Monitoring Displacement vs. Depth in Lateral Pile Load Tests Using Shape Accelerometer Arrays

Suivi de déplacement c. profondeur en essais de charge latérale aux pieux utilisant des réseaux flexibles d'accéléromètre

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ABSTRACT
Shape accelerometer arrays provide an alternative to inclinometer probes for determining horizontal displacement versus depth profiles during lateral pile load tests. These arrays typically consist of triaxial chip-based accelerometers located at 0.3 m intervals within flexible waterproof tubing. These shape arrays can provide a continuous readout of displacement, velocity, acceleration, and rotation at each accelerometer location. Because the shape arrays are relatively new and have not been used for this application, their performance was evaluated relative to conventional inclinometer probes during a full-scale lateral pile load test. The test results indicate that the shape arrays can provide accuracy comparable to that from an inclinometer for static loadings, although some problems were noted in coupling the array to the installation pipe which could hinder dynamic measurements.

RÉSUMÉ
Les réseaux flexibles d'accélomètre fournissent une alternative aux inclinomètres a sonde pour la détermination des profiles de déplacement horizontal contre profondeur, durant les essais de charge latérale aux pieux. Ces réseaux consistent, typiquement, des accéléromètres triaxiaux de puce, situés aux intervalles de 0,3m dans des tubes flexibles et imperméables. Ces réseaux peuvent fournir de l'information continuelle du déplacement, de la vélocité, d l'accélération et de la rotation à chaque emplacement d'accéléromètre. À cause que les réseaux sont nouveaux et n'étaient pas encore utilisés pour cette application, leur performance était évaluée en relation des inclinomètres à sonde conventionnels durant un essai de charge latérale à pleine échelle. Les résultats d'essais indiquent que les réseaux peuvent fournir la précision comparable à celle d'un inclinomètre en ce qui concerne des charges statiques, cependant on a noté quelques problèmes par rapport au couplage du réseau au conduit d'installation qui pourraient entraver les mesures dynamiques.

Keywords : shape accelerometer array, lateral load test, pile load test, instrumentation, displacement

1 INTRODUCTION

When performing lateral load tests on deep foundations, it is desirable to obtain horizontal displacement versus depth profiles. These profiles can be used in conjunction with lateral load versus displacement curves to calibrate programs which analyze the response of laterally loaded piles. In addition, the displacement versus depth curves can be used to determine bending moment versus depth profiles. Horizontal displacement versus depth profiles have typically been determined using inclinometer probes or strings of downhole inclinometers. Typical inclinometer probes require the user to measure slope at 0.6 m intervals within a special grooved pipe which is typically concreted into place within the pile. The displacement of the pile must be held constant over a 15 to 20 minute period while the inclinometer measurements are made. Strings of down hole inclinometers can also be installed at various intervals within the inclinometer pipe. This option is more expensive but allows measurements to be obtained simultaneously and more quickly. Nevertheless, the displacement of the foundation must be held relatively constant for a period of several seconds so that the inclinometers can stabilize and provide an accurate reading. This requirement usually precludes their use for dynamic applications.

An alternative for determining horizontal displacement of piles is provided by an instrument called a "ShapeAccelArray" (SAA) (Danisch et al, 2005, Measurand, 2009a). The array consists of triaxial chip-based accelerometers located at 0.3 m intervals within joint-connected rigid segments covered by a waterproof covering (electrical "heat-shrink" tubing). The SAA can be inserted within a conventional PVC pipe which is concreted into place along the length of the pile. The array can provide a continuous readout of displacement, velocity, acceleration, and rotation at 0.3 m intervals. As a result, the array can potentially be used to monitor lateral pile behavior during dynamic as well as static loadings.

Because the shape arrays are relatively new and have not been used for this application, a field test was performed to evaluate their performance relative to conventional inclinometer probes. The results from these tests provide a comparison of the measured displacements obtained from the two systems.

2 LOAD TEST LAYOUT AND INSTRUMENTATION

To evaluate the development of passive force with displacement, a lateral load test was performed on a pile cap with and without backfill soil against the cap. The test was performed in the summer of 2007. Additional details regarding the testing are provided by Heiner et al. (2008). As shown in Figure 1, the concrete pile cap ($f'_c \approx 41$ MPa) was 3.35m x 4.57m in plan view, 1.77m high, and provided a relatively "fixed-head" boundary condition. The cap was supported by six 324-mm OD steel pipe piles which were embedded 75 mm into the cap. The piles were filled with 41 MPa concrete and were connected to the pile cap by a reinforcing cage consisting of six #25 (#8 US) vertical bars which extended 4 m into each pile and 1.55 m into the pile cap. The vertical bars in the reinforcing cage were surrounding by a #13 (#4 US) bar spiral with a 152 mm pitch. Load was applied to the pile cap by two 2700 kN hydraulic actuators in an incremental procedure to produce pile cap deflection increments of about 6 to 13 mm up to a maximum displacement of about 90 mm.

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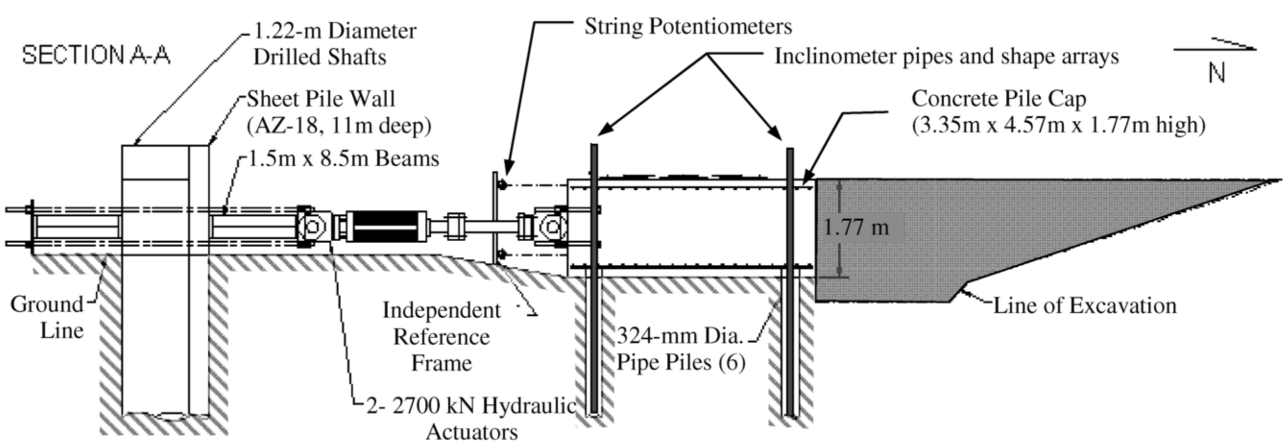

Figure 1 Configuration of pile cap, piles and instrumentation for later load test.

Pile cap displacement was measured using three pieces of instrumentation: string potentiometers, inclinometers, and shape accelerometer arrays. A brief summary of each measurement system is provided in the following sections of this paper.

2.1 *String potentiometers*

During the lateral load test, displacement of the pile cap was measured by four string potentiometers located near the top and bottom of the back side of the pile cap as shown in Figure 1. The string potentiometers had an accuracy of 0.25 mm. The top two string pots were located 0.078 m from the top of the pile cap while the bottom two string pots were located 1.31 m below the top of the pile cap. The string potentiometers were attached to an independent reference frame.

2.2 *Inclinometer pipe and probe*

A 70 mm outside diameter inclinometer casing was installed to a depth of about 13.1 m below the top of the cap in the center pile of the front and back rows of piles as shown in Figure 1. The inclinometer casings extended about 250 mm above the top of the pile cap. A wheel unit was used to hold the cable so that the reference point for the inclinometer readings was 884 mm above the top of the pile cap. Inclinometer readings were obtained at 0.61 m intervals using a Digitilt inclinometer probe (manufactured by Slope Indicator) with a DataMate portable data acquisition unit. Measurements were taken using the standard procedure of two, bottom-up passes to reduce error. A standard pulley assembly attached to the top of the casing was also used to provide a reliable measurement datum. Inclinometer readings were taken at both the beginning of the lateral load test and at the maximum displacement level. Because about 30 minutes were required to read both inclinometers, readings at intermediate displacement levels were not taken to minimize creep effects on the load-displacement curve. While the inclinometer readings were taken, the two hydraulic actuators kept the pile cap displacement relatively constant. The limit of precision for conventional inclinometers after all systematic errors are eliminated is ± 1.24 mm per 30 m (Mikkelsen, 2003).

2.3 *Shape Accelerometer Array*

A 27 mm inside diameter schedule 40 PVC electrical conduit was tied to the side of the two inclinometer pipes in the front and back row piles as shown in Figure 1. The PVC pipe was installed to a depth of 15.3 m below the top of the pile cap. The electrical conduit extended upward through the pile cap and terminated approximately 75 mm above the cap. The PVC pipe was concreted together with the inclinometer casing into the pipe pile.

The accelerometer arrays, (SAAR: ShapeAccelArray, Research model), are manufactured by Measurand, Inc. They contain MEMS (Micromachined Electro-Mechanical System) accelerometers with a range of ± 2 g and a noise figure limited to 2 mG RMS by internal filtering. Data can be sent digitally through cables to a computer at over 100 samples/second. The arrays were installed so that the top vertex was located at the top of the pile cap and they extended to a depth of 7.32 m below the top of the pile cap. Because the accelerometer array has a maximum diameter of 25 mm at the joints, nylon webbing webbing (1 to 2 mm thick) was inserted along the side of the array to "seat" the tube against the inside wall of the PVC pipe. The webbing was attached to a "pig" which was pushed into the hole below the array as illustrated in Figure 2.

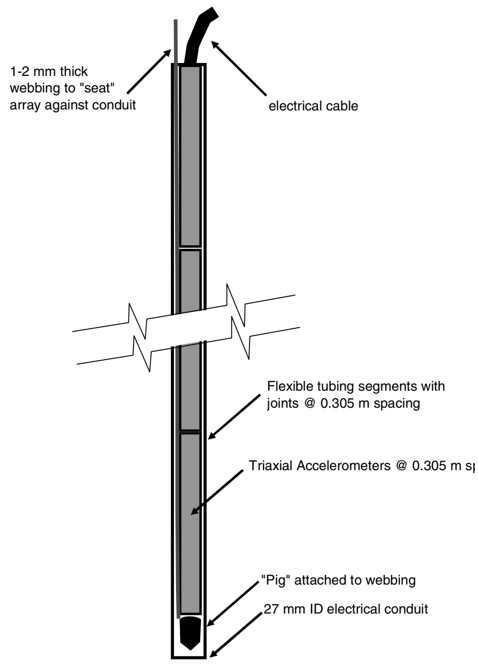

Figure 2. Schematic diagram showing arrangment of shape accelerometer array in 27 mm ID electrical conduit with webbing to seat the accelerometer against the conduit wall.

Each array was connected to a data concentrator which was in turn connected to a card in the computer. Data was recorded at a sampling rate of 30 Hz during the testing using a desktop computer. The arrays provided triaxial static and dynamic accelerations for each joint. Application software ("SAARecorder") calculated positional data at the vertices of the arrays using the static components. For static or slowly-changing deformations, the accelerometers are used to measure tilt angles θ of each segment, according to the equation

$$\theta = \sin^{-1}(kv) \tag{1}$$

where k is a constant, v is the output voltage of the accelerometer, and. kv is the acceleration relative to the gravity with a range of +1 to -1. In this respect the measurement is similar to that of conventional inclinometers; i.e. gravity-referenced tilt. However, azimuth in the SAA is resolved by performing 3D joint-angle calculations using the joint construction (bend without twist) as a constraint (Measurand, Inc. 2009a), rather than the grooves in inclinometer casing. The algorithms employ rotational transforms, which can be solved because the joints are constrained to bend in any direction without twisting. Field measurements conducted by the manufacturer indicate that the precision of an SAAR is similar to that of conventional inclinometers: ± 1.5 mm per 30 m (Measurand, Inc., 2009b).

3 TEST RESULTS

Initial displacement readings were taken from all three measurement systems before any lateral loads were applied and these initial values were subtracted from the displacements recorded from subsequent displacement increments to determine the change in displacement. Plots showing the displacement versus depth profiles obtained from the north and south shape arrays are provided in Figure 3. The curve shapes appear to be reasonable and show a marked change in slope at the base of the pile cap as expected. Despite the fact that the pile cap is 1.77-m thick, there is still a small slope to the displacement vs. depth profile within the cap which indicates that the cap is rotating slightly and is not completely fixed against rotation. Because the displacements are all referenced to the bottom accelerometer, displacement is assumed to be zero at a depth of 7.32 m.

Average displacements measured by the string potentiometers at two levels are also shown in Figure 3. On average, displacements from the shape array were 2.3 mm less than the string potentiometer displacement with a standard deviation of 0.8 mm. The observed discrepancies can be attributed to three possible sources: (1) instrumental error in the rotation measurement, (2) error associated with poor seating between the shape array and the pipe wall, and (3) displacement of the pile below the level of the array which would not be measured. In this case, a large part of the error appears to be associated with poor seating of the array. For example, an offset of 2.3 mm would bring all the shape array measurements into very good agreement with the displacement from the string pots. The remaining 0.8 mm standard deviation would then be relatively consistent with the expected instrumental error.

A comparison of displacement versus depth curves obtained from the north and south inclinometers and the shape arrays is provided for the maximum pile cap displacement in Figure 4. In addition, the average displacements measured by the string potentiometers at two levels are provided for comparison. A few adjustments to the raw data needed to be made to make the comparison accurate. The top of the pile cap was chosen as a reference point for both systems. Because the references for the south and north inclinometer readings were located 0.914 m and 0.884 m, respectively above the cap, these distances were subtracted from the depth readings indicated by the inclinometer to change the reference to the top of the pile cap. Both accelerometer arrays were placed such that the top vertex was at the top of the cap, thus no adjustments were made to the depth readings from the arrays.

Further adjustments were made to the displacement data from the accelerometer array because the arrays only extended 7.32 m below the top of the cap, while the inclinometer profiles which extended to 12.6 m showed that the piles had already displaced a small amount at a depth of 7.32 m. Therefore, to facilitate comparison, the displacement of each node in the accelerometer array was increased by the displacement measured by the inclinometer at a depth of 7.32 m.

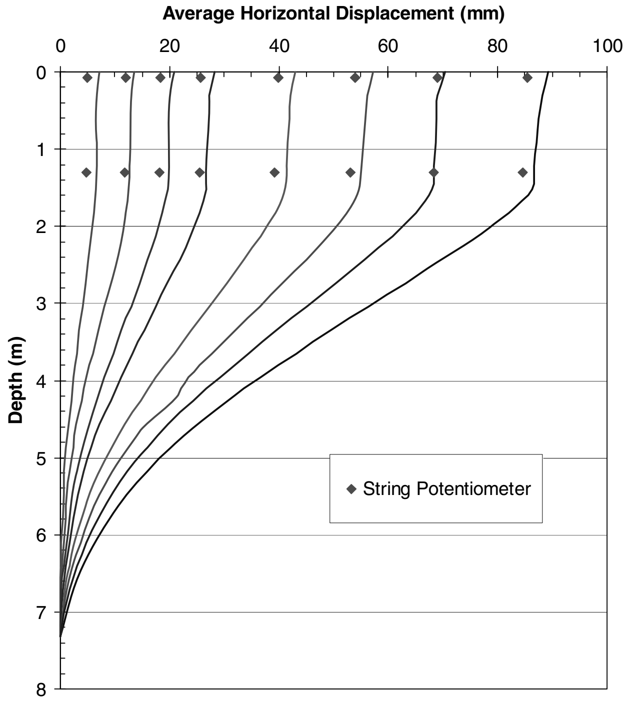

Figure 3. Horizontal displacement versus depth curves obtained with the north and south shape arrays at a number of load increments during the lateral load test.

Displacement profiles from the inclinometer and shape arrays shown in Figure 4 are generally in very good agreement suggesting that the two methods provide reasonably comparable accuracy. Typically, the difference in the measured displacement was less than 1 to 3 mm. This is consistent with the 1-2 mm precision expected from both devices. On average, the differences were about 2% for the north array and 4% for the south array.

Pile cap displacements obtained from the string pots are also shown in Figure 4 for comparison. In this case, corrections for errors associated with displacement below the base of the array have already been made as discussed previously. Nevertheless, the shape arrays tend to differ from the measured values by 2 to 5 mm. As discussed previously, part of this difference may be attributable to problems with seating the array against the pipe wall. These seating problems may also make it difficult to obtain accurate readings during dynamic loadings.

Recent improvements in the SAA installation procedure since these tests were conducted may reduce potential seating errors. Since early 2008 SAAs have been supplied with joints that expand significantly under axial compression, seating them tightly within a 27-mm ID PVC tubing. The arrays also have an over-covering of stainless-steel braid, which provides a tighter fit, improved azimuth control and protection against abrasion. No webbing is used. This suggests the need for follow-on testing to characterize the effects of these modifications, which are claimed to be tighter, under static and dynamic loading.

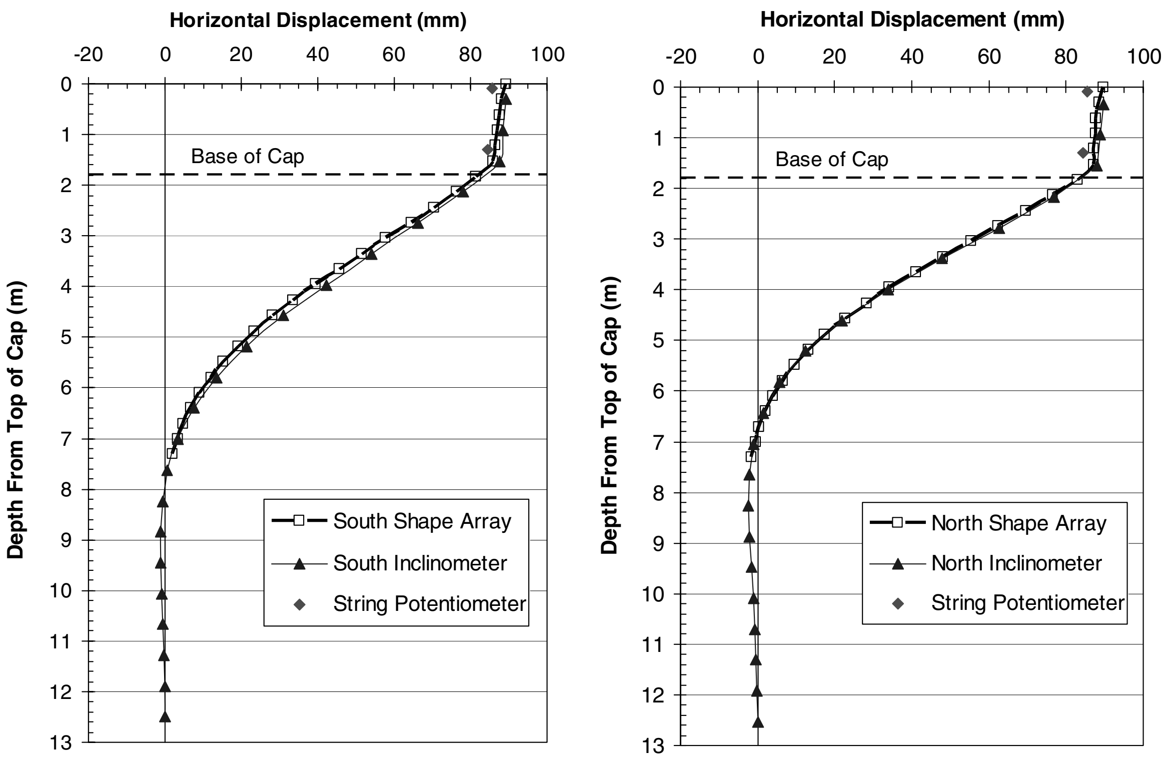

Figure 4. Comparison of horizontal displacement versus depth profiles obtained with the shape arrays, inclinometer probes, and string potentiometers for the maximum load during the lateral load test.

4 CONCLUSIONS

Based on the results of the field tests and the analysis of the test results, the following conclusions can be drawn:

1. The shape accelerometer array system can provide reasonable displacement versus depth profiles for lateral pile load tests under static conditions, particularly at large displacements.
2. Results during this study indicate that the difference between inclinometer and shape array displacements was typically less than 2 mm of one another indicating that the measurement accuracy is comparable. This is consistent with the 1-2 mm precision expected from both devices. Additional comparison testing would be desirable.
3. In comparison with conventional inclinometer measurements, the shape array system offers the advantage of providing nearly continuous displacement data at each sensor location during a test. This eliminates long delays in the load test schedule and creep displacement which can adversely influence the pile head load-displacement curve.
4. Improved methods of coupling the array to the PVC pipe are needed to improve accuracy during static loading, particularly at small displacements, and to allow useful measurements during dynamic loading.

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