Monitoring of Shoring Pile Movement using the ShapeAccel Array Field

Abstract: A ShapeAccel Array Field (SAAF) unit was installed alongside an inclinometer casing on a king pile of the caisson shoring structure. The pile chosen for this study was located on the lakeside wall as it provided a location for potentially large movements.

Monir Precision Monitoring Inc. (Monir) was interested in the performance of the SAAF for monitoring pile movement and comparing its data to that of a manual microelectromechanical system (MEMS) inclinometer probe. Of specific interest was comparison of the data across a range of temperatures to confirm suitable temperature compensation of the SAAF.

Very good correlation was noted between the data from the two different instruments. Several statistical methods were used to compare the data. It was noted that the data from the SAAF and manual inclinometer readings were consistent within 1 mm, which matches the repeatability typically seen in this type of installation.

The project was from April to October of 2015 so the extreme temperature variation into the winter months was not experienced, however the SAAF showed suitable temperature compensation during the spring/summer/fall over temperature changes between -1°C and 33°C.

Background
The project site is a high-rise condominium located along the shore of Lake Ontario. The structure extends approximately 15 metres below grade to accommodate several levels of underground parking.

Caisson walls were used for shoring of the excavation with W-section steel piles placed in the king piles between filler piles to act as primary supports. The depth of the excavation, the site’s proximity to the lakeshore, and the considerable size of the structure all contributed risks for construction. Monir provided a monitoring system that utilized inclinometers and surveying methods to help mitigate these risks.

Multiple inclinometer casings were installed on the steel piles at each face of the excavation to monitor the shoring wall movement. Readings were manually taken by field technicians by lowering a MEMS inclinometer probe down into the casing and then taking measurements at two foot intervals and comparing results to initial data. Cumulative deformation and absolute shape were determined from these data.
Purpose
A SAAF unit was installed alongside an inclinometer casing on the same king pile. The pile chosen for this study was located on the lakeside wall as it provided a location for potentially large movements.

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Scope
The monitoring period for this project was from the start of excavation to when the structural elevation was to grade. This duration was approximately 7 months from April to October of 2015.

The frequency of readings for the inclinometers was weekly while the SAAF collected data on a daily basis by utilizing a datalogger. The inclinometer readings were compared with the SAAF data collected on the same day. These results are discussed in a later section.

Installation of Instrument Enclosures

Inclinometer
An inclinometer casing is a grooved ABS-plastic pipe that comes in 5’ or 10’ sections. There are various pipe diameters available with differing wall thicknesses for specific geotechnical applications. For the project, a 59 mm (2.32 in) inner diameter (ID) casing was used.

In order to monitor pile movement, the inclinometer casing was mechanically fastened to the pile prior to being placed into the drilled hole and filled with concrete. It is important to ensure that the casing is secure against the pile in order to transfer deformation from the steel. The grooves within the casing must also be aligned to face the direction of expected movement, i.e. into the site, in order to maximize the directness of measurement.

ShapeAccel Array Field
The SAAF instrument was designed to fit within a 27 mm ID (Schedule 40) PVC electrical conduit. The installation process is similar to inclinometer casings but with some minor differences. Firstly, the PVC casing required more fastening to secure it to the pile to prevent buckling, due to the conduit being more slender and flexible than the inclinometer casing. Secondly, unlike the inclinometer probe, the SAAF instrument does not require tracks to navigate down the casing. Therefore, the measurement orientation is independent of the conduit.

Figure 1 shows the completed installation of the PVC casing alongside the inclinometer casing.
Installation of SAAF

After the pile has been placed into the ground, the SAAF was inserted into the PVC conduit. The unit was shipped enfolded on a wooden reel. On site, a reel stand was used to facilitate smooth deployment of the instrument and to minimize any twisting and flexing of the joints as shown in Figure 2.

Once the SAAF was completely inserted, a set screw was tightened to keep the instrument in place. An azimuth offset was recorded relative to an X mark on the SAAF and the direction of anticipated
movement which allowed for adjustment of data in the software to show movement into site. An initial reading was required to ensure the instrument was operational and to provide the baseline values. It was originally planned to set up remote monitoring for the SAAF, but site conditions did not allow for it during that time. Instead, a laptop was directly connected to the SAAF and reading samples were taken. Remote monitoring was set up at a later date.

**Remote Monitoring of the SAAF**

The SAAF offers two features that differentiate it from the inclinometer: automated remote data collection and real-time monitoring. Although the project in question did not require either of these features, it provides many prospective applications that may be of interest in the future.

In order to enable remote monitoring, additional hardware was required. Monir assembled a datalogging station composed of a Campbell Scientific CR1000 datalogger, SAAF to datalogger interface, modem, power regulator and DC power supply. Figure 3 shows the configuration of the assembly.

Instrumentation software and a datalogger program specifying collection parameters and frequency were prepared. The program collected movement values along the X (into site) and Y-axes (parallel to site), temperature at each segment depth, and specified a daily collection period.

The datalogger was installed on site approximately three weeks after the SAAF was installed. No AC power was available for the duration of the project; a 12 V battery was used instead. Batteries were swapped weekly during regular manual inclinometer readings.

![Figure 3: Assembly used for remote monitoring consisting of a modem, power regulator, CR1000 datalogger, SAAF to datalogger interface, and 12 V battery (starting counter clockwise from the top right)](image-url)
Remote vs. Manual Readings
One distinct advantage of the SAAF in this application as it is a remote instrument that allows for collection data at a higher frequency. While the option of installing in-place inclinometer sensors is a possibility, the SAAF allows for a more cost effective solution.

Data Collection and Processing
Measurand’s SAACR_raw2data application was used to convert raw data from the CR1000 to a delimited text file with parameters specified in the previous section. This was needed to obtain individual displacement values at each section of the SAAF and compare it with the inclinometer in a spreadsheet as shown on Figure 4. The raw data may be directly opened by Measurand’s SAAView software, which offers powerful graphical applications but does not provide numerical values.

![Figure 4: Sample comparison of data between the SAAF and inclinometer on a spreadsheet](image)

Data Comparison of SAAF Data to Inclinometer Data
With a correction azimuth of 305° and a depth correction of 1.6 metres to the top of the inclinometer casing, the SAAF and inclinometer cumulative displacement readings were plotted together. The reading frequency started with approximately weekly intervals before moving to less frequent readings of 2 to 3 weeks, Monir was able to accumulate twenty sets of comparative data from April to October of 2015. Figure 5 is an example of the plots showing progression of the excavation, installation and stressing of tieback supports, and the erection of the underground structure.

Although the measurements of the SAAF and inclinometer were at differing depths, comparative readings at the nearest depths yielded a maximum difference of 2.5 mm in cumulative displacement. The average incremental differences between readings were within 0.3 mm and standard deviations within 1.1 mm. Table 1 summarizes the results.
When looking at the changes from reading to reading, the maximum difference between the SAAF and inclinometer at comparative depths was 0.9 mm with a maximum average difference of 0.3 mm and standard deviations within 0.4 mm.

Table 1: Comparative analysis between SAAF and inclinometer data

<table>
<thead>
<tr>
<th></th>
<th>Cumulative Displacement (mm)</th>
<th>Incremental Displacement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Value</td>
<td>2.5</td>
<td>0.9</td>
</tr>
<tr>
<td>Maximum Average</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Maximum Standard Deviation</td>
<td>1.1</td>
<td>0.4</td>
</tr>
</tbody>
</table>

**Temperature Correlation**

Critically speaking, the last three sets of data had more deviation than earlier data. When looking at potential factors, temperature compensation was a possibility. However, in terms of absolute temperature and the difference between minimum and maximum temperatures in the SAAF during a reading, nothing conclusively pointed to any external factors significantly different than those experienced by previous readings.
Figure 6 displays the temperature at each sensor depth versus time. The red dotted line is the difference between maximum-minimum temperatures during a reading. The largest temperature difference was experienced in April with 13°C and the smallest temperature variation was during readings in June with 2°C. As expected, the smallest temperature variations occurred at the lowest depth of 16 metres while the largest variations were closest to the surface with a maximum difference of 18°C for the duration of the project.

Figure 6: Temperature at each sensor location versus time

**Points of Interest during Monitoring**

It is important that pile movement is monitored during certain stages of the excavation. Gathering data during these periods can reveal crucial information regarding the performance of the shoring system and can verify many design assumptions for the shoring engineers.

**Cantilever Movement**

The first point of interest occurs when the excavation reaches the first support elevation, such as the location where a tieback or strut will be installed. The cantilever created by the exposed pile face generates the first loading scenario for the shoring structure; many design parameters can be correlated to the pile movement information gathered during this time.
**Shoring Deformation**

Another point of interest corresponds to the installation of supports, and behaviour of the supports during active excavation. Typically the pile will show into site movements until the support member is engaged (i.e.: a tieback is stressed). Out of site movement typically corresponds to stressing of the tiebacks, which can result in negligible to considerable movement, depending on the method of shoring utilized as well as the existing ground conditions (i.e.: soldier pile lagging tends to exhibit more movement in general than a caisson wall). These movements not only indicate performance of the supports, but also the general behaviour of the shoring system as a whole.

**Comparison of Pile behaviour at a Tieback Location**

Figure 7 shows pile movement collected by the SAAF compared to the inclinometer at a tieback location.

![Pile Movement at Tieback Location](image)

**Figure 7: Pile movement at tieback location**

**Decommissioning and Removal**

The removal of the SAAF from the project site was relatively straightforward. A field technician traveled to site along with the wooden reel that came with the instrument and a reel stand. Carefully, the SAAF was pulled out of the PVC conduit and placed on to the reel making sure the joints were not bent at angles greater than 45°. It was equally crucial to keep the SAAF from twisting and flexing, the X marker at each joint of the instrument was aligned with each other to ensure that no torsion was present. Wiring from the SAAF to the datalogger was disconnected and the datalogger station was removed. These components will be reused for future project.

**Lessons Learned**

In reviewing the test process, a few items were highlighted to be executed differently to yield better results for future studies.
**Baseline Collection**

As noted previously in the installation of the SAAF section, the instrument was connected to a laptop computer and multiple initial readings were taken with several seconds of recorded data. When the SAAF data was compared to the inclinometer data there was approximately 3 to 5 mm in difference between maximum cumulative displacements, although the absolute profiles were similar. With subsequent readings, it appeared that the initial SAAF reading was likely not valid as comparison data.

In future installations, there should have been more initial data, perhaps an adjustment/stabilizing period before readings and ideally have a datalogger active to generate more continuous baseline data.

**Timing of Baseline Collection**

In discussions with Measurand, it was noted that grout curing has been known to cause movements. This was compounded with the SAAF casing not being secured against the pile flange and being more flexible than the inclinometer casing. Settling may also be an issue so proper installation with the set screw is vital.

The processing of the data requires an accurate reading of the azimuth after installation in order to ensure the movement in the direction of interest is obtained.

**Accurate Point of Reference upon Installation**

Another important step is to get an accurate measurement of a reference point to the first sensor location. This allows correlation of each depth with a datum such as ground surface or in this case, the top of the inclinometer casing.

**Conclusion**

The primary reason for this test project with the SAAF was to determine if the data was comparable to that of an inclinometer in applications of monitoring shoring wall movements. Overall, very good correlation was noted between the data from the two different instrument. Several statistical methods were used to compare the data. It was noted that the data from the SAAF and manual inclinometer readings were consistent within 1mm, which matches the repeatability typically seen for this type of installation.

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