyser can easily be moved between locations (no need for recalibration) to spread the cost. This is particularly advantageous if the sampling frequency varies over the project as the capital investment is not locked to a particular location, as it generally is with the other technologies.

Table 1. Comparison of strain monitoring technologies

Method	Vibrating Wire	FBG	BOTDR
Sensor	Vibrating wire	Fibre Bragg Grating	Optical fibre
Measurement	Discrete	Discrete	Distributed
Strain resolution	0.5-1με	0.1-10με	2-30με
Limit of spatial resolution	50-250mm	~2-40mm (length of grating	~1m
No. of measurements	1 per copper cable	Typical 40 sensors	20,000-100,000 (up to every 50mm)
Measurements time	Several cycles (of 600Hz-3KHz)	Capable of acoustic freq. (up to 5MHz)	4-25min
Maximum strain	3000με	~10,000με	~10,000με
Analyser cost	$2,000-20,000	$20,000-100,000	$100,000-200,000
Sensor cost	Sensor $150-500	Gratings ~$50-500	Fibre ~$0.2-20 per metre
Feature	Established technique	High strain accuracy, fast response	Distributed measurements

Optical Fibres/Cables

A simple optical fibre is shown in Figure 1A. This fibre costs ~20 cents per meter, but is fragile and care must be taken when installing it. Extra layers of protection are often placed around more than one fibre to form a cable. Special strain sensing optical fibre cables are available. These are more robust, but still transmit the strain applied through to the glass optical fibre and allow the strain to be measured. As these are not currently produced in large quantities, they can cost up to ~$20 per meter. Although this is considerably more expensive, these are likely to be faster to install as they do not require such gentle handling. Examples of these fibres are shown in Figures 1B and 1C. More ro-

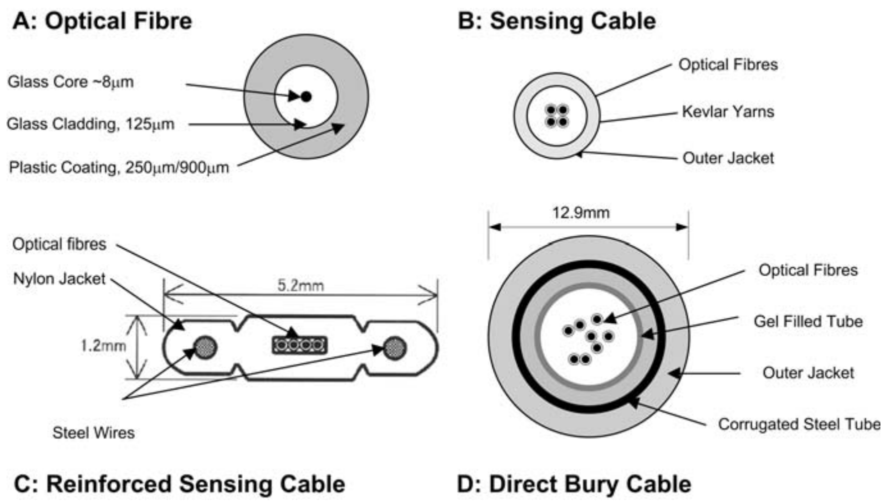

Figure 1. Types of optical fibre and cables.

bust forms of standard telecom cables have thick plastic coatings, sometimes reinforced with steel, around a gel-filled tube containing the optical fibres (as shown in Figure 1D). This makes these cables unsuitable for strain sensing as the optical fibres move inside rather than carry strain. However, this type of cable can be used to carry the optical signal between the sensing cable and the analyser. This is particularly useful for connecting a remote monitoring location to the site office as the cable is very robust and still inexpensive (~$1 per meter).

Time Response

Apart from taking a distributed measurement rather than point measurements, the other major difference between the techniques listed in Table 1 is the speed at which the samples can be taken. The speed at which a VWSG can be sampled is limited as several oscillations at the resonant frequency are required to make a measurement (typically 600Hz-3KHz, depending on the pre-tension). FBGs have the advantage that they can be sampled at very high frequencies, including acoustic and ultrasonic frequencies. This could have applications in dynamic and Statnamic load testing. In contrast the distributed strain measurement based on BOTDR takes much longer for a single measurement (typically 4-25 minutes). This technique is based on detecting the very weak backscattered signal (a more detailed explanation can be found in the previous GIN articles). The analyser needs to average the signal in order to give a good signal to noise ratio, although the measurement time should be limited to avoid thermal effects during the reading. The required measurement time is expected to reduce with continued improvements in optical technology, particularly detectors (laboratory measurements at 1KHz have recently been reported). The analysers currently commercially available are more suitable for long term structural health monitoring.

Analysers

BOTDR distributed strain analysers have been commercially available for over ten years. But with increasing interest in the area there has also been several new analysers launched by different manufacturers. There are important differences between the analysers currently available as they perform the measurement in different ways, which may have a have a significant affect on the performance and suitability for a particular application. The most established is analyser is the Yokogawa AQ6803. This is a compact single unit with built-in screen for viewing the data. The latest analyser from Advantest, the N8510, is currently only available in Japan and is undergoing safety certification for other markets. Unlike the AQ6803 this is run with a separate computer. This means that upgrading, e.g. to a larger hard disk, is possible. Both these models are based on spontaneous Brillouin scattering as described in the previous GIN article. A

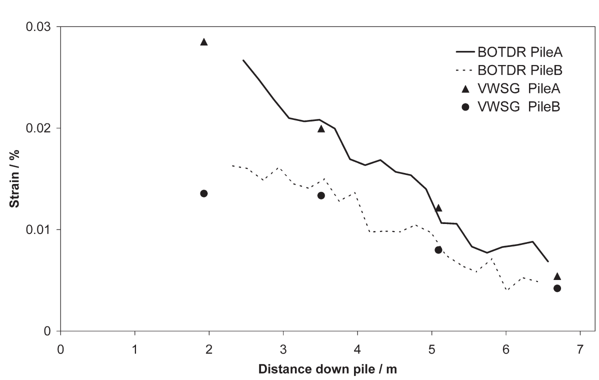

Figure 2. Strain profile measured in a pile group with BOTDR and VWSGs during a static load test at 95% of failure.

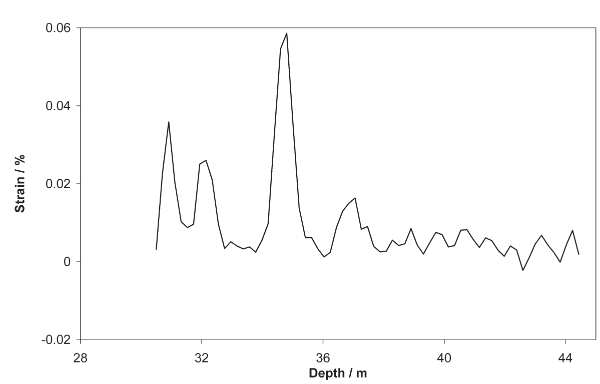

Figure 3. Strain profile measured with BOTDR in a pile after curing, during which one level of basement was excavated. Peaks are due to cracks up to ~0.3 mm width.

different measurement system is used in the OmniSens STA100/200 and Oz Opitcs 'Foresight'. These models enhance the optical signal by using a counter-propagating pump pulse of light. This boosts the signal to noise ratio, improving the strain resolution or reducing the measurement time, but has the disadvantage that access to both ends of the fibre are required, therefore a break in the cable means that measurements can no longer be made anywhere along the cable. It also means that for some installations it may not be possible to make any measurements until the fibre installation is complete. The Sensornet DTSS also uses simulated Brillouin scattering but in a reflective configuration, so that it can measure up to a break in the cable. This model also varies the power injected into the optical fibre so it can independently measure strain and temperature from the same optical fibre. However it is currently only capable of taking a reading every 1m, so it may not be suitable for all applications.

The following sections give some examples of applications of BOTDR measurements which were conducted by the Cambridge geotechnical group using a Yokogawa AQ6803.

Strain Profiles in Piles – Installation Techniques

The optical fibre is typically installed under a pre-tension so that if the structure being monitored goes into compression the cable does not go slack. The area of interest is very easy to identify from the measured strain profile. Changes in strain are then observed by subtracting the initial strain profile from new measurements. In the case of a pile the pre-tensioned optical fibre can be attached to the rebars with clamps or epoxy. Figure 2 shows a comparison between the strain profile measured in a pile group with VWSGs and BOTDR. The agreement is very good. An additional unstrained fibre may be used for temperature compensation (this may be a different fibre contained in the same cable or a separate cable installed nearby). For analysers requiring access to both ends of the cable it must be installed in a loop. This is also the preferred configuration for reflective analysers as in the case of a break they can still obtain the full strain profile by measuring each direction up to the break. By installing the optical fibre down one side of a pile and back up the other, the pile can be tested individually and later connected to adjacent instrumented piles to allow several to be measured at once.

An installation of cables on both sides of the pile can also be used to measure lateral movements in addition to the axial movements. This technique has been tested on secant pile walls to monitor the lateral movement during construction of a large basement in London. As the wall bends one side goes into compression and the other in tension. The advantage of the BOTDR technique over a conventional inclinometer is that the optical fibre cable can be routed through any structure built on top of the wall so that the measurements can be performed throughout the life of the building, without requiring direct access to the top of the wall.

Crack Detection – Spatial Resolution

One of the perceived limitations of BOTDR for strain sensing is that the spatial resolution is normally quoted as 1m. This limitation comes from the physical length of the pulse of light in the optical fibre, a 10 nanosecond pulse is ~1 metre long. However BOTDR can still be used to measure localized features such as cracks. BOTDR gives a centre weighted average over ~1m, so a very short (less than 5cm) region of strain such as a crack will be detected as a sharp spike (in fact a Gaussian curve with a width of ~30cm). The height of the spike can then be used to estimate the crack width. Figure 3 shows tension cracks developed during the curing of a pile and subsequent heaving of the ground on a basement and building construction site in London. These cracks have a width of up to ~0.3mm. Measuring the strain profile all the way along the pile means cracks are easy to detect. Conventional point gauges may not be located exactly on the crack and therefore may be unable to detect it. If there are more than one crack within a very short distance (less than 4 measurement steps), they will not be individually resolved, but the combined crack width would be measured.

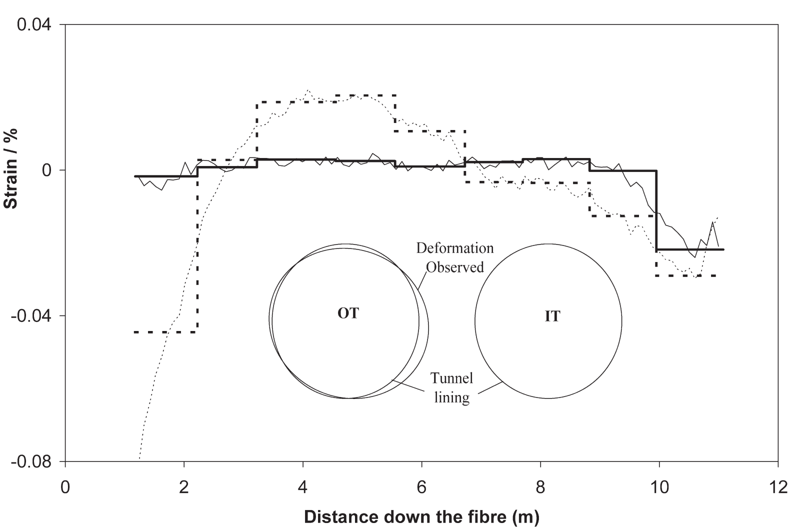

Figure 4. Strain developed around first of twin tunnels during the construction of the second tunnel in close proximity. Solid lines when face of 2^{nd} TBM is level with monitoring location, dotted lines when 2^{nd} TBM is more than two tunnel diameters past. Thin lines are measured data. Bold lines are strains calculated,knowing attachment points. Inset is a schematic of the movement observed.

Tunnelling – Point Attachment

In some circumstances it is not possible to bond the fibre continuously to the structure. Point attachment can still be used to monitor multiple points along the structure; the movement being the strain measured multiplied by the distance between the attachment points. An example is the use of BOTDR to monitor the first of twin tunnels during the construction of the second tunnel in Singapore. The two tunnels are in close proximity (minimum clear separation being 2.3m or 0.4 times the tunnel diameter). The tunnel is part of the new Circle Line Stage 3, between Serangoon and Bartley stations, commissioned by the Land Transport Authority. The optical fibre is attached at 11 locations around the section of the tunnel, monitoring ~ 2/3 of the ring (track and TBM supply pipes prevented monitoring in the invert). This was repeated every 7 rings (a spacing of 9.8m) with a total of 14 rings being monitored. Figure 4 shows the strain developed at two times during the tunnelling. From these strains the relative movement of the anchor points can be estimated. The strain profile is smoothed because of the ~1m gauge length. However, because the position of the attachment points is known, the exact strain profile can be recovered and is shown in bold (this process may be used even if the attachment points are separated by less than the gauge length).

Conclusion

There is increasing interest in the use of distributed strain measurement based on BOTDR technology. It can have considerable performance and financial advantages when a large number of measurements are required to obtain strain profiles for accurate monitoring of geotechnical construction processes. With the recent launch of several new fibre optics analysers there is more choice of equipment that can provide such measurements. However, as with any form of monitoring, the limitations need to be understood and the equipment and sensors must be installed appropriately to obtain good information from the system (and of course a good understanding of the geotechnical processes to make sure that you are measuring the right thing!).

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Monitoring by Manual and/or Automated Optical Survey

Joel L. Volterra

The following articles about manual and/or automated optical survey have been published in previous episodes of GIN:

- Cook, D. "Robotic Total Stations and Remote Data Capture: Challenges in Construction", GIN- 49, December 2006, pp 42-45.
- Kontogianni, V., Kornarou, S., and S. Stiros. "Monitoring with Electronic Total Stations: Performance and Accuracy of Prismatic and Non-prismatic Reflectors", GIN-50, March 2007, pp 30-33.
- Beth, M., Dorwart, B., Flanagan, R., Greening, T., Roy, D., Jensen, N., Rutledge, D. "Discussions of Cook's GIN-49 Article", GIN-50, March 2007, pp 33-38. Also reply by Cook.
- Hope, C. and Chaqui, M., "Manual Total Station Monitoring", GIN-56, September 2008, pp 28-30.
- Marr, W.A., "Monitoring Deformations with Automated Total Stations", GIN-56, September 2008, pp 30-33.

I applaud John Dunnicliff for his persistence in soliciting these articles, and the authors who have provided lessons for the rest of us. The articles address specific issues which make or break an optical monitoring program. I can attest, from personal experience on projects awarded to low bidders, to the lack of accuracy generally obtained by manual surveys and also improperly installed or maintained automated optical survey in the New York City market, where reports of regular fluctuations of 0.25 inch horizontal or vertical are as common as reported changes of 0.000 feet, both of which are equally concerning. Low bid procedures simply do not allow the monitoring programs to reach their fullest potential.

Often raw data become the end product, without temperature corrections and without accompanying information necessary to allow for temperature corrections by third parties. This issue is wider than survey data alone, and in this writer's opinion, it plagues the instrumentation community. The inclusion of thermal corrections on the instruments themselves and of the structures upon which they monitor requires judgment, interpretation, quality assurance and time. Adequate time is not usually available if instrumentation work is included in the general construction contract, because construction work may cause deformation of adjacent structures before adequate baseline data have been documented. This limitation can be overcome by the owner entering into a specialty contract directly with an instrumentation consultant during the design phase, so that adequate baseline data can be established before construction can cause any deformation of adjacent structures.

Improved communication ... should not be interchanged with simply _increased_ communication ...

Further publications and open discussions can only result in industry-wide advancement. As stated by the above authors, the use of total stations for optical survey is not new. What would appear new is the gaining or wider acceptance of the use of automated motorized total stations (AMTS) (also referred to as robotic total stations – RTS) to monitor building deformations adjacent to active construction. Increased efforts are being made by designers on behalf of owners to incorporate these and other improved technologies in project specifications where they are deemed appropriate.

In general the practice has previously been limited to specialty consultants bidding an alternative to a manual system in order to obtain improved results at a more cost effective and less labor intensive effort. The word is out however, and as a result, owners, architects and engineers have learned that they can easily obtain sufficient information (from manufactures or colleagues or publications) to include such requirements in project specifications. Unfortunately they may do this without possessing the direct experience or knowledge to appreciate the nuances of such a system, nuances that are touched upon in the above articles. The result is often an inability on behalf of owners and their project teams to evaluate sufficiently the qualifications of the monitoring personnel, the performance of the monitoring program, and/or to enforce or obtain the quality of information specified and ultimately strived for and purchased.

I agree that more emphasis should be placed on:

- properly written and enforced specifications
- less low bid awards, because these preclude comparing similar scopes and abilities, and hamper the ability to collect adequate baseline data well in advance of the construction contract
- increased input and involvement from qualified engineers to interpret collected data
- improved communication between parties. *Improved* communication differs from, and should not be interchanged with simply *increased* communication, which often results in too frequently scheduled and over-attended meetings and/or too frequent often daily hard copy submissions of unnecessary background data.

... less inclusion in low bid construction contracts, because this hampers the ability to collect adequate baseline data.

A qualified engineering team with adequate resources and an understanding of anticipated deformations and the consequences of such deformations (even if they have little direct instrumentation experience) may be better suited than an experienced surveyor undertaking the work with technicians. Surveyors generally lack a comprehensive understanding of the larger picture and as a consequence large amounts of unnecessary data will usually be generated, submitted and/or made available online, with little or no emphasis placed on that relatively small percentage of data which are relevant and critical to the active construction-related activities. This small percentage are the data that are likely to result in significant short-term deformations and which are worthy of regular examination by qualified professionals.

... instrumentation programs lose out on reaching their fullest potential.

Therein is the missing link in many programs. In many programs the instrumentation data are provided separately without interpretation. In others, even more frequently, vital construction records are not available—records that are essential for comprehending, validating or writing-off the observed trends or spikes. In these situations, knowing when to sound an alarm or change construction procedures becomes increasingly difficult, and instrumentation programs lose out on reaching their fullest potential.

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Some Views on a Recent Addition to our Instrumentation Tool Box—the ShapeAccelArray (SAA)

P. Erik Mikkelsen
John Dunnicliff

The March 2008 episode of GIN included two articles about the ShapeAccelArray (SAA) instrument, a wireless MEMS-based system for real-time deformation monitoring. The first was by Tarek Abdoun and Victoria Bennett of Rensselaer Polytechnic Institute (RPI), who played a major part in the development of the instrument. The second was a case history by Matthew Barendse of New York State Department of Transportation. The instrument is manufactured by Measurand Inc. (www.measurand.com).

The same episode of GIN included an article on MEMS basics by Barrie Sellers and Robert Taylor, a description of performance testing of MEMS-based tilt sensors by Thomas Sheehan, David Mazzei and John McRae, and a question and answer (Q&A) exchange between the GIN editor and the developers of the SAA. The Q&A was an attempt by the editor to clarify some of the characteristics the SAA, but several readers were not satisfied with the exchange.

Without doubt the SAA is a valuable addition to our instrumentation tool box. It typically provides deformation data at ten times the detail provided by traditional in-place inclinometer (IPI) installations, i.e. 3 m (10 ft) typical gage length for an IPI versus 0.33 m (1 ft.) for the SAA. The data acquisition and graphical presentations are much better integrated than other more modular systems such as Campbell CR1000, with many options to present data from Microsoft Excel to web accessible SQL databases. However, as good as these improvements are, various characteristics need to be taken into account if this instrument is to be chosen in preference to conventional probe inclinometers or other types of IPI. The purpose of this article is to make an attempt at putting some of these characteristics in perspective.

When considering the selection of IPIs as opposed to conventional probe inclinometers, the higher hardware cost must be balanced against the much lesser labor cost. And are real-time data truly needed? In our experience, fully automated, full profile, real-time inclinometer data are not needed for the majority of applications. However, the development of innovative sensors over the last 10 to 15 years has substantially lowered costs of IPI systems, making their application more feasible and attractive. The SAA development is a welcome addition.

When "directly compared" the probe inclinometer can achieve an accuracy equal to or better than the SAA.

Accuracy

Abdoun and Bennett state, *The accuracy of deformation measurement of the SAA is +/- 1.5 mm per 30m. This figure can be directly compared to the reported system accuracy of traditional probe inclinometers, +/- 7.6mm per 30m.* However, it seems to us that this has an apple/orange flavor, because a primary reason for this increased accuracy results from the SAA system, **like all IPI systems,** having no placement errors associated with moving an inclinometer probe up and down the grooved casing. Assuming no sensor drift, similar accuracies can be obtained with other types of IPI.

Machan and Bennett (October 2008) say, for MEMS-based **probe** inclinometers, *the inclinometer system capability, precision, and reliability have not been independently evaluated and demonstrated*—note that this is the same Bennett of RPI who played a major part in the development of the SAA.

It is important to understand that the reported +/- 7.6mm per 30m accuracy for probe inclinometers includes a **correctable** allowance for systematic error of +/-6.3 mm, plus a random error of +/-1.3 mm (Mikkelsen, 2003). The systematic error is proportional to installation properties such as verticality, and the +/- 6.3 mm tolerance is for less-than-ideal installations. When "directly compared" the probe inclinometer can achieve an accuracy equal to or better than the SAA.

It is also important to understand that with any type of IPI there is a potential for reduced accuracy because of sensor drift, whereas with conventional probe inclinometers any drift is removed from the determination of deformation by the A^0 - A^{180} procedure. But Abdoun and Bennett state, *The use of MEMS accelerometers virtually eliminates concerns of long-term drift in the SAA*. This view is supported by Sellers (2008), who reports on long-term MEMS tiltmeter zero stability tests, which have been running for eight months. The drift is of the order of 0.1 mm/meter per year.

Abdoun and Bennett also state that *The SAA system accuracy specification was derived empirically from thousands of frames of wireless data over a period of 1.5 years, from three different field locations.* In order to know what the **true** deformation is, it is necessary to compare the data with an absolute standard. Perhaps there is some confusion in terminology here, such that the statement refers to precision (repeatability) rather than accuracy (closeness to truth).

3D or 2D for Static Measurements?

The concluding words by Abdoun and Bennett in the Q&A exchange are, *These are true 3D devices.* Machan and Bennett (October 2008) repeat the claim: *The sensor array is capable of measuring 3-D ground deformations at 1-ft (30-cm) intervals up to depths of 330 ft (100 m).* These statements need explanation. Neither pair of authors explains, but perhaps all they mean is that MEMS are omni-directional sensors.

The SAA is not compressible axially and it cannot be used to monitor settlement in a near-vertical borehole. Confinement by the surrounding soil would prevent the formation of any significant zig-zagging S and C shapes caused by buckling of the axially-compressed pipe in which the SAA segments are installed. In all likelihood the pipe would either push out of the ground as the soil settled past it, or it would fail by shearing. The same issue would arise if the SAA is installed without a casing. For this reason, when inclinometer casings are subjected to large amounts of settlement, it is necessary either to use telescoping couplings or to surround the casing with an axially-compressible pipe.

... the SAA provides 2D and not 3D data ...

Therefore, when the SAA is installed in a near-vertical borehole and there is vertical compression, the SAA provides 2D and **not** 3D data. Examples are monitoring stability of a cut or natural slope where there may or may not be vertical compression, and monitoring horizontal deformation at the toe of an embankment on soft ground where there **is** vertical compression.

Dynamic Measurements

It is claimed that the SAA can measure both statically and dynamically, i.e. that it has the capability to record vibration and earthquake acceleration, and therefore if used in an earthquake-prone location it would be an added benefit to have all dynamic components measured for a complete seismic record. But how good would such dynamic records be? To obtain representative dynamic records it is essential to ensure a solid connection between sensors and ground, and this is unlikely to happen if the SAA is installed using sand backfill or loosely inside PVC access pipe.

Method of Installation

Abdoun and Bennett describe early installations in which inclinometer casing was grouted into a borehole, the SAA lowered into the casing and backfilled with sand, to allow for retrievability by jetting. They accept the concern about incomplete sand backfilling and describe an alternative installation procedure. A 25 mm (1 in.) pipe is either grouted in a borehole or is surrounded by sand backfill, and the SAA inserted within the pipe together with a flat webbing to allow for retrievability.

Sand is not a suitable backfill material in any circumstances.

Sand is not a suitable backfill material in any circumstances.

For dynamic measurements, neither of the above methods is suitable, and the SAA must be grouted and non-retrievable.

Sensor Alignment

It is claimed by Bennett et al (2007) that the SAA uses “fiber optic orientation sensing”, but we see no evidence of any sensor in the SAA system to measure orientation (azimuth). This aspect needs to be explained. The array has a tough external anti-torque jacket, but we have no information about how resistant this is to torque. The array has to be manipulated into the correct orientation and any down-hole spiral would not be known.

Temperature Sensitivity

Abdoun and Bennett say, under their heading Temperature Sensitivity, *A digital temperature sensor is included within the SAA near each microprocessor. Thus, each temperature sensor calibrates the MEMS sensors in the eight segments surrounding it.* Machan and Bennett (October 2008) say, *The use of MEMS sensors in inclinometer applications is relatively recent, since 2005. There are limitations to this technology, including temperature sensitivity and related effects.*

We agree that these sensor calibrations are sufficient for typical underground applications where temperature variations are small, but for applications where a significant temperature gradient is expected, such as behind and in excavated walls, individual temperature sensitivity factors are needed. For example, at a recent lock wall improvement project where vertical IPI-MEMS were installed there was about 15 °C variation from spring to fall, causing a significant change in sensor output. In the specifications for the SAA listed by Bennett et al (2007), they state: *Effect of temperature after compensation: < 0.1 degree per °C (preliminary).* This is < 360 arc-seconds per °C, a level that may be unacceptable if a significant temperature gradient is expected. Sellers and Taylor say, for MEMS, *They have low drift and thermal coefficients, about one arc second per degree C*. But test results by Sheahan, Mazzie and McRae show that, if subjected to significant temperature changes, MEMS are temperature sensitive enough to warrant individual characterization of temperature response, together with sensors to measure temperature.

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