Performance of a new installation method for SAA instrumented flexures

Performance d’une nouvelle méthode d’installation pour un SAA

Christiane Levesque, Lee Danisch, Terry Patterson
Measurand Inc., Canada, christiane@measurand.com

Byung Won Han
Geotechnical Department, Baytech Korea Inc., South Korea

ABSTRACT: In geotechnical engineering, in-place inclinometers are often used to measure soil deformation, but impose significant limitations on number of data points and survivability. In recent years, integrated systems of inclinometers called ShapeAccelArray (SAA) instrumented flexures have enabled in-place monitoring with greater ease of installation and higher spatial density of data points than conventional systems. A new form of joint in the SAA, along with the high spatial density of segments, enables the use of a new model SAA to track the shape of the inner surface of a casing, without need of centering the SAA inside the casing. Advantages include higher survivability through large deformations, ease of installation/removal, and reduction of installation variables. In this paper we present laboratory and field results of the new installation method, and discuss the use of inner-surface measurements to derive data compatible with the centre-line measurements of conventional inclinometers.

RÉSUMÉ: Dans le domaine de la géotechnique, les inclinomètres sont souvent utilisés pour mesurer la déformation des sols. Mais ceux-ci sont sujets à des limites importantes sur la survie de l'instrument et le nombre de données recueillis avant l'instrument est brisé. Au cours des dernières années, les systèmes intégrés d’inclinomètres appelés ShapeAccelArray (SAA) ont permis la surveillance automatique de la déformation. Ceci avec une plus grande facilité d'installation et de la densité spatiale plus élevée de données que les systèmes conventionnels. Une nouvelle forme de joint dans le SAA, ainsi que la densité spatiale des segments, permet l'utilisation d'un nouveau modèle de SAA pour suivre la forme de la surface intérieure d'un tube de mesure pour inclinomètre, sans avoir besoin de centrer le SAA à l'intérieur du tube. Les avantages incluent la capacité de survie plus élevé à la face de grandes déformations, la facilité d’installation et la réduction des variables d'installation. Dans cet article, nous présentons les résultats des essais au laboratoire et sur le terrain de la nouvelle méthode d'installation.

KEYWORDS: SAA, inclinometer, deformation, monitoring.

1 INTRODUCTION

Traversing or manual inclinometers have long been used in geotechnical engineering in order to monitor deformation in soils and rock. These instruments are manually inserted into a grooved casing and lowered at a predetermined interval, allowing the operator to measure the cumulative deviation of the casing, or more generally the shape of that casing. These readings are then compared to a baseline reading in order to monitor deformation of the casing.

The desire to automate these readings has led to the development of in-place inclinometers, and more recently the ShapeAccelArray (SAA). An SAA is an instrumented flexure which is composed of rigid segments with flexible joints. Each rigid segment contains MEMS accelorometers which measure tilt in a 360° by 360° sphere. Each reading of an SAA is a snapshot of the shape of the borehole. By comparing these readings to a baseline reading of the SAA, it is possible to determine the deformation of the borehole, much like with a traditional inclinometer.

SAAs have been shown to survive great deformations in soft soils such as clays, and sands (Dasenbrock 2010). This is mostly due to the large shear zones involved in these types of soils. For installations in rock, the survivability of both SAAs and traditional inclinometers is severely reduced. A new model of SAA was designed in order to increase the longevity of SAAs in these types of installations (Danisch et al. 2014a), and in general to make vertical installations much easier and less prone to human error. The new SAA model, referred to as SAAV, contains a new joint design which is very resistant to twist and provides better flexural qualities. These improvements enable a new method of installation (Danisch, 2014b, Danisch et al. 2015). The purpose of this paper is to review the following:

- Lab testing of the SAAV comparing results obtained from the SAAV with those from dial gauges.
- Preliminary field testing of the SAAV comparing the SAAV results with manual inclinometer readings taken in the same casing.

2 BACKGROUND

SAAs are constructed of rigid segments connected together with flexible joints. Segments are typically 500 mm in length, but can also be built to standard lengths of 200 mm, 305 mm, and 1000 mm. Each SAA segment contains 3 MEMS accelerometers that are used to measure tilt relative to gravity, as well as a digital temperature sensor. These MEMS accelerometers are calibrated through a range of temperatures (-35 °C to 60 °C) over a 360° by 360° range, allowing the SAA to have great precision whether it is installed vertically (3D data), or horizontally (2D data).

The most commonly used type of SAA is the SAAF, which often contains over 100 segments, and is connected to an earth station in order to remotely and automatically collect borehole deformation data. Over 75,000 metres of SAAF have been installed. Its composite joints are designed for low-cost production, but have some drawbacks in terms of elastic range, both in torsion and in bending, and rely heavily on a covering of stainless steel braid to resist twisting.

SAAFs are typically installed in a 27 mm inside diameter (ID) PVC casing. Under the force of gravity, and when an additional axially compressive force is applied to the SAAF at the surface, the joints swell out and snug up inside the casing. During insertion, the joints extend due to gravity, allowing the

SAA to slide into the casing. Excellent results are obtained if measures are taken to ensure smooth entry without torsion, into a casing that is installed with some care to prevent sinuation and ovalization. Otherwise, the control of azimuth between segments may be compromised due to twisted joints, and re-use can be limited if the joints lose some of their elastic properties under repeated use.

A new model, SAAV, is currently being field-tested. SAAV has more robust joints, which enable the new installation method. The new joints have a wider range of elastic return under torsion or bending. They are less dependent on an overall covering of braid, which is still necessary, however, as a protective and anti-stretch layer. An axially compressive force on the instrument no longer causes the joints to swell, making it easier to insert the smaller diameter SAAV into an imperfectly installed casing. As discussed in Danisch et al. (2015), the new joint design allows for the installation of the SAAV into a larger casing using the new installation method.

When the SAAV is inserted into a large diameter casing (e.g. 59 mm ID), and a modest (e.g. 20 kg) compressive force is applied, the segments of the SAAV zigzag inside the casing in a random fashion, as shown in Figure 1. Although the zigzag pattern is not all in a single plane, there is sufficient information from the 3D polyline measured by the SAAV instrumented flexure, to define the inner surface of the casing. The data are sufficient to determine the medial axis of the casing as well as measure deformation.

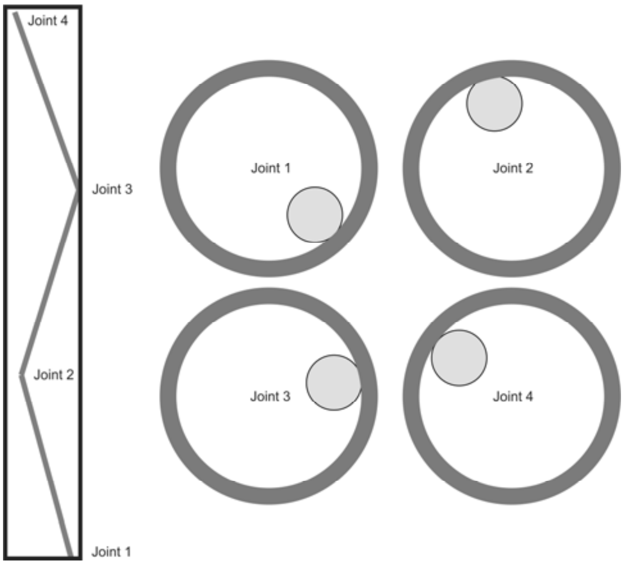

Figure 1. Example of SAAV installed inside a larger casing. Note that the joint placement does not zigzag back and forth in a plane but goes randomly along the inside of the casing when looked at in plan view.

3 LABORATORY TESTING

3.1 *Test set-up*

In order to validate the new installation method, a 16 m SAAV was installed into a 16.2 m PVC casing with a 59 mm ID, and wall thickness of 7 mm. SAAV segments were 0.5 m long. The PVC was chosen because it is similar to 70 mm inclinometer casing.

The casing was installed in the stairwell of a concrete dam using a system of brackets. These brackets, shown in Figure 2, were used to deflect the PVC casing. A dial gauge with resolution of 0.02 mm was positioned on each bracket in order to measure deflection independent of the SAAV measurements. The position of these dial gauges was recorded for every installation of the SAAV. A section of brackets spaced 0.5 m apart is located in the middle of the test set-up. This section allowed for better control of the width of the shear zone. For the tests done in the lab, the shear width was set at 0.5 m. Deflections of up to 20 mm were applied in the top section of the casing (upper 7 brackets). The deflections were applied in steps of 3 mm to 5 mm. When a deflection was applied at an individual bracket, data were collected from the SAAV and all of the dial gauges were read.

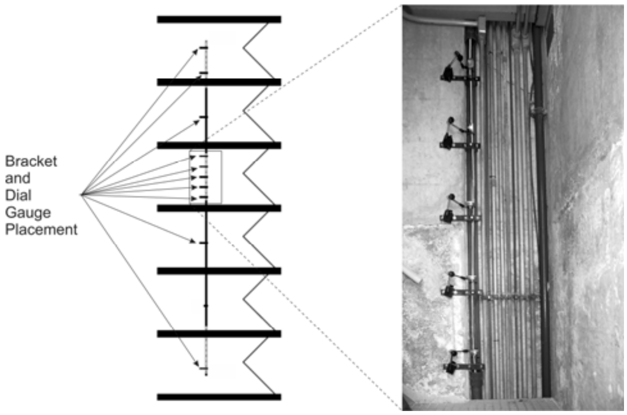

Figure 2. Experimental set-up in dam staircase. The SAAV casing is the left-most tube. In the main shearing section (shown in the rectangle), five support brackets are positioned approximately 0.5 m apart.

3.2 *Laboratory results*

SAAV data were used to determine the shape of the conduit after each deflection. When the dial gauge elevations did not correspond to the elevations of the SAAV joints, the SAAV deformation was linearly interpolated at the dial gauge elevations. A total of 446 SAAV and dial gauge readings were taken and are presented in Figure 3.

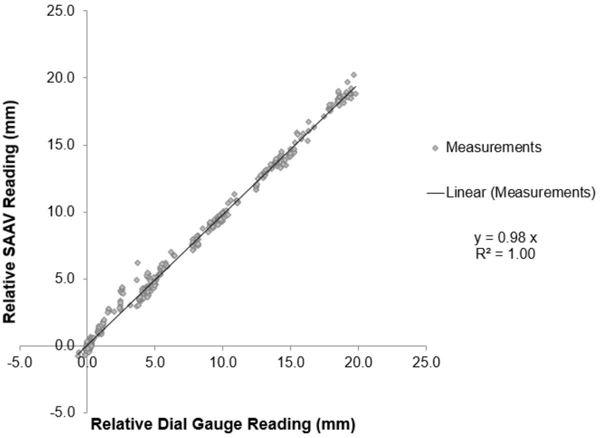

Figure 3. Comparison of SAAV readings and corresponding Dial Gauge readings.

A histogram of the difference between the SAAV and dial gauge data is presented in Figure 4. The mean of the difference was found to be 0.10 mm, with a variance of 0.19 mm and a standard deviation of 0.44 mm.

3.3 *Discussion of laboratory results*

From the results presented, it can be seen that an SAAV installed in a casing using the new installation technique can be used to precisely measure deformation. As can be seen, the SAAV data and dial gauge data give very similar results. The

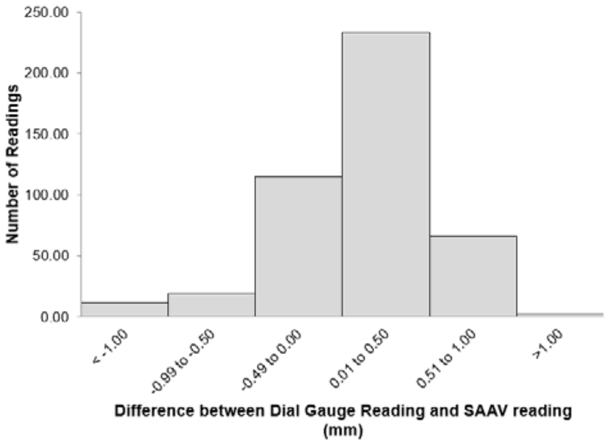

Figure 4. Histogram of the difference between the Dial Gauge readings and SAAV readings.

largest differences in readings occured at the shear zone. This is because the width of the shear zone and the length of the SAAV segments are the same, meaning that the shear is measured over a single segment. To get a better result, the shear width should be at least 1 m for 0.5 m segments.

4 FIELD TESTING

Results obtained from the laboratory testing of the SAAV were excellent, but testing was completed over a very short period of time in stable temperatures using small deformations. In the field, SAAs are subjected to large changes in temperature and can undergo very large deformations. For this reason it was important to test the new installation method in the field.

4.1 Field installation details

An active slide was selected as a test site for SAAV. This site was already being monitored using a manual probe inclinometer. The inclinometer casing on the site is 31.1 m (102’) long, with 0.6 m sticking up above the ground surface. The casing has an outside dimension of 85 mm and a 73 mm ID. The casing was installed in January of 2016 and read 4 times using a 0.6 m (2’) manual inclinometer probe prior to installing the SAAV. The last of these four inclinometer readings was taken on April 12, 2016; the day before the SAAV was installed.

A 30.5 m SAAV with 0.5 m segments was used for the test. The SAAV was installed by unrolling the SAAV directly from the shipping reel into the existing inclinometer casing, as shown in Figure 5. Once the SAAV was in the casing, axial compression was applied at the top and a special installation kit was used to lock the SAAV into position, see Figure 6. Compressive force was transmitted to the SAAV by plastic PEX tubing. The instrument was then connected to a data logger which was programmed to collect data once a day.

The SAAV collected data from April 13, 2016 until June 16, 2016. The SAAV was then removed in order to collect another manual inclinometer reading. This inclinometer reading was used to verify that the SAAV was in fact properly following the deformation of the slope.

Figure 5. Installation of SAAV into an existing inclinometer casing.

Figure 6. Special installation fixture used to lock SAAV in position. Note the PEX tubing at the top of the SAAV has been cut back so that the lid for the casing protection can be closed.

4.2 Field test results

Data collected immediately after the installation of the SAAV are presented in Figure 7. The figure shows the absolute shape of the SAAV inside the inclinometer casing, as well as the calculated medial axis. The medial axis of the absolute shape data was then compared to the cumulative deviation of the borehole measured using the manual inclinometer probe, see Figure 8.

As previously mentioned, data were collected from the SAAV between April 13, 2016 and June 16, 2016. Deformation data collected during this period are shown in Figure 9. Note that Figure 9 is a rough working plot before any calculation of the medial axis, using direct subtraction of the initial zigzag shape from the deformed zigzag shapes.

The inclinometer data, SAAV data and cumulative precipitation measured between January 1, 2016 and September 9, 2016 were compiled and are presented in Figure 10.

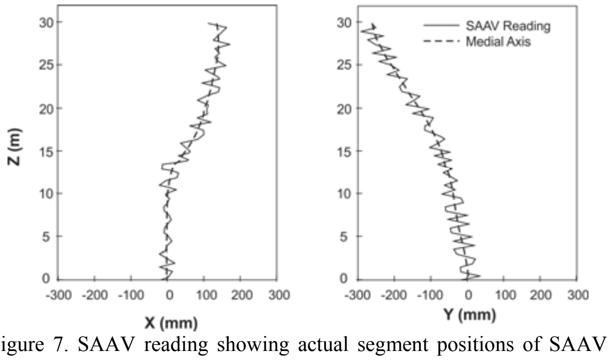

Figure 7. SAAV reading showing actual segment positions of SAAV and the calculated medial axis for reading on April 13, 2016.

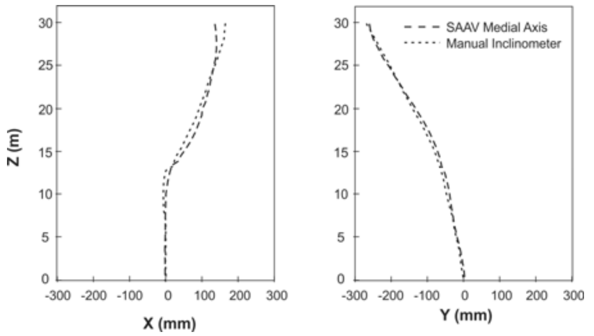

Figure 8. Comparison of SAAV medial axis and the cumulative deviation as measured by manual probe inclinometer the previous day.

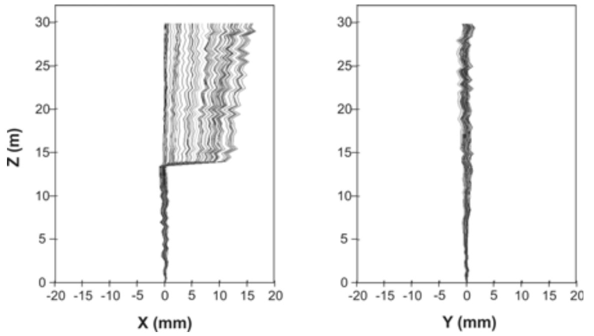

Figure 9. SAAV deformation data collected between April 13, 2016 and June 16, 2016, without using medial axis calculation.

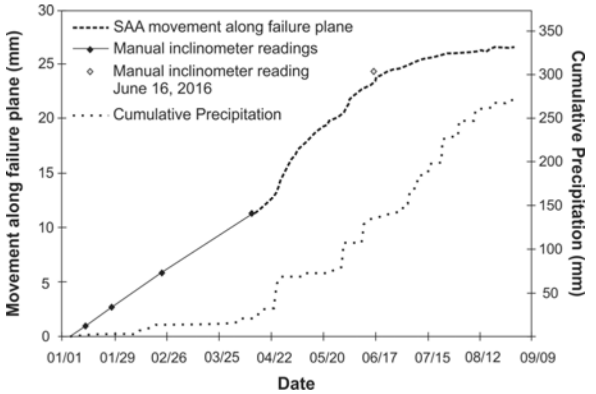

Figure 10. Compilation of inclinometer and SAAV readings measured for the site. Note the manual inclinometer reading taken June 16, 2016 is within 1 mm of the SAAV reading for the same date.

4.3 Discussion of field testing results

As shown in Figure 8, the medial axis calculated using the SAAV data is very similar to the cumulative deviation plot from the inclinometer data. The biggest difference between these two plots is located near the surface of the installation.

As previously mentioned, Figure 9 shows deformation calculated from a direct subtraction of a reference SAAV shape from the subsequent SAAV shape data; without calculating the medial axis. The saw tooth pattern in the deformation is caused by settlement of the SAAV in the casing, and some rotation due to relaxation of the PEX tubing, which bends within the casing. In order to reduce the saw tooth artifact and rotation in future installations, the PEX tubing is being removed from the SAAV design, and replaced with much stiffer fiberglass rods.

Figure 11 shows deformation based on movement of the medial axis. The medial axis was calculated from the vertices of the SAAV shape data. The vertices represent contact points between the SAAV and the inner surface of the casing. The medial axis is found by applying a convolution-based digital filter to the data points. The filter also has a side effect of reducing the saw tooth artifact arising from segment pairs with equal and opposite tilt changes. The tilt changes are due not to soil deformation, but to slight movements of the SAAV within the casing due to the PEX relaxing. The filtering, followed by a rotation correction applied automatically to segments undergoing rotation about their axes without change of tilt magnitude, greatly reduces the artifacts seen in Figure 9. There is some smoothing of the data near the shear zone; a consequence of the pairwise filtering.

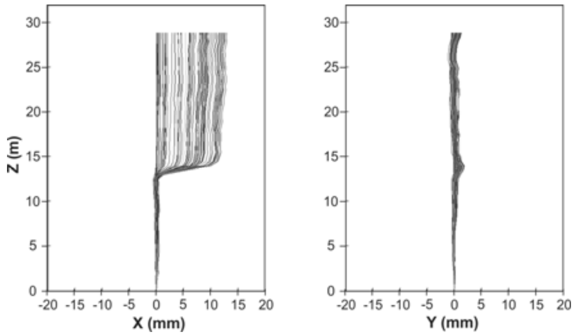

Figure 11. SAAV deformation using medial axis calculation.

As seen in Figure 10, the SAAV data collected at the shear zone was within 1 mm of the deformation measured using the manual inclinometer. At the time of writing this paper, a plan was in place to remove the SAAV a second time and take another reading with the inclinometer probe. A fix for removing the PEX and replacing it with fiberglass rods will be implemented and the SAAV will be re-installed on the site.

5 CONCLUSIONS

Laboratory and field testing of the new SAAV indicate that this new type of SAA can be used to precisely measure deformation.

During the preliminary field testing of the SAAV, PEX tubing used in the installation of the SAAV was found to have undesirable creep. Although the results could be corrected to remove the effect, this component will be removed for future SAAV construction. Field testing of the random cyclical installation method continues on other SAAV.

6 ACKNOWLEDGEMENTS

The authors would like to thank NB Power for the use of their facility to do the laboratory testing described in this paper. We would also like to thank Barr Engineering and the North Dakota Department of Transportation for their participation in the field testing of the new SAAV.

7 REFERENCES

Dasenbrock D (2010). Automated Landslide and Instrumentation Programs on US Route 2, in Proceedings of the University of Minnesota 58th Annual Geotechnical Engineering Conference, St. Paul, pp. 165-185.

Danisch, L., Beran, T., Levesque, C. and Gonzales, L. (2014a) Toward Longer Lifetimes for Remote Deformation Monitoring Installations in Rock and Hard Soils, Using SAA Shape-Sensing Arrays, in Proceedings of VIII Congreso Chileno de Ingenieria Geotecnica, Chile.

Danisch, L. (2014b) Cyclical Sensor Array, U.S. Patent 20160108719, May 1, 2014.

Danisch, L., Levesque, C. and Alpizar Barquero, A. (2015) Monitoring and Scanning using SAA Shape-Sensing Arrays, in Proceedings of the XII Congreso Nacional de Geotecnia, Costa Rica.