An Evaluation of ShapeAccelArray (SAA) Performance for Dam Monitoring

Jason Bond, Lee Danisch
Measurand Inc., Fredericton, NB, Canada
John Fletcher, Phillip Gilks
NB Power, Keswick Ridge, NB, Canada

ABSTRACT
The expansion of concrete caused by alkali-aggregate reaction (AAR) causes significant deformation at the Mactaquac Generating Station, Keswick Ridge, New Brunswick, Canada. Several technologies are used to monitor the deformation behaviour, among which are inverted pendulums. The inverted pendulums provide critical information regarding the overall tilt of the concrete structures. The expenses associated with installing such technology and the relatively short life expectancy has led engineers to investigate the feasibility of using ShapeAccelArray (SAA) as a supplementary technology. A 36.6 m (120') SAA was installed in close proximity to an inverted pendulum in the concrete structure of a dam to evaluate the minimum resolution of SAA measurements. Inverted pendulums can achieve a precision of at least one order of magnitude better than conventional inclinometers or SAA, therefore this test offered advantages over other SAA evaluations comparing inclinometer and SAA results. Preliminary data from the first few months of installation are presented and analyzed, and conclusions are drawn from the perspective of assessing SAA as a tool for monitoring deformation in dams.

RÉSUMÉ
L'expansion du béton causée par la réaction alcalis-granulats (RAG) pruduit le déformation à la Mactaquac Generating Station, Keswick Ridge, Nouveau-Brunswick, Canada. Plusieurs technologies sont utilisées pour surveiller le comportement de déformation, parmi lesquelles des pendules inversés. Les pendules inversés fournissent des informations critiques concernant l'ensemble de l'inclinaison de la digue d'admission. Les dépenses liées à l'installation de cette technologie et de l'espérance de vie relativement courte, a conduit les ingénieurs à étudier la faisabilité de l'utilisation de ShapeAccelArray (SAA) en tant que technologie complémentaire. A 37 m (120 '), SAA a été installé à proximité d'une pendule inversé dans la structure en béton d'un barrage pour évaluer la résolution minimale de measures de SAA. Pendules inversés peut atteindre une précision d'au moins une ordre de grandeur meilleure que les inclinomètres ou SAA, donc ce test offre des avantages par rapport à d'autres évaluations de la SAA d'inclinaison et de comparer les résultats SAA. Les données préliminaires du premier mois de l'installation sont présentés et analysés, et les conclusions sont tirées de la perspective de l'évaluation de la SAA en tant qu'outil de suivi de la déformation dans les barrages.

1 INTRODUCTION

The NB Power Mactaquac Generating Station (Figure 1) is located 20 kilometers north of Fredericton, New Brunswick, on the Saint John River and was commissioned in 1968. Today the station has six units with a generating capacity of 672 megawatts.

Figure 1: Mactaquac Dam, Keswick Ridge, NB (from Agora, 2008)

In the late 1970s, Mactaquac began to show cracking concrete and separating joints. In the early 1980s, instrumentation was installed in the powerhouse and the water retaining structures to measure the effects of the openings and cracking. Instrumentation included borehole extensometers, plumblines, 4-pin gauges and joint meters.

In the mid 1980s the phenomenon occurring at Mactaquac was identified as Alkaline Aggregate Reaction (AAR). In 1988, remedial measures began to relieve the stress caused by AAR and these activities continue. A diamond wire saw is used to make 15 millimeter slot cuts in the powerhouse and the water retaining structures. Before cutting, multi-strand tendons and anchors were installed on the downstream face of the dam to provide enhanced stability. To date, there have been 28 different areas cut with 15 of these requiring regular re-cutting due to the high AAR growth rate.

2 MONITORING USING INVERTED PENDULUMS

To monitor the slot cuts and tilting of the different structures, inverted pendulums and other instruments are used. At the Mactaquac Generating Station, inverted pendulums are used to determine the relative movement between the embedded anchor and the reading table located at the top of the instrument (Figure 2). A wire-centering device (shuttle) is used to derive changes in the vertical profile of both the X and Y directions in a borehole with respect to the anchor.

Each instrument consists of a 1 mm diameter stainless steel wire, anchored at the bottom of a casing and installed in a precision drilled hole. The wire is tensioned at the top by a float and tank assembly. A measuring device is installed directly below the float and a shuttle is lowered down the hole to centralize the wire at each measuring point.

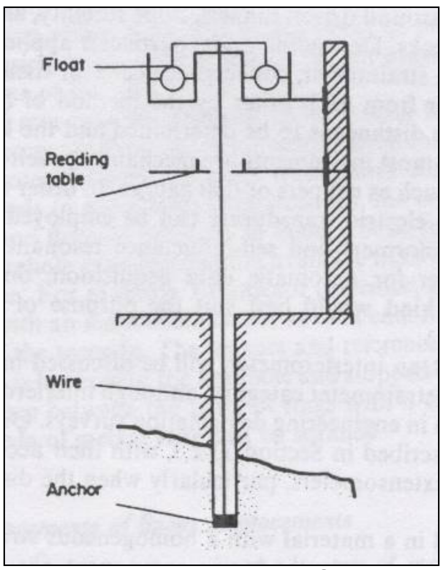

Figure 2: Inverted Pendulum Components (from Chrzanowski, 1993)

The first two inverted pendulums at Mactaquac were installed in October of 1987. The measuring equipment has undergone several modifications and upgrades since this time. Since 2001, an RXTX instrument made by Telependulum has been used. This is an optical instrument that measures the wire position directly and offers a much higher accuracy than the older type pulsotronic/micrometer combination. It also offers a larger range of movement than the Telemac instruments. The RXTX's also allow for direct connection to a computer for data collection, eliminating the risk of errors in transposing information.

The inverted pendulums that are presently being used have an accuracy of ± 0.3 mm. There are currently 15 inverted pendulums in service. Slot cutting and tilting of the structure affects the life expectancy of the inverted pendulums which is normally between 8 to 12 years. A typical installation cost (including the precision drilling of the borehole) is $100,000. Most of the inverted pendulums currently in place will need to be replaced 2 more times before the affected structures are de-commissioned. A set of readings can take anywhere from 3 to 8 hours to complete, resulting in a total of 600 hours per year required for reading all the inverted pendulums. Because of the relatively high cost of maintaining and reading the inverted pendulums, a more cost effective solution is being pursued.

3 MONITORING USING SHAPEACCELARRAY

ShapeAccelArray (SAA) is a sensor that can be placed in a borehole or embedded within a structure to monitor deformation (Danisch *et al*, 2008). It consists of a continuum of segments containing triaxial, micro electro mechanical system (MEMS) accelerometers (Figure 3). Each segment has a known length. By sensing the gravity field at each segment, the bend angles between each segment can be calculated. Using the calculated bend angles and known segment lengths, the shape of an SAA can be determined. SAA can be used to determine 3D shape when installed vertically and 2D shape when installed horizontally. 3D shape can be determined when SAA is not vertical, with a degradation in accuracy according to the cosine of the zenith angle.

SAA is typically installed in 1" (27 mm ID) PVC conduit which is grouted within a borehole. The flexibility of the SAA joints enables it to bend up to 90° and withstand large deformations. Data can be sent wirelessly to a server for automated processing and to enable remote data analysis in real-time. Data can also be periodically downloaded using a PC for analysis.

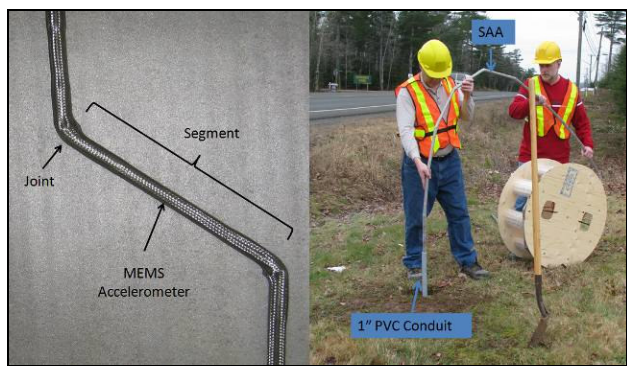

Figure 3: SAA Components and Field Installation

Figure 4 illustrates soil monitoring results that were achieved using a 24 m (80') SAA over a 1.5 year period. Over 400 mm of deformation is detected at ~ 13 m (43') depth. Below the shear zone, millimeter level precision is achieved in the relatively stable soil. Figure 5 illustrates typical results of variation in position of an SAA segment with time in 'stable' soil. This particular cross-section is located 12.2 m from the bottom of an SAA and the results occur over a 173 day period. Similar sub-millimeter results were obtained when hundreds of sensors from other SAAs that were analyzed.

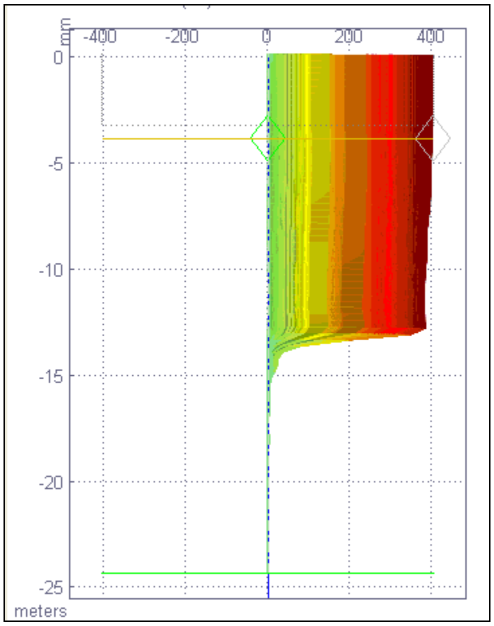

Figure 4: Deformation captured using SAA for soil monitoring application

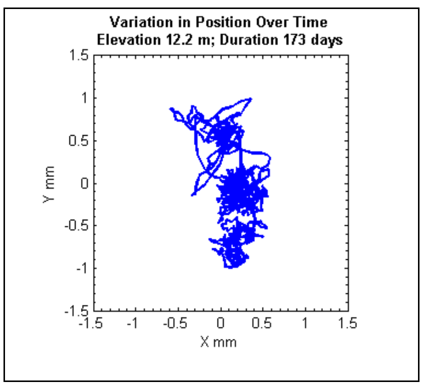

Figure 5: Cross-Section of SAA Segment in 'Stable' Soil

SAA accuracy is a function of the number of tilt measurements made along the length of the SAA. The accuracy of a tilt measurement made by a single SAA segment is dependent upon the zenith angle at which tilt is measured as well as the number of samples used in the averaged measurement (Measurements of the gravity field are used to calculate 3D coordinates of the SAA. Using more samples, i.e, using a larger averaging value in software, reduces the noise in the coordinate output). An analysis of data collected in laboratory conditions indicates that when a tilt measurement is made at < 20° from zenith and 1000 samples are used, the uncertainty in the measurement is ± 0.005°. An analysis of tilt angles calculated from field data collected at < 20° from zenith and 1000 samples indicates that an uncertainty of ± 0.029° is achieved due to variable environmental conditions. The linear uncertainty in a tilt measurement, σ_{tilt_linear}, associated with the angular uncertainty of an SAA tilt measurement, $\sigma_{tilt\_angular}$, can be approximated using Equation 1:

$$\sigma_{tilt\_linear} \approx \pm\ L \times \sin(\sigma_{tilt\_angular}) \qquad [1]$$

Where:

L = SAA segment length

Using the uncertainty in tilt angles calculated from the field data, if the segment length is 305 mm, σ_{tilt_linear} = ± 0.15 mm. If the segment length is 500 mm, the σ_{tilt_linear} = ± 0.25 mm. The uncertainty at any segment along the length of an SAA, σ_{seg} , can be approximated using Equation 2:

$$\sigma_{seg} \approx \pm \sqrt{(N \times \sigma^2_{tilt\_linear})} \qquad [2]$$

Where:

N = segment number from the reference end of the SAA (top or bottom depending upon what is considered stable)
$\sigma^2_{tilt\_linear}$ = the square of the linear uncertainty calculated using Equation [1]

As an example, consider a 36.6 m SAA installed near vertical with 120, 305 mm segments that is sampled 1000 times. The expected uncertainty at the top of the SAA is ± 1.6 mm. If 10,000 samples are used instead of 1000 samples, the results should improve by a factor of √10 yielding an uncertainty of ± 0.51 mm at 36.6 m. Equation 2 only accounts for random errors (normally distributed, Gaussian noise) in tilt measurements. It does not account for biases (e.g., unaccounted for temperature sensitivity, miscalculated gain coefficients). The positional uncertainty at any segment depends upon the uncertainty in both the X and Y tilt sensor measurements (for vertical installations). To take both error sources into account, rigorous propagation of random uncertainty is required using least squares methods.

In practice, there is a limit to the benefit attained from averaging which is dependent upon the resolution of the tilt measurements made by the MEMS sensors. Additionally, biases such as slight movements of the SAA within its casing and unmodelled temperature effects (each MEMS accelerometer has temperature sensitivity) will further increase the uncertainty in an SAA measurement. Both of these sources of uncertainty are addressed by SAA technology in that:

a) The joints are designed to swell and expand when in compression so that they occupy voids between them and the inner diameter of its casing; and
b) Variation in sensor output with temperature change is characterized for each sensor by determining offset and gain coefficients during production.

This investigation and ongoing research will help to quantify how well the above innovations perform in an effort to reduce the gap between the theoretical and achievable accuracy of the technology.

4. TEST INSTALLATION

In an attempt to obtain a cost effective alternative for monitoring tilt of the structures at Mactaquac Generating

Station, NB Power installed a 36.6 m (120') SAA in December of 2008. The SAA consists of 120, 305 mm (1') segments. A second generation inverted pendulum (IIEESS) "S" located in the east end pier of the intake structure was chosen as the test site (Figure 6, Figure 7). Approximately 0.3 meters away from the second generation pendulum is the abandoned casing of the first generation inverted pendulum. The proximity of the two boreholes and the ability to reuse the existing infrastructure made this an attractive location for the test.

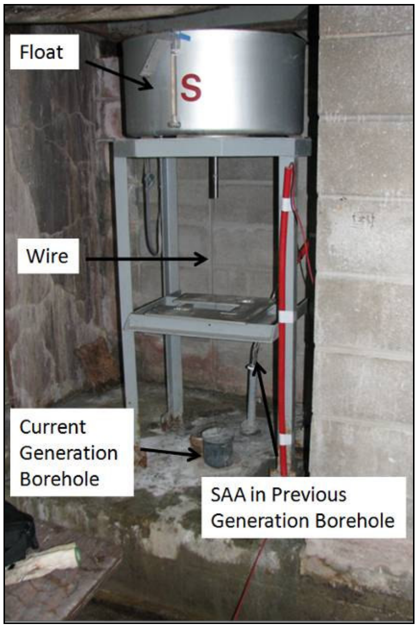

Figure 6: Test Site: IIEESS 'S' and SAA in East Pier

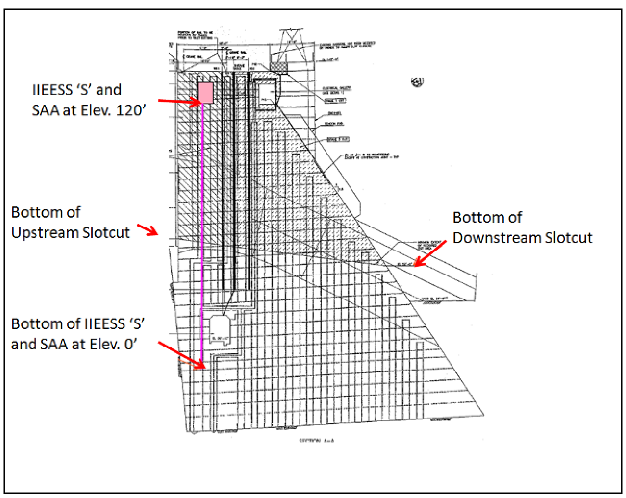

Figure 7: Cross Section of Dam at Inverted Pendulum and SAA Test Site

Schedule 40, 27 mm ID, PVC conduit was grouted in the abandoned inverted pendulum casing (59 mm ID). The SAA was placed in the 27 mm casing. Monthly profile readings were taken every 2 meters at IIEESS 'S' to a depth of 35 meters. The X and Y displacements calculated from these readings provided known values from which the accuracy of the SAA could be assessed. The SAA provided measurements every 0.305 meters and extended approximately 1 m beyond the depth of the pendulum.

To be an effective supplementary technology, NB Power requires a precision of ± 1 mm in each displacement component. Although this value is smaller than the previously calculated value of ± 1.6 mm (using the uncertainty of tilt measurements for field installations), it was expected that a) further averaging of the tilt measurements (i.e., using more than 1000 samples) would help to bring the accuracy to the desired level and b) this environment would be more controlled than normal field installations and offer the opportunity to approach 'laboratory' results.

5. RESULTS

Simultaneous, monthly observations were made using both the inverted pendulum and SAA technologies. Analysis focused on data that were collected from January 2008 until April 2009.

5.1 Inverted Pendulum Results

Figure 8 and Figure 9 illustrate X and Y displacements respectively, as calculated from the inverted pendulum observations. The displacements are calculated relative to a baseline set of observations made on January 13, 2009. It can be seen that the maximum displacement occurs at the top of the pendulum and varies between -0.5 mm to 0.5 mm in both X and Y directions. The tilt begins at approximately 15 m (50') elevation.

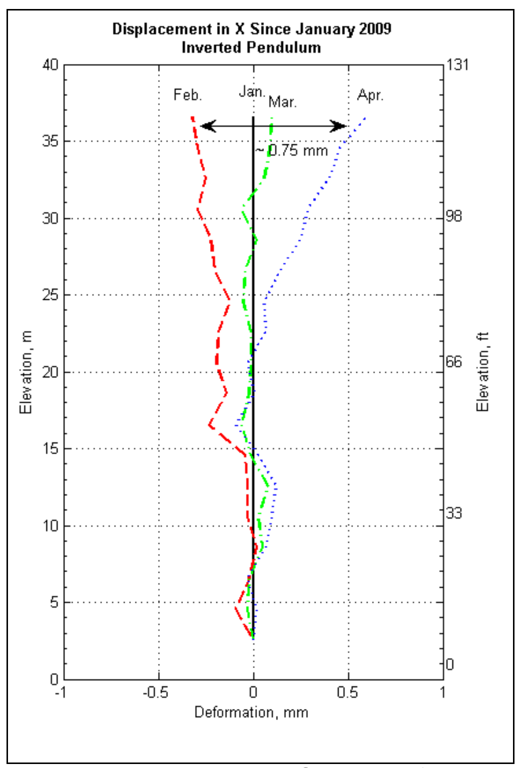

Figure 8: X Displacements Calculated from Inverted Pendulum Measurements

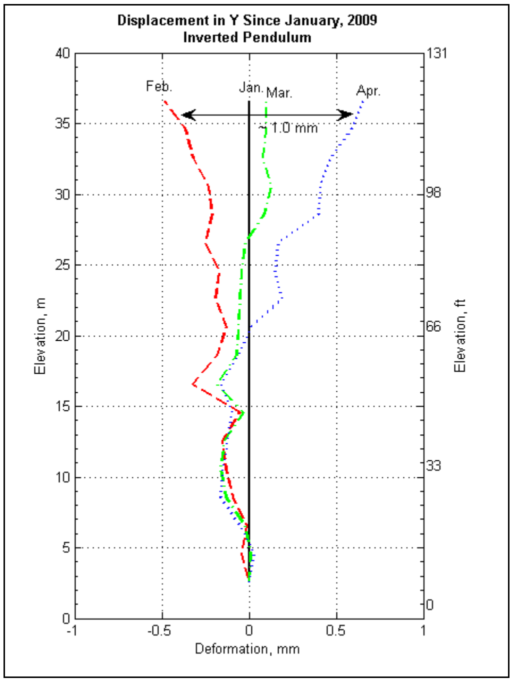

Figure 9: Y Displacements Calculated from Inverted Pendulum Measurements

5.2 SAA Results

Since the accuracy of the inverted pendulum is higher than that of the SAA, it was not expected to be able to extract the same displacement detail as from the inverted pendulum. Data were collected at each measurement campaign using a PC running SAA Recorder software. 10000 samples were collected over a period of approximately 1 hour. To reduce the noise levels of the results, this data was averaged before producing X, Y, Z coordinates for each segment. Coordinates were referenced to the bottom end of the SAA.

Figure 10 and Figure 11 illustrate X and Y displacements respectively, as calculated from the SAA observations. The displacements are calculated relative to a baseline set of observations made on January 13, 2009. Based upon the inverted pendulum results (showing ~1 mm of deformation or less) and the expected accuracy for an SAA of this length, the peak-to-peak spread in the monthly results is larger than anticipated.

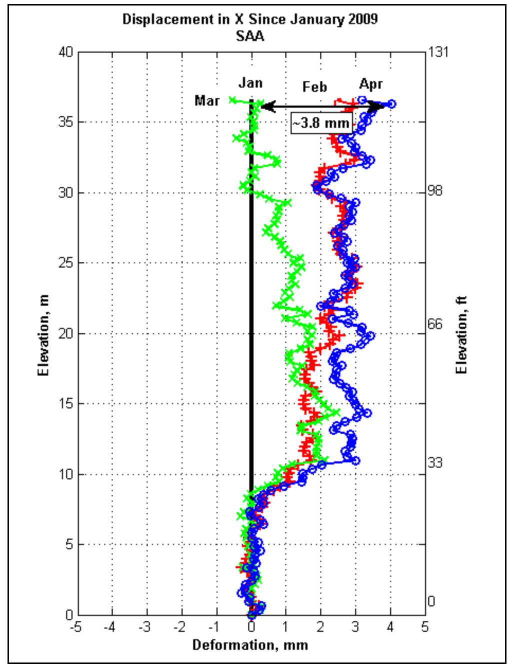

Figure 10: X Displacements calculated from SAA Measurements

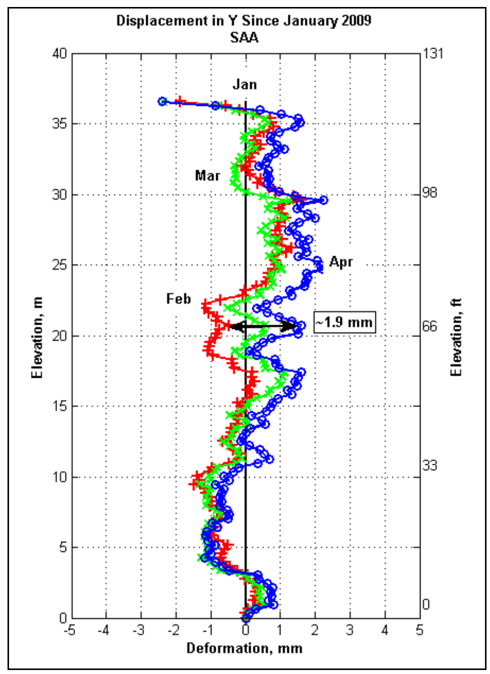

Figure 11: Y Displacements calculated from SAA Measurements

To further investigate the cause of this variation, displacements along the SAA were calculated with respect to its mean position over this 4 month period. Initial analyses of these results suggested that the SAA was still settling within its casing during the first data collection campaign in January (and perhaps in subsequent months as well). Figure 12 and Figure 13 illustrate displacements calculated from the mean position from February through April in X and Y components respectively. It can be seen from Figure 11 that January's result are inconsistent with those of subsequent months even below 10 m elevation, where the SAA should be stable. This instability is likely the cause of the relatively large deformation at ~10 m elevation illustrated in Figure 10. Since January is the reference starting shape, all subsequent measurements appear to have a large variation from this unsettled state.

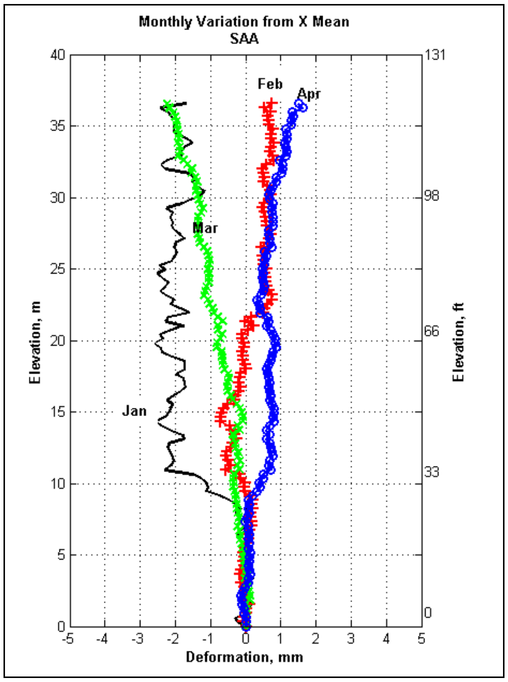

Figure 12: X Variation from the Mean

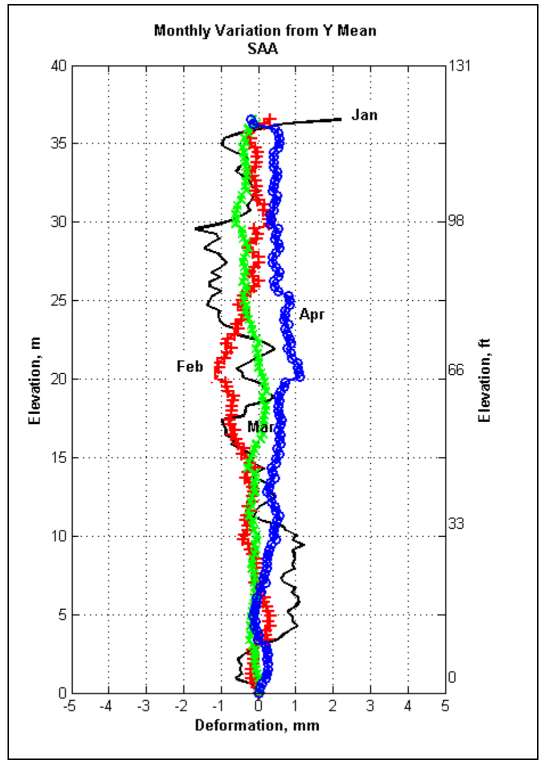

Figure 13: Y Variation from the Mean

An initial analysis of the data indicated that the month to month variations were not caused by temperature changes, which were measured using digital temperature sensors in the SAA at 8 segment (2.4 m) intervals. Monthly temperature variations were less than 2°C at each measuring location. Even when changes in temperature were 0.5°C or less, significant variation in the SAA position occurred. The poor correlation with temperature changes and changes in position lead the analysis to be focused on mechanical explanations for the apparent deformations.

The SAA is designed to fit tightly into its casing by virtue of the elastomeric properties of its joints. The joints have a larger diameter than any other portion of an SAA and will swell when compressed. Compression may be caused by gravity or by adding force to the top of an SAA that is installed within a borehole. Compressing the joints minimizes the space between them and the 27 mm ID of the casing. Normally this process takes a few days for the SAA to reach a steady state. In the case of the Mactaquac Generating Station installation, vibration caused by water flow in a nearby penstock was suspected to prolong this process. Variations in the SAA fit within the borehole could persist into the March and April measurement campaigns when flows are at a maximum during the spring freshet.

There are two main types of error that can result from the variation in compression of the SAA joints inside its casing:

a) the tilt can change slightly due to lateral movement of the segment as the joint dimensions change at the top and/or bottom of a segment, and
b) the joint lengths change by a small amount as they extend or compress, causing segments to

sample a different portion of the casing as they translate axially.

This second error source caused by changing joint lengths is related to depth positioning errors of traversing probe inclinometers as described in Mikkelsen (2003). This error source can cause various apparent displacements depending upon the overall shape of the casing and whether the tilt sensors rise or descend relative to the reference measurement location.

As an example, Mikkelsen (2003) presents the case of a curved casing and the impact that depth positioning errors have on the displacement results. By plotting slope readings vs. depth (incremental deviation plot), the casing curvature can be seen. The shape of the cumulative displacement plot will tend to be echoed in the incremental deviation plot if depth is not controlled. If the depth of the reference (in this case, the bottom most location) does not change, then an overall deformation associated with the change in shape will not result. In the case of a travelling probe with a bottom pose above or below previous bottom poses, and curvature at the bottom, both overall deformation and change of shape will occur.

Whether any of the cumulative deformations calculated from the SAA measurements are due to joint-length changes is, as yet, not certain. Since the bottom most segment is against a firm stop, it is not expected. Instead, the variations in SAA position are suspected to be caused by lateral movement of the segments.

The variations in position illustrated between February and April in Figure 12 and Figure 13 are representative of the expected uncertainty of a field installation for this length of SAA (~ ±1.6 mm for a 36.6 m (120') SAA). Part of the variation illustrated is caused by the true movements of the structure of up to 0.5 mm in positive and negative X and Y directions (as indicated by the inverted pendulum results).

A closer look at Figure 12 and Figure 13 shows peak to peak variations in X and Y components of less than ± 0.5 mm below 10 m elevation. Above this elevation, the results between measurement campaigns diverge. It is believed that this behavior is caused by tilt errors described by the aforementioned scenario a). The joints at the lowest depths within the borehole are the most likely to swell under the weight of the SAA and therefore the least likely to demonstrate this error.

Although the magnitudes of these movements are negligible for most soil monitoring applications, they become significant for applications like this one which require very high precision. In order to capitalize on the full potential of SAA for applications requiring accuracies of ±1 mm or better, a tighter fit of the joints within the SAA casing is necessary. One approach would be to grout the SAA in place. A more attractive alternative, which allows removal and reuse of an SAA is to add a mechanical 'snugging' system. Such an approach must ensure that the separation between the joints and ID of the casing is less than the desired accuracy of the system (in this case < ±1 mm). The method must be designed so that friction from added elements does not prevent insertion.

To further evaluate the potential of the SAA, an analysis of the precision of the monthly observations was conducted. Over 10000 SAA readings were taken each month to get an average solution over a period of just over 1 hour. From these sets of monthly data, subsets consisting of 1000 samples were used to determine the precision within a set of solutions. Figure 14 and Figure 15 illustrate a typical set of results. Equation [2] has been used to plot a parabola in these figures indicating the expected uncertainty along the SAA based upon laboratory conditions (σ_{tilt_linear}.= ±0.005). It can be seen that over this one hour time period, the expected results for laboratory conditions are achieved. A precision of better than ± 0.5 mm is achieved over 36.6 m with averaging at 1000 samples. By devoting further research and development to a mechanical snugging mechanism of SAA within its casing, similar precisions should be repeatable over the long term. As more data are collected over the upcoming months, a clearer image of the behavior of the SAA within the borehole and of the achievable accuracy of SAA will be attained.

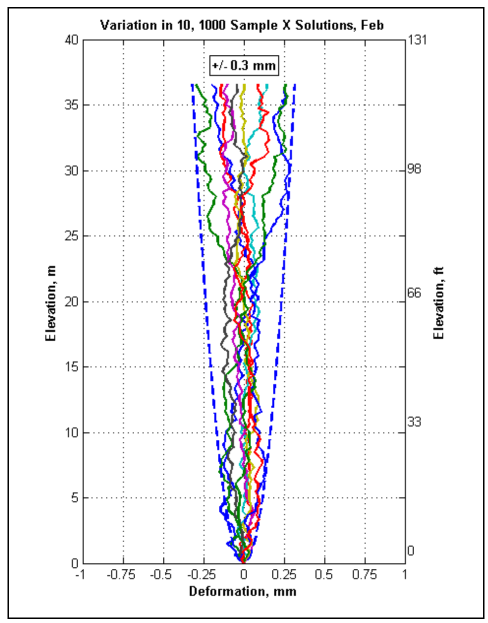

Figure 14: Variation in X Solutions for 1000 Sample Subsets

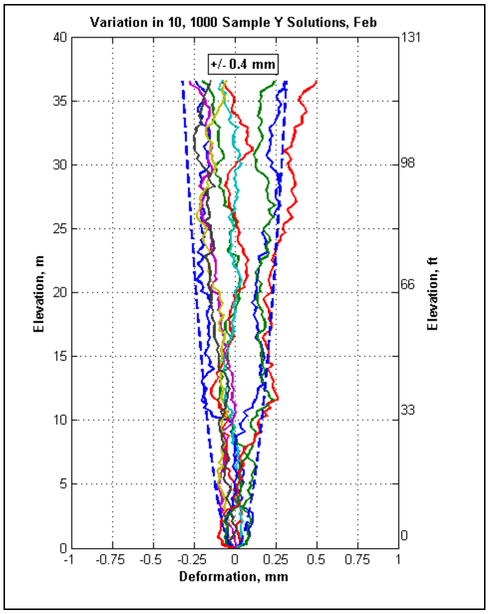

Figure 15: Variation in Y Solutions for 1000 Sample Subsets

6. CONCLUSIONS

Initial analyses of the SAA data collected at the Mactaquac Generating Station indicate that small movements of the SAA within its casing are presently limiting the achievable accuracy. An analysis of a subset of the data collected from February to April (once the SAA has somewhat settled within its casing) is reflective of the expected uncertainty for field installations (~ ±1.6 mm for a 36.6 m (120') SAA). Analyses indicate that the SAA has not reached a steady state within its casing. This type of environment which experiences constant vibration from the flow of water through nearby penstocks poses different challenges from soil monitoring applications. As data continues to be collected, further analysis will be conducted to better assess the achievable accuracy of SAA in this environment.

An analysis of subsets of data collected over a shorter time span (~ 1 hour) indicated that a precision of better than ± 0.5 mm is achieved over the SAA length for 1000 sample averages. Since it is unlikely that these results are significantly influenced by settlement and SAA movements within its casing, they are indicative of what accuracy is possible when a 'snugging' system is developed for high accuracy applications. Further work will be devoted to reducing the space between the SAA and the inner wall of its casing to achieve this goal. The installation at Mactaquac, which includes a high-accuracy pendulum next to the SAA, is an ideal location for this work.

REFERENCES

Agora 2008. *Agora Virtual Museum*. http://agora.virtualmuseum.ca/, accessed on 15 April 2009.

Chrzanowski, A. 1993. "Modern Surveying Techniques for Mining and Civil Engineering." Chapter 33 in *Comprehensive Rock Engineering. Principles, Practice & Projects*, 1st ed, Pergamon Press, New York, NY, USA, 3:773-809.

Danisch, L 2008. *Accuracy Report*. http://www.measurandgeotechnical.com/ , accessed on 21 April 2009.

Danisch, L., A. Chrzanowski, J. Bond and M. Bazanowski 2008. Fusion of Geodetic and MEMs Sensors for Integrated Monitoring and Analysis of Deformations. *13th FIG Symposium on Deformation Measurement and Analysis / 4th IAG Symposium on Geodesy for Geotechnical and Structural Engineering*. LNEC, Lisbon, Portugal, 12-15 May.

Mikkelsen, P.E. 2003. Advances in Inclinometer Data Analysis. *Symposium on Field Measurements in Geomechanics, FMGM 2003*, Oslo, Norway, September. Available at: *www.slopeindicator.com/pdf/papers/advances-in-data-analysis.pdf*

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