# Geotechnical Instrumentation News

***John Dunnicliff***

## Introduction

This is the fifty-fourth episode of GIN. A meaty one this time, all about MEMS.

## MEMS

In the June 2007 episode of GIN I wrote:

> Micro-electro-mechanical systems (MEMS) appear to have potential applications in our business. Perhaps as tiltmeters. Perhaps as sensors in inclinometers. Perhaps as sensors in-place inclinometers, both for horizontal and vertical deformation monitoring.

When I wrote that, I knew **nothing** about MEMS! But now, having twisted the arms of colleagues and done some heavy interaction and editing, I know enough to be dangerous.

First, here's what I found out about 'who is making what?':

- RST Instruments (www.rstinstruments.com) has been actively engaged in MEMS inclinometer product development for three years, with current MEMS products including digital inclinometer probes, in-place inclinometers, underwater tiltmeters, and tilt beams. Upcoming MEMS products include portable tiltmeters, horizontal digital inclinometers, wireless devices, and 24 bit digital bus in-place devices, which support up to 128 points on a single 4-conductor cable.
- Geokon (www.geokon.com) has been manufacturing MEMS-based tilt sensors for the last two years. Instruments have included tiltmeters, and probe inclinometers for operation vertically, horizontally, and in the sloping faces of concrete-faced rock-fill dams. One interesting development has been the manufacture of addressable in-place inclinometers. At a construction site in Boston, twenty MEMS tiltmeters have been installed in a borehole, connected together by a single cable. Each of the twenty MEMS tiltmeters is automatically addressed by a datalogger.
- Since 2003, Soil Instruments Ltd. (www.soil.co.uk) have been manufacturing probe inclinometers, portable tiltmeters, in-place inclinometers, track twist sensors and tiltmeters with MEMS sensors. A primary application for these tiltmeters has been the monitoring of live railroad tracks for distortion during adjacent work such as piling or tunneling.

Perhaps other manufacturers are making MEMS-based instruments, and if they read this I'm sure they will tell me, so that I can share with you next time.

Here are four articles. The first one (Sellers and Taylor) gives some basics. The second one (Sheahan et al) reports on some performance testing. The third (Abdoun and Bennett) and fourth (Barendse) tell us about one commercial product.

I'd been hoping for case history information on MEMS-based inclinometers, in-place inclinometers and tiltmeters, but nothing came out of the woodwork. Perhaps in the future—yes please! I'd also welcome discussions of these four articles. If anyone is interested in submitting a discussion, will you please let me know as soon as possible, so that I can plan ahead? Guidelines for articles are on www.bitech.ca. Discussions should follow the same guidelines, but should have a maximum length of 1½ pages in the magazine format. One particular issue for possible discussion—careful readers will note some differences in view about stability with time, and it would be good to have more views on that.

## International Symposium on Field Measurements in Geomechanics (FMGM), September 2007

The 7th International Symposium on Field Measurements in Geomechanics (FMGM) was held in Boston, MA during September 2007. The proceedings are available on CD from ASCE, and can be ordered on-line at https://www.asce.org/bookstore/book.cfm?book=7841. The list price is $125 and member price is $93.75.

There are some very worthwhile papers in the proceedings. The one that impressed me most was "The Use of the Fully-grouted Method for Piezometer

Installation" by Contreras, Grosser and Ver Strate of Barr Engineering Company in Minneapolis. It includes comprehensive sections on the theoretical background, materials, installation procedure, criteria for grout, lab testing of grout, computer modeling to support the applicability of the method, and field verification. What more could we want?! I plan to re-publish this paper, and a few others selected from the FMGM proceedings, in future episodes of GIN.

PowerPoint versions of the FMGM 2007 Keynote Lecture and eight Theme Lectures are posted on www.fmgm.no.

The next FMGM symposium will be held in Germany in 2011. Watch this space!

### Closure

Please send contributions to this column, or an article for GIN, to me as an email 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.

Here's tae us, wha's like us? Damn few, and they're a' deid, mair's the pity (Scotland).

For those of you who have joined the GIN community recently, perhaps a few words of explanation are needed here. When I started writing these 'columns' in 1994, Birger Schmidt gave me a beer mat with about 15 drinking toasts in different languages, and I used them in turn to close each episode. I decided to keep the tradition going.

# MEMS Basics

**J. Barrie Sellers**
**Robert Taylor**

### What are They?

An Internet search revealed: "Micro-Electro-Mechanical Systems are the integration of mechanical elements, sensors, actuators and electronics on a common silicon substrate through microfabrication technology". There are numerous of types of MEMS, a large and rapidly growing high technology area. The first to appear in the geotechnical field are accelerometers (similar in principle to the sensors used in most inclinometers), which are being used as tilt sensors.

The initial mass market for MEMS accelerometers was for automotive airbags, which typically have ranges exceeding +/-30 g. Sensors built for airbag systems typically have noise and drift much worse than older tilt technologies, making them not very useful for geotechnical applications.

Recently, MEMS sensors have become available with full scale ranges of 1 g or less, and with drift and resolution specifications equal to or better than previous technologies. These have sparked considerable interest among geotechnical instrument manufacturers for applications including in-place inclinometers, tiltmeters, tilt beams, probe inclinometers and strong-motion accelerographs.

Figures 1 and 2 show commercial examples of tiltmeters. Note that the small graduations on the scales are in millimeters, the numbers in centimetres.

### How do They Work?

Like the accelerometer that has been used in inclinometers since about 1970, a MEMS tilt sensor is based on a flexure-suspended proof mass which is deflected as the component of gravity changes with tilt angle. A position sensor senses this movement by differential capacitance sensors of exceptional sensitivity.

*Figure 1. Two MEMS Sensors Mounted 90 Degrees Apart to Create a Geokon Biaxial Tiltmeter.*

The proof mass, flexible mounting, position sensor, and supporting electronics are all constructed from a single wafer of non-metallic material, usually silicon.

### How are They Read?

Analog measurement is typical: a DC supply is applied and a signal proportional to acceleration is returned. Because of the long cable lengths that frequently are required in geotechnical applications, some additional electronics are typically included at the sensor: such as a precision voltage regulator, and line-driving amplifier(s). They are read with the same type of readout that is used for servo accelerometer type tilt sensors. They may also be data-logged, for example using a Campbell Scientific CR-1000 Measurement and Control System. To enhance resolution and noise rejection, the logger can make a number of readings and take the average. This allows resolutions of about 3 to 5 arc-seconds to be attained.

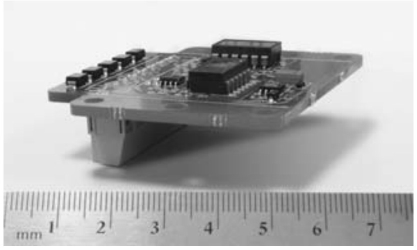

*Figure 2. RST Instruments' Biaxial MEMS Tiltmeter Internal Assembly, Including Two MEMS Sensors and Supporting Electronics on a Single Circuit Board.*

### How Many Conductors are Required in the Cable?

The uniaxial sensor requires four conductors: positive power, ground, signal out and signal ground. The biaxial sensor requires six conductors. If a thermistor is added, two additional conductors are needed.

### What is Good About Them?

They are inexpensive. They have a very high shock tolerance, very much more so than servo accelerometers. For example, 0.2 g sensors can survive 20,000 g shock. They have low drift and thermal coefficients, about 1 arc-second per degree centigrade. The intrinsic linearity of MEMS accelerometers is very good, due to the minute deflections of the proof mass. They are stable, sensitive and accurate, and can be used with cables up to about 500 meters. The sensors themselves are small, about 13 mm in one case, permitting the packaging to be correspondingly small and light. The power consumption is low, typically 20 mW, which is an advantage both in battery life and in warm-up time.

### What is Bad about Them?

As far as we can tell, not much. They are slightly less sensitive than servo accelerometers and vibrating wire tilt sensors and the range is limited to +/-15 degrees. Other ranges are available with a corresponding reduction in sensitivity and angular accuracy. They are voltage output devices so cable connections and waterproofing are a little more critical than vibrating wire types. In comparison with vibrating wire tilt sensors, they require more conductors in the cable and therefore more complicated multiplexing.

### Summary

At this time we believe that MEMS sensors potentially have significant advantages over alternative tilt sensing technologies, but time and experience will let us know more about performance. It is expected that as MEMS accelerometers continue to improve, they will occupy an ever-increasing portion of the geotechnical tilt market.

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# Performance Testing of MEMS-based Tilt Sensors

***Thomas C. Sheahan***
***David Mazzei***
***John McRae***

### Introduction

The introduction of geotechnical instrumentation based on Micro-Electrical-Mechanical Systems (MEMS) brings with it the need to prove the ability of such devices to perform to project specifications. In particular, because MEMS-based instrumentation is relatively new to geotechnical engineering, and because of typically harsh application environments, project owners and other stakeholders want data that prove the performance of these devices over a variety of conditions and time ranges.

This article describes the performance testing of MEMS-based tilt sensors for use with in-place inclinometers. The need for this testing arose because in-place inclinometer specifications for a construction project required that the tilt sensors should be tested by a testing laboratory independent of the manufacturer and should have the performance characteristics given in Table 1.

The equipment and testing procedures used, the specifications to be met, and the results of the performance testing compared to those specifications are presented. The work was carried out in the Northeastern University Geotechnical Research Laboratory.

### Basic Proof-Testing Equipment

Six identical MEMS-based Geokon tilt sensors were each mounted in a stainless steel housing, and these housings were fastened to a 15 in. long, stainless steel platform (so-called "sine bar") with two-point support (Figure 1). The tilt sensor readings were recorded electronically using a Geokon datalogger and the datalogging software Multilogger Version 4.0.2.70 by Canary Systems, Inc. run on a laptop dedicated to the test being performed.

This set-up ensures that the six tilt sensors and housings are simultaneously inclined at the same angle in the A-A axis (refer to Figure 1 for the axis definitions). Steel shims, previously calibrated by Geokon, were used to

**Table 1. Outline of Specified Performance Criteria**

| Type of Test | Performance Criteria |
|---|---|
| Short-term repeatability at constant temperature | ± 40 arc-seconds or less. |
| Temperature sensitivity | With temperature increasing from 50°F (10°C) to 68°F (20°C) and subsequently decreasing from 68 to 50°F, a maximum indicated reading change corresponding to 250 arc-seconds. |
| 90-day zero stability at constant temperature | A maximum deviation corresponding to 50 arc-seconds throughout the entire time period. |

raise the sine bar to desired inclinations, resulting in the tilt sensors and their corresponding housings being inclined from 0° to +10° to the vertical. The tilt sensors can also be tested for angles 0° to -10° to the vertical by either using the same shims on the other side of the sine bar or simply rotating the housings 180°. For B-B or cross-axis inclinations (again, refer to Figure 1), the sine bar was placed on a steel plate with three-point support and inclined using another set of calibrated shims provided, with tilt sensor-housing inclinations varying from 0° to +5° to the vertical. For temperature testing, the sine bar-housing assembly and tilt sensors were placed in an environmental test chamber. This chamber has a temperature range from -75 to 200°C (-103 to 392°F) with an accuracy of ±0.3°C (0.5°F). Figure 2 shows the six tilt sensors in housings mounted on the sine bar and placed in the temperature chamber. A side access port allows for the cables to be connected externally to the datalogger.

For all testing, the datalogger recorded tilt sensor readings in volts, and then calibration factors (provided by Geokon) were used for converting voltage readings to degrees and arc-seconds (3600 arc-seconds = 1°).

### Short-term Repeatability over Two Cycles at Constant Temperature

The specification stated that the minimum angular range of the tilt sensors had to be ±10° to the vertical in the A-A axis direction, and this was verified during the course of this repeatability specification. This specification required that over the range -10° to +10° to the vertical in the A-A axis direction at a constant temperature of 20°C (68°F), the repeatability of readings had to be within 40 arc-seconds or less. This same tolerance also had to be met or exceeded when the B-B axis (or cross-axis) was set using the steel platform so that the sensors were 5° to the vertical, and the same set of A-A axis inclinations were cycled twice.

The specifications for the first part of this testing (varying A-A axis inclination and no B-B axis inclination) were met or exceeded with the exception of one cycle difference reading for one tilt sensor (a difference of 43.3 arc-seconds). Because of the consistency of the other data – all other cycle differences were less than 40 arc-seconds – this reading appears to be due to operator error. It can reasonably be concluded that the specification is met or exceeded. For the two-axis tests, in which the B-B axis inclination was set at 5° to the vertical, there were no readings beyond the specification threshold.

### Temperature Sensitivity Testing at Various Angle Combinations

This set of performance tests examined the repeatability of readings at positive and negative inclination angles and temperature variations. The sine bar and six tilt sensors were placed in the environmental chamber (Figure 2) and the sine bar inclined along the A-A axis

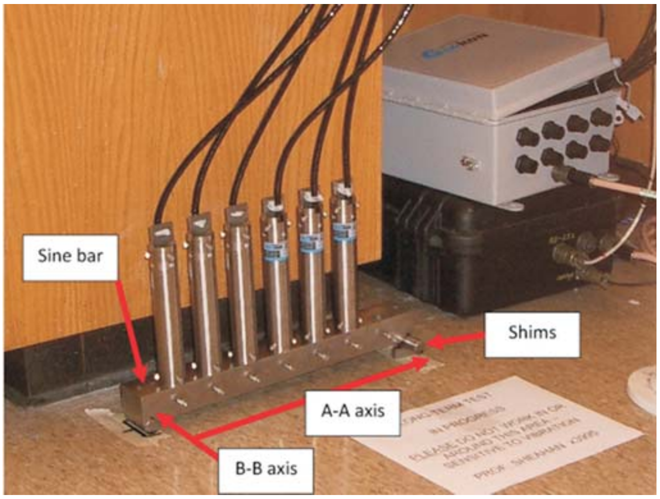

*Figure 1. Six tilt sensors and housings on the sine bar for axis A-A inclination, axis definitions shown.*

*Figure 2. Six tilt sensors and housings on the sine bar for axis A-A inclination in the environmental test chamber.*

**Table 2. Performance Results for 5° A-A Axis Inclination Stability, B-B at 0°, Varying Temperature**

| | | Average Tilt Sensor Readings volts[a] | | | | | |
|---|---|---|---|---|---|---|---|
| | | Tilt sensor no. | | | | | |
| **Temperature** | | **1** | **2** | **3** | **4** | **5** | **6** |
| 0°C (32°F) | | 0.7148 | 0.6772 | 0.6804 | -0.4997 | -0.6044 | -0.5488 |
| 20°C (68°F) | | 0.7147 | 0.6738 | 0.6792 | -0.4930 | -0.5997 | -0.5575 |
| 40°C (104°F) | | 0.7147 | 0.6715 | 0.6768 | -0.4887 | -0.5966 | -0.5636 |
| 20°C (68°F) | | 0.7148 | 0.6743 | 0.6787 | -0.4944 | -0.6022 | -0.5583 |
| 0°C (32°F) | | 0.7145 | 0.6776 | 0.6792 | -0.4995 | -0.6071 | -0.5519 |
| | | | | | | | |
| **Max. absolute diff. between reading sets** | volts | 0.0003 | 0.0060 | 0.0037 | 0.0110 | 0.0106 | 0.0148 |
| | arc-seconds | 3.88 | 78.73 | 48.03 | 144.07 | 138.43 | 193.11 |

[a] Average of 5 readings for each temperature.

such that the sensors were tilted 5° to the vertical. Three of the tilt sensors were rotated in the sine bar slots to give negative readings (tilt sensors 3, 4 and 5) for this sine bar inclination, while the other three were set to give positive readings. The chamber temperature was cycled through 0°C (32°F), 20°C (68°F), 40°C (104°F), 20°C (68°F), and 0°C (32°F). Note that the temperature range tested was significantly more rigorous than that specified. Each temperature was held for two hours, and then temperature readings taken every five minutes for one-half hour to ensure stability. After this, a set of five readings for each sensor was taken, with readings taken about 15-20 seconds apart. These readings were averaged for each sensor.

For each sensor, the absolute differences were calculated between the averages of all temperature data sets, and the maximum absolute difference identified. According to the specification, this maximum absolute difference had to be less than 250 arc-seconds. This analysis is shown in Table 2 for the six sensors. Raw voltage readings are given since these are the basis for computing the maximum difference between reading sets, which are then converted into arc-seconds. Referring to Table 2, as an example, for sensor No. 1, the maximum absolute difference was between the average of the first 0°C (32°F) readings and the average of the second 0°C (32°F) readings, which was 0.0003 volts or 3.88 arc-seconds. The largest difference for all sensors was approximately 193 arc-seconds.

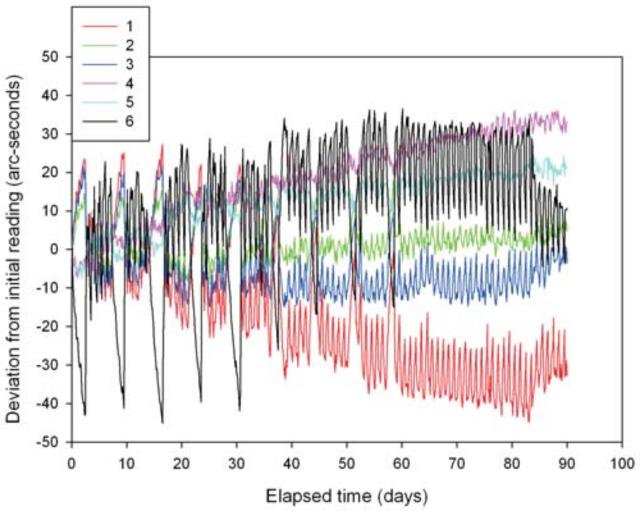

*Figure 3. Performance testing for 90-day stability, A-A @ 5°, constant temperature.*

### 90-day Zero Stability under Constant Inclination and Temperature

The final performance check was to determine how the tilt sensors would perform over an extended time period under constant inclination and temperature conditions. The six sensors were placed on the sine bar, which was inclined along the A-A axis (Figure 1) such that the sensors and housings were 5° to the vertical. With the temperature maintained at 20°C (68°F), readings were taken at least twice per day for 90 days. The specification stated that the variation in readings for any sensor could not exceed 50 arc-seconds, which Figure 3 shows was met or exceeded. It is noted that the 90-day zero stability data can be influenced by bending and tilting of the apparatus during the test. This is why the precaution was taken of orienting the positive axis of three of the sensors (1, 2, and 3) at 180 degrees to the other three, resulting in 3 positive readings and 3 negative readings for the same sine bar inclination. The higher levels of drift shown by the two sensors at the ends of the sine bar are mirror images of each other – as if the ends of the sine bar curled up very slightly during the test. A more accurate presentation of the long term drift results would involve elimination of these apparatus effects. This could have been done by repeating the test with the sensors left in the same relative positions on the sine bar but with each sensor rotated 180 degrees.

A less accurate method for eliminating the apparatus effect would be to subtract the average absolute drift after 90 days of all 6 sensors (about 6 arc-seconds) from the long term drift of each sensor. When this is done, referring to Figure 3, it can be seen that the maximum rate of drift (for tilt sensor no. 4) was about 30 arc-seconds per 90 days. Another way of expressing this would be approximately 0.2% of full scale per year. The rate of drift appeared to be diminishing towards the end of this 90-day period. Tests have commenced to investigate the rate of drift over longer periods of time.

### Conclusions

A series of performance tests was performed on MEMS-based tilt sensors to assess their performance in three primary areas: short-term repeatability, temperature sensitivity, and 90-day zero stability. In all three of these areas, the six tilt sensors tested met or exceeded the performance criteria required by the project specifications. The results indicate that these devices can provide reliable performance under the specified conditions, and provide evidence that MEMS technology has tremendous potential for geotechnical instrumentation.

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# A New Wireless MEMS-Based System for Real-Time Deformation Monitoring

***Tarek Abdoun***
***Victoria Bennett***

### Abstract

Geotechnical instrumentation using Micro-Electro-Mechanical Systems (MEMS) are relative newcomers to this conservative industry. This article aims to describe a new MEMS-based system for in situ deformation and vibration monitoring. After an introduction to the design and methodology of this system, some of the questions surrounding the use of MEMS sensors will be addressed, including temperature sensitivity, long-term stability and relative cost. Methods of installation and retrieval will also be briefly described. Finally, a description and validation of recorded field data from an instrumented unstable slope in California will be presented.

### Introduction

This system has been developed in an effort to combine recent advances in the miniaturization of sensors and electronics with an established wireless infrastructure to enhance geotechnical monitoring. The concept is based on triaxial MEMS accelerometer measurements of angles relative to gravity. These same MEMS accelerometers also provide signals proportional to vibration during earthquakes or construction activities. Three accelerometers are contained in each 30 cm (1 ft) long rigid segment for measuring x, y, and z components of tilt and vibration. The rigid segments are connected by composite joints that prevent torsion but allow flexibility in two degrees of freedom. These rigid segments and flexible joints are combined to form a sensor array called ShapeAccelArray, or SAA, which is capable of measuring three-dimensional (3D) ground deformations at 30 cm (1 ft) intervals to a depth of 100 m (330 ft). These sensor arrays are manufactured

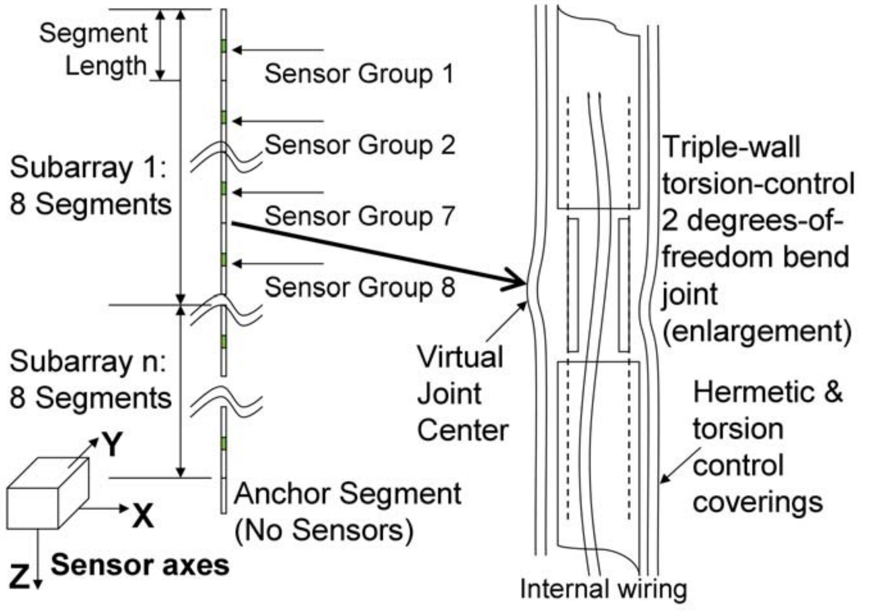

*Figure 1. Schematic of SAA subarray assembly.*

by Measurand Inc. (www.measurand.com), with whom this article's authors have worked for the past five years.

Arrays are constructed by connecting subarrays of eight segments end-to-end. Microprocessors, one per subarray, collect data from groups of sensors and transmit this digital data to the surface using just two communication wires; see Figure 1 for a schematic of the SAA assembly. Because they require only two communication wires, arrays are thin enough to fit into 25 mm (1 in) casing for installation and are flexible enough to be rolled up on a reel for shipping and storage. Traditional probe inclinometers require guide casing to measure ground deformations. The torsion-restrained joints of SAAs and 3D calculation method associated with the torsion constraint make this grooved casing unnecessary. Upon field installation, the manufacturer recommends lifting the SAA off the bottom of the 25 mm (1 in) casing and ensuring it can be rotated without resistance. If it is purposely torqued with 10 N-m (7.4 ft-pounds), it is possible to achieve approximately 0.3 degrees rotation per segment, with elastic return if the torque is removed. Users should seek to minimize this resisting torsion. This can be realistically achieved in a valid installation.

*Figure 2. 32 m (104 ft) SAA on shipping reel.*

The SAAs are factory-calibrated and completely sealed, requiring no field assembly or calibration. Because each segment of the SAA contains three orthogonal sensors, arrays can be installed vertically or horizontally. The intended installation orientation does not need to be specified when ordering. Orientation is selected in the software. Each sensor has an output that is the sine of the angle of tilt over a range of 360 degrees. Calculations use data from the sensors having maximum sensitivity for a given orientation. The sensor arrays arrive at the jobsite on an 86 cm (34 in) diameter reel, see Figure 2, and can be lowered into vertical, or pushed into horizontal, 25 mm (1 in) casing. The initial shape of the installation, or the absolute deviation of the installation from a virtual vertical or horizontal line, can be immediately viewed on a laptop. An SAA is modeled as a polyline in the software, with x, y, and z data representing the vertices of the polyline. In the case of near-vertical installations, the vertices correspond to the joint-centers of the array in 3D. For near-horizontal installations, the vertices show vertical deformation only versus horizontal position.

Wireless SAA data transmission is possible with the inclusion of an on-site data acquisition system, called a wireless earth station. For the fifteen field arrays installed to date, this wireless data transmission has been available within 24 hours of the instrument installation. Similar to traditional probe and in-place inclinometers, data from the SAA represents deviations from a starting condition or initial reading. These data are sent wirelessly, over the cellular telephone network, to Measurand's automated server, where data are made available to users through Measurand's viewing software (a download included with purchase of the wireless earth station) and an internet connection. Automated SAAs typically collect data once or a few times a day but this collection frequency can be specified by the user and changed at any time, through the same wireless interface used to receive the data.

### Temperature Sensitivity

This is a topic of discussion for many geotechnical engineers in regard to all instrumentation. A full temperature calibration is done on each MEMS sensor individually prior to its inclusion in an array. Measurand has completed a study of the temperature coefficients of the MEMS accelerometers and found that the change in output of the sensor is linear with temperature. Calibration files associated with each SAA allow the automatic calibration for temperature effects in each individual sensor. 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. This configuration is deemed sufficient for typical underground applications as the ground temperature is usually constant below 1.5 m (5 ft) from the surface. A denser construction of temperature sensors would be possible but only necessary if a large temperature gradient is expected across any consecutive eight segments, or if the temperature gradient is in a location where ground deformations are expected.

### Stability with Time

Data correction procedures have been used for several decades to remove any long-term drift of the gravity-sensing transducers from the calculated deformation data of probe inclinometers. The use of MEMS accelerometers virtually eliminates concerns of long-term drift in the SAA. MEMS accelerometers are manufactured from pure silicon, using photolithographic methods developed by makers of computer chips. They were originally developed for, and continue to be used in, the automotive industry for airbag deployment. Automotive sensors undergo exhaustive testing in extreme environments and must remain stable for at least 10-15 years. The internal structure of MEMS accelerometers is based on the bending of cantilevered beams of pure silicon, with dimensions less than 1 mm (0.04"), due to the force of gravity. Deflections of the tiny beams are measured using electric-field technology, also built into the

MEMS using photolithographic techniques.

The lack of sliding parts and the near-inertness of pure silicon make for a stable sensor technology. Stability over time has been confirmed by data from three SAAs, sampled several times per day, over a period of 1.5 years. The deformations from portions of the arrays known to be in stable soil (below observed shear zones) were monitored over the entire period of measurement. After an initial settling-in period (see "Installation and Retrievability" section below), data in the stable soil were found to deviate from their initial readings by no more than +/-1.5 mm (+/-0.06 in), including in arrays over 32 m (104 ft) long.

### Accuracy of Deformation Measurement

The accuracy of the deformation measurement of the SAA is +/- 1.5 mm per 30 m (+/- 0.06 inches per 100 ft). This figure can be directly compared to the reported system accuracy of traditional probe inclinometers, +/- 7.6 mm per 30 m (+/- 0.3 inches per 100 ft), because both of these specifications are referenced to a virtual straight line, or the initial reading of both instruments. 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.

The MEMS accelerometers mounted in pipes on a mechanical goniometer readout have an absolute accuracy similar to that of conventional inclinometers and excellent 'linearity' over a 45 degree range. 'Linearity' is actually the match of the arcsine of the output to the tilt in degrees since MEMS accelerometers exhibit a sinusoidal response to tilt (output voltage = sin (angle)). Accuracy, as for traditional probe inclinometers, is best near either pure vertical or pure horizontal (probe inclinometers are usually specified within +/-3 degrees of vertical). In the case of MEMS accelerometers, the sinusoidal response causes a very gradual degradation away from the pure pose, due to a decrease in slope of the sinusoid away from its "zero-crossing". At +/-10 degrees from vertical, the sine curve slope is degraded by only 1.5 percent, and at +/- 45 degrees is degraded by only 29 percent. Similar numbers apply to deviation from a horizontal position, due to the use of three MEMS accelerometers per segment.

Because the SAA is left in place permanently or semi-permanently, it does not have the potential of errors due to mechanical mismatch between a wheeled instrument and a grooved casing, and there is less opportunity for operator error. This advantage is most apparent when the casing becomes extremely distorted.

### Cost

SAAs are priced to be competitive with inclinometers including the consideration that with SAAs the user has 3D deformation and 3D vibration data, wireless transfer of data, and an automatic data collection at frequent time intervals and 30 cm (1 ft) spatial intervals. A 29 m (96 ft) long SAA, including software, costs less than $14,000.

### Ordering Lengths

SAAs are ordered in multiples of eight segments (2.4 m or 8 ft) to a total length of 100 m (328 ft) and can be sent back to Measurand for shortening, lengthening or repair. Arrays are shipped factory-calibrated and ready to install, see Figure 2. There are no provisions for modifying the length of the array in the field.

### Bending of a Segment in the Array

Conventional in-place inclinometers stop giving correct data if the ground deformation is large enough to cause the connecting rod to make contact with the inside of the casing. The 30 cm (1 ft) length of the rigid segments in the SAA, however, makes it less likely that a segment would bend due to this kind of local shear. This short segment length tends to reduce bending of the segments, forcing bends to be taken in the flexible joints which have a 45 degree range of motion and pull strength of 2.2 kN (500 lbs). The recommended installation of SAAs in 25 mm (1 in) casing also helps prevent sensor damage or inaccurate readings due to the effects of shear across an abrupt boundary. The casing acts as a physical, spatial filter for bends at shear boundaries. If one of the SAA's rigid segments did bend, it would cause an error in the tilt reading at that segment, which would propagate as an incorrect displacement in the rest of the data, to the extent that the tilt of the circuit board inside no longer represented the tilt between the nearby joint centers. The ground deformation profiles above and below the damaged segment would be correct but displaced from each other. Further bending could damage a circuit board; in this case, if the circuits are not shorted, the data above the affected segment could possibly still be retrieved. In a recent installation, a segment was bent about 15 degrees near its center by a large impact during shipping. Since the circuit boards are near the ends of the segments, the segment was straightened and the array checked out fine during on-site diagnostic testing.

### Installation and Retrievability

The SAA system was designed to be retrievable; a desirable option to offset the capital cost. The method of SAA installation has evolved in response to maintaining retrievability and accurate deformation measurements. The first three field SAAs were installed in traditional probe inclinometer casing. The casing was grouted into the borehole and the annulus between the SAA and the casing was backfilled with sand; this method is briefly described in the following section. The sand backfill was chosen because it could be flushed out of the casing with pressurized water from the top of the borehole and the SAA could be extracted.

Concerns about incomplete backfill due to sand bridging are valid. SAA data from field installations using this method of installation showed +/- 1 mm (0.04 in) zig-zags a few days after installation. This shape remained constant over a year of monitoring and is attributed to the slight settling of array segments within the casing as sand bridges are broken, usually within the first month after installation.

Because this settling trend was observed for the first three field installations of SAAs, an installation method using a 25 mm (1 in) casing to support the SAA within a borehole was developed. The method allows for the use of either sand or grout backfill, depending on the anticipated deflection magnitude and the desire to retrieve the array. In this method, 25 mm (1 in) casing is held with sand or grout in a borehole, an existing inclinometer casing, or other large casing. If sand is used, the increased stiffness of the 25 mm (1 in) casing compared to the SAA alone tends to minimize zig-zagging should the sand settle, assuming due care has been taken to avoid voids larger than 30 cm (1 ft).

In the small casing method, the SAA is lowered into the 25 mm (1 in) casing using flat webbing to fill the 3 mm (0.1 in) annular space between the SAA and the casing. The SAA and the webbing are anchored together at the far end of the borehole by an enlarged end of the webbing. Pull may be exerted on the webbing and the SAA to facilitate removal. This new method of installation has been utilized with ten field arrays to date (nine of them using sand as backfill) and has eliminated the zig-zag pattern of deformation observed with sand backfill in the first three field installations.

The small casing method has been shown to respond to sub-mm (less than 0.04 in) local shear deformations in the surrounding soil. In sand especially, the 25 mm (1 in) casing will tend to bend rather than shear and the short segment lengths of the SAA conform to the bends. Testing with a 25 mm (1 in) casing held by vises has shown that an "S" curve of the casing with total lateral displacement of 50 mm (2") within 60 cm (24") does not bend the segments of an SAA inside the casing, and the SAA may be pulled past such a curve by hand for retrieval. This "gentle" response to external forces is thought to account for the ability of the SAA to keep reading when other nearby inclinometer casings have sheared. Many users of the SAA opt for the use of sand backfill because of the greater likelihood of retrieving the array.

*Figure 3. Installation of the SAA for unstable slope monitoring in California*

## Unstable Slope Installation

In June 2006, a 20 m (64 ft) array was installed in an unstable slope in California, which has been documented as an ancient landslide prone area, 225 m (738 ft) long and 100 m (330 ft) wide, by Caltrans' geotechnical site reports. Four conventional probe inclinometer casings were installed at the highway level, through this region, from 2002 to 2005, and ground deformations were large enough to shear some of these casings. The SAA was installed approximately 1 m (3 ft) away from a new inclinometer casing installation. Figure 3 shows the SAA installation. Threaded 3 m (10 ft) long sections of 7.6 cm (3 in) diameter inclinometer casing were used in a 12.7 cm (5 in) diameter borehole. The annulus between the SAA and the casing was backfilled with coarse sand. This backfill was compacted, to the extent possible, by striking the side of the casing with a mallet during the sand placement (Abdoun et al. 2007). As mentioned above, this method of installation has been superseded by the 25 mm (1 in) casing installation method due to concerns about sand bridging. Figure 4 shows a comparison of SAA data with conventional probe inclinometer data for a nine month monitoring period. The National Weather Service reported that the amount of rainfall during the 2006-2007 rain season in this area of California was nearly 30 cm (1 ft) below the average and the recorded ground deformations are correspondingly low, less than 10 mm (0.4 in). However, the trends are visible and comparable.

## Conclusion

The California field test was an excellent trial opportunity for this new MEMS-based system and SAA data were comparable to traditional probe inclinometer data. The results of the field installation also addressed some of the questions about the use of MEMS sensors in geotechnical instrumentation and furthered confidence in this system's temperature calibration. The first field installations also raised other questions about the best installation method for the SAA. Several subsequent successful installations have been completed using the 25 mm (1 in) casing method. The successful monitoring at these sites is ongoing and the data confirms the SAA system accuracy to

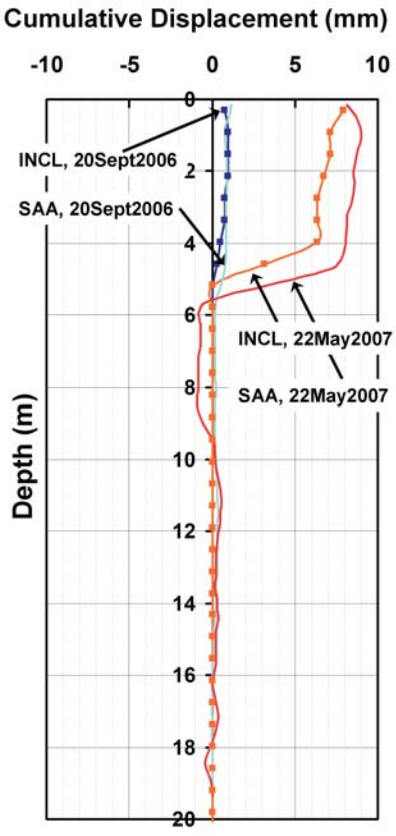

*Figure 4. Unstable slope ground deformations at California test site.*

be comparable to conventional inclinometers, but with improved spatial resolution. Automated wireless data collection, retrievability, improved spatial resolution, and long-term accuracy will earn this MEMS-based system a place in the instrumentation inventory of the geotechnical community.

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### Editor’s Note

When editing the above article by Abdoun and Bennett I questioned their use of the term “3D”. The following summarizes my questions and the authors’ answers.

**Q.** In the Introduction you say, “… is capable of measuring three-dimensional (3D) ground deformations”. And in the “Cost” section you say, “SAAs are priced to be competitive with inclinometers including the consideration that with SAAs the user has 3D deformation ... data”. For me, “3D” in a vertical installation means that the instrument can be used to measure the same thing that a conventional inclinometer does (A and B) plus vertical compression, for which the hardware must telescope in conformance with the ground alongside, and for which there must be sensors to measure axial length change. Hence it isn’t clear to me how the SAA can be used to measure the z component of deformation. Can we agree that, even though “three accelerometers are contained in each 30 cm (1 ft) long rigid segment for measuring x, y, and z components of tilt ...” that, in the application corresponding to a typical probe inclinometer application, the SAA is used to measure only the x and y components?

**A.** You are correct that the SAA is not compressible in z in the sense of a telescoping array. However, because the SAA can be mounted in a flexible small-diameter (25 mm; 1 in) casing or used without a casing, is flexible at frequent intervals (30 cm; 1 ft), and can measure data rapidly and automatically, it can be placed usefully in significantly non-straight shapes or can undergo very large changes in shape. Examples of such shapes include an initially straight line, vertical or at an angle, that becomes deformed into an “S” curve or a “C” curve during slope failure. Other examples are shapes that are initially “S” or “C” shaped and become more deformed during failure. Shapes like those will respond to 3D changes in the soil including vertical compression, and the SAA will be able to follow the changes at high speed, at high spatial resolution, and with minimal fear of the casing shearing or falsely staying straight during the movement. It is true that a traditional manual inclinometer scanning such a shape, and the SAA, both measure x and y directly and use knowledge of measurement intervals or segment length, respectively, to calculate z “indirectly”, so in your sense both are ”2D" instruments. However, the traditional probe inclinometer or a traditional chain of in-place-inclinometers would not be able to conform to any but the most gentle of “S” or “C” shapes, or 3D shapes. As a simple example of a 3D measurement, consider the measurement of the settlement of sand in a large casing, by virtue of the zig-zagging of an SAA in the sand. Or, as a more useful measurement, consider data we have collected from SAAs directly placed in full scale soil models (6 m; 19.7 ft height) without casing, in large shake-table installations in the USA and Japan. Initially straight arrays followed major lateral deformation (0.8 m; 2.6 ft) of the soil model, conforming to the 3D shape of the failure, including settlement in z direction (0.16 m; 0.5 ft), which agreed very well with independent measurements of the settlement using traditional displacement sensors.

**Q.** You say, “Arrays can be installed vertically or horizontally. The intended installation orientation does not need to be specified when ordering. Orientation is selected in the software”. This seems to say that an individual sensor that was used in a vertical installation can also be used in a horizontal installation, when it’s zero axis has been changed by 90 degrees? How can this be so, unless the sensors have a 360 degree range?

**A.** Each sensor has an output that is the sine of the angle of tilt over a range of 360 degrees. Sensitivity is maximum near the zero-crossing of the sine wave, so vertical calculations employ the x and y sensor outputs, which are at their zero crossings when vertical, and horizontal calculations employ the z sensors, which will be at their zero crossings when horizontal. The arrays “know” when they are upside down and vertical. This knowledge requires the z sensor in addition to the x and y. These are true 3D devices.

# Field Evaluation of a MEMS-Based, Real-Time Deformation Monitoring System

**Matthew B. Barendse**

## Introduction

In 2006, New York State Department of Transportation (NYSDOT) partnered with Rensselaer Polytechnic Institute to participate in the field evaluation of a new in-place inclinometer (IPI) system based on Micro-Electro-Mechanical Systems (MEMS) sensor technology. The instrument, known as the ShapeAccelArray, or SAA, is manufactured by Measurand, Inc. of Fredericton, New Brunswick, Canada. To the author's knowledge, Measurand is one of only two companies to make such a device; the other is Geodaq, Inc. of Sacramento, California. The demonstration project selected was the replacement of a 96-year-old steel truss bridge over the Champlain Canal in eastern upstate New York.

The goals of this evaluation were to: measure vertical and horizontal ground displacement, assess the reasonableness of the measured data, and devise methods to install and subsequently extract the SAA.

## Project Site Conditions

The Champlain Canal was first opened in 1819. In the project area, the canal was largely coincident with an existing meandering stream named Wood Creek. Circa 1908, the canal was upgraded for larger traffic by widening and straightening its alignment to its current position (Figure 1). Record plans for the project site show that dredged spoils were used to fill the old creek and canal, as well as to build berms adjacent to the new canal.

Geologically, the site lies near the northern extent of a large glaciolacustrine deposit known from previous experience to contain deep deposits of soft, compressible varved silts and clays. The generalized subsurface profile is shown in Figure 2. In the layer of primary geotechnical interest, the very soft silty clay layer, natural moisture contents ranged from 37% to 82%.

Most of the Casagrande classifications plot in the CH range, with liquid limits from 40 to 71 and plasticity indices from 22 to 46. Laboratory testing indicated the compression index varied from 0.52 to 1.76 and the overconsolidation ratio from 1.0 to approximately 3.5.

## Embankment Foundation Treatments

The new highway alignment is shifted south of the existing, thereby requiring new bridge approach embankments up to 5 m (16 ft) high. The 62 m (203 ft) long truss bridge will be supported on H-piles bearing on bedrock. Treatments for the east and west embankments differ slightly due to a number of factors: this article will focus on the east side, where the SAAs were installed.

Prefabricated vertical drains (PVDs), commonly known as wick drains, were determined the most cost-effective solution to reduce post-construction settlement of the embankment and to minimize dragload and lateral pressure on the piles. The PVDs were pressed to a depth of 20 m (66 ft) in a square grid pattern with 1.2 m (4 ft) spacing. A surcharge fill 1.5 m (5 ft) higher than the proposed finished grade was then constructed utilizing a temporary three-sided geosynthetic reinforced earth wall to match the proposed footprint of the bridge abutment. A fill waiting period of one year was specified with the provision that the waiting period could be shortened on the basis of field monitoring results.

## East Embankent Instrumentation Program

Six subsurface settlement platforms and five vibrating wire piezometers monitored settlements and pore pressures during the waiting period. Lateral deformations of the foundation soils were monitored by a traditional probe inclinometer located between the sur-

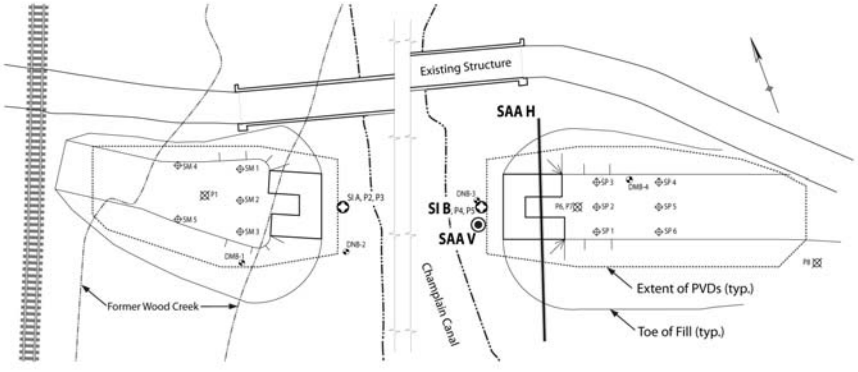

*Figure 1. Bridge replacement site plan.*

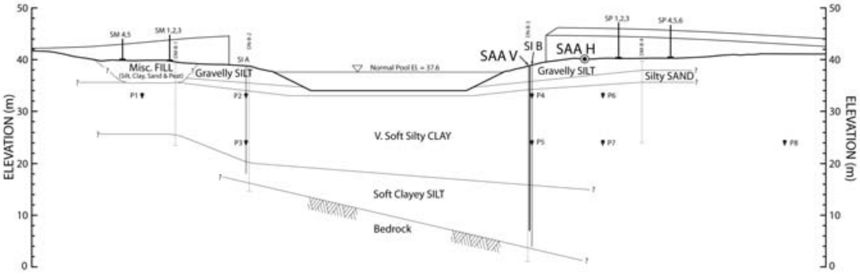

*Figure2. Interpreted subsurface conditions.*

charge and the canal side slope. Supplementing this were two SAAs, both 31.7 m (104 ft) long, one installed horizontally and one vertically as shown in Figures 1 and 2. (For a thorough description of the SAA technology, refer to Abdoun and Bennett in this episode of GIN, or Danish et. al., 2004.)

## SAA Installation

Due to the relatively high unit cost of the SAA, devising an installation procedure that could also reasonably assure later retrieval was considered a worthwhile endeavor. This proved challenging as the SAA must be in intimate contact with the ground to record deformations during operation, and yet also be extractable from a potentially severely distorted shape. The difficulty is compounded by the fact that the maximum tension recommended on the joints is only approximately 2.2 kN (500 lbs). Prior to the field installation, NYSDOT bench tested a technique using a 9.8 m (32 ft) long mockup SAA in a test boring. The method involves installing the SAA and a tremie hose inside 50 mm (2 in) plastic casing and backfilling the annular space with clean sand. To free the SAA, the sand is flushed from the hole by pumping water to the bottom through the open-ended tremie hose. Water pressure up to approximately 2 MPa (150 psi) is used to fully saturate and eventually liquefy the sand. The use of sand backfill with inclinometers is acknowledged as a method that is prone to voids or inconsistent support (Green and Mikkelsen, 1988) and will be a topic of further discussion later in this article.

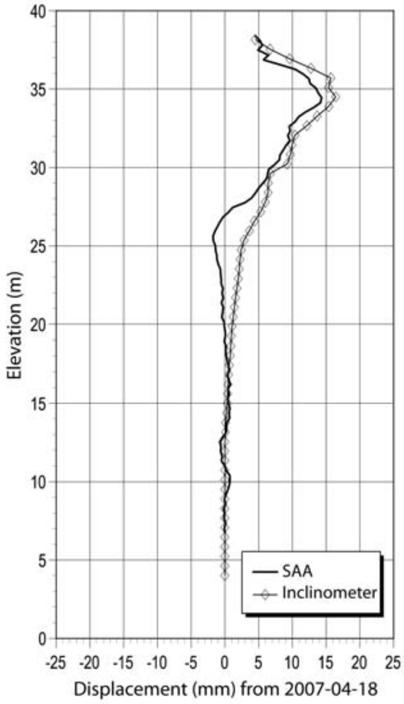

*Figure 3. Vertical SAA and inclinometer (SI B) comparison on July 13, 2007. Note:Corrected for groove orientation*

The vertical SAA was installed at the demonstration site in a drill hole roughly 2.4 m (8 ft) south of the conventional inclinometer. Threaded sections of monitoring well casing (50 mm [2 in] ID Schedule 40 PVC) were inserted into the hole and grouted in place using a water/bentonite/cement mix, mixed in that sequence and proportioned 1/0.06/0.06 by weight. To keep the casing dry prior to adding the sand, steel drill rods were used to counteract buoyancy in lieu of water. Next, 3 mm (0.125 in) wire-wound steel cable and 10 mm (0.375 in) plastic tremie tubing were taped approximately every 1.5 m (5 ft) to the SAA. The SAA was lowered into the well casing by hand, taking care not to damage any joint by bending it beyond 45 degrees, and held suspended off the bottom of the hole by the cable. Silica sand was slowly funneled into the top of the hole while striking the top of the casing intermittently with a rubber mallet. No additional compactive effort or tamping was used.

Installation of the SAA in the horizontal orientation was simpler than the vertical in that intimate contact with the ground was less critical (gravity would keep the device on the bottom of the casing), and both ends of the device would be accessible during removal. The SAA was slid directly into 25 mm (1 in) ID PVC electrical conduit pipe and laid in a small trench within the gravel drainage blanket atop the PVDs. As the SAA fits “snugly” within the conduit, cable-pulling lubricant was used to reduce friction. To verify readings later on and serve as a check for settlement of the reference end, stickup rods with survey targets were attached over both ends of the SAA.

## Cellular Contact and Power Supply

Cellular coverage was verified prior to the installation. Wires from both SAAs were run to a lockable metal cabinet housing the data collectors, 100 amp-hour deep-cycle battery and modem. A solar panel trickle charger and cellular antenna were mounted over the cabinet. During the first 10 months, battery power remained fairly constant given the moderate direct sunlight and several readings taken per day.

## The Data

Figure 3 shows the profile of inclinometer SI B compared with the vertical SAA over the same time period. The general shapes of the upper part of the curves are comparable, however near elevation 25.5 the SAA shows approximately 2 mm (0.08 in) of “negative” displacement. This represents movement towards the surcharge load and therefore raises some questions. Possible explanations are complications due to settlement of the sand, counterflexure of the casing, or an incorrect roll calibration (i.e. twist) in the instrument itself. It is also noted that the SAA exhibited very small zigzag movements between elevations 9 and 13. At this point, the sand is considered the most likely culprit for both anomalies.

Figure 4 shows the settlement profile of the horizontal SAA. Interestingly, the peaks of the curves are offset towards the south side of the surcharge, reflecting the influence of the existing embankment on the preconsolidation of the clay layer. The settlement magnitude is about 30% less than measured with the settlement platforms, owing to the SAA’s location nearer the end of the embankment.

## Retrieval and Landslide Monitoring

In August 2007, an ancient landslide, approximately 600 m (2000 ft) long by 35 m (115 ft) deep, was reactivated on a NYSDOT construction project in western New York. The decision was made to pull the vertical SAA from the demonstration site slightly ahead of schedule and install it on the slide.

Field retrieval at the bridge site looked promising at first, as sand began to flow from the hole approximately 15 minutes after the pump was turned on. However, following a (perhaps overzealous) water pressure spike, the method became ineffective at removing the sand. A new top-down approach was adopted by gluing together 3 m (10 ft) sections of 12 mm (0.5 in) PVC pipe and working them down the hole while jetting water. Although having to glue sections of pipe was somewhat inconvenient and ran the risk of losing a section down the hole, this method did have the advantage of requiring very low pressure to remove the sand in 3 m (10 ft) increments. Approximately 5 m (16 ft) from the bottom of the hole the wash water suddenly became turbid, likely indicating that the pressure spike caused a break in the well casing. This presumably interfered with maintaining adequate pressure using the tremie hose method.

Installation at the landslide was modified based on lessons learned at the demonstration site and other experience by the manufacturer. The SAA was installed inside 25 mm (1 in) PVC electrical conduit which was placed into a previously installed 70 mm (2.75 in) ABS inclinometer casing. To reach a stable layer beneath the assumed shear plane, extra sections of conduit were attached such that the top sensor of the SAA was 10 m (33 ft) down from the top of the hole. The annular space was again filled with clean sand, although this time the space was filled with water so that the sand would be allowed to slowly settle out of suspension. Inside the 25 mm (1 in) conduit, a flat nylon strap was used as space filler to provide a tighter fit with the SAA. The retrieval system was also modified in the hopes that lower pressures can be used to expel the sand. Three tremie hoses were installed with their ends at different depths within the hole. During removal they will be attached to the pump one at a time from highest to lowest.

## Discussion

The practice of using sand backfill with inclinometers has a somewhat speckled past and this project proved no exception. Data stability at the landslide was improved by the addition of the smaller casing to house the SAA. The manufacturer's current installation recommendation is to grout 25 mm (1 in) casing directly into the ground and simply insert the SAA. While eliminating the need for sand backfill entirely is undoubtedly preferable, it is unknown what radius of bending would render the device irretrievable in this scenario. Furthermore, this method may be inappropriate if vibration monitoring is considered a critical aim. In any case, making the device sacrificial is perhaps perfectly justifiable on larger projects. Smaller scale jobs stand to benefit from further thinking and experimentation with installation and retrieval methods. Clearly there is opportunity for innovation in this area.

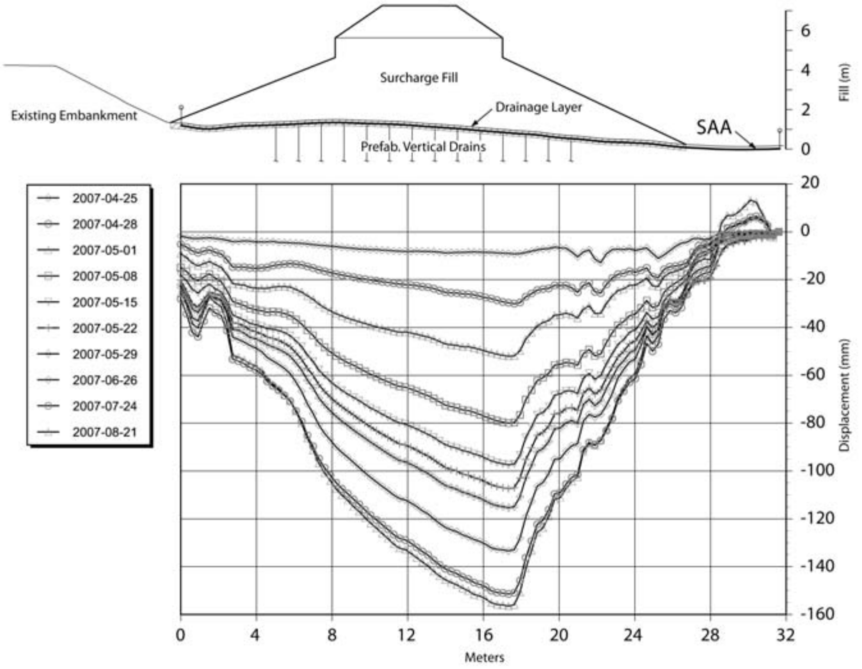

*Figure 4. Cross Section through Horizontal SAA. Notes: Initialized on April 24, 2007. Fill completed on May 1, 2007. The slight upward movement at the south end of the array is due to the stickup rod being moved by construction operations.*

A potential drawback is that once it is installed, the SAA cannot be removed to inspect a faulty sensor and reinstalled as easily as traditional IPI probes might be. At both test sites occasional minor "hiccups" were recorded; that is, readings which were considered questionable or erroneous based on engineering judgment. These unexpected hiccups may very well be attributed to other factors, such as the sand backfill, however one cannot completely rule out instrument error. This issue might eventually be resolved by an improved understanding of the signal processing of the MEMS microchips themselves.

## Conclusions

The SAAs provided continuous ground deformation profiles in both vertical and horizontal applications, utilizing autonomous remote data acquisition. Given the small overall displacement magnitudes at the bridge site, the vertical SAA results correlate fairly well with the traditional probe inclinometer. The horizontal SAA results are consistent with the predicted foundation response and, as one would expect based on elastic theory, show proportionally less subsidence than the subsurface settlement platforms.

The sand backfill in the vertical installation provided reasonable support, as demonstrated by the correlation of results with the probe inclinometer, however it may also have been the cause of some of the apparent discrepancies. The sand backfill was successful in allowing subsequent extraction of the SAA.

This article demonstrates that although some practical details remain in need of further field trials, this MEMS-based IPI system can be used for real-world applications in its current state of development. In summary, NYSDOT is encouraged by these initial results and will continue applying and testing this new technology.

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