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

Suivi de déplacement c. profondeur en essais de charge latérale de pile avec des réseaux-accéléromètres-forme

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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 results from these tests 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 pipe which could hinder dynamic measurements.

RÉSUMÉ

Les réseaux-accélomètres-forme fournissent une alternative aux inclinomètres a sonde pour la détermination des profiles de déplacement horizontal contre profondeur, durant les essais de charge de pile latérale. Ces réseaux consistent, typiquement, des accéléromètres triaxiales de base puce, trouvées aux intervalles de 0,3m dans des tubes flexibles et imperméables. Ces réseaux-accélomètres-forme peuvent fournir de l'information continuelle du déplacement, de la vélocité, de l'accélération et de la rotation à chaque endroit ou se trouve un accéléromètre. À cause que les réseaux-accélomètres-forme 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 complète. Les résultats de ces essais indiquent que les réseaux-forme peuvent fournir la précision comparable à celle d'un inclinomètre. En ce qui concerne des chargements statiques, cependant, on a noté quelques problèmes par rapport à l'assemblage du réseau dans le tuyau, qui pourraient entraver les mesures dynamiques.

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

Mots clés : réseau-accélomètre-forme, essai de charge latérale, essai de charge de pile, instrumentation, déplacement

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 lateral pile analysis programs. 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. 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 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) (Danish et al, 2003, Measurand, 2009a). These arrays consist of tri-axial chip-based accelerometers located at 0.3 m intervals within joint-connected rigid segments covered by a waterproof covering (electrical "heat-shrink" tubing). The accelerometer arrays 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 deflection, a lateral load test was performed on a pile cap with and without backfill soil against the cap. Additional details regarding the testing are provided by Heiner et al. (2008). As shown in Figure 1, the pile cap was 3.35m x 4.57m in plan view and 1.77m high and provided a "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 concrete and were connected to the pile cap by a reinforcing cage consisting of six 25 mm (#8 US) bars which extended 3 m into each pile and 1.55 m into the pile cap. The vertical bars in the reinforcing cage were surrounding by a (13 mm (#4 US) bar spiral with a 150 mm pitch. Load was applied in to the pile cap by two 2700 kN hydraulic actuators in an incremental procedure to produce pile head deflection increments of about 6 to 13 mm.

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

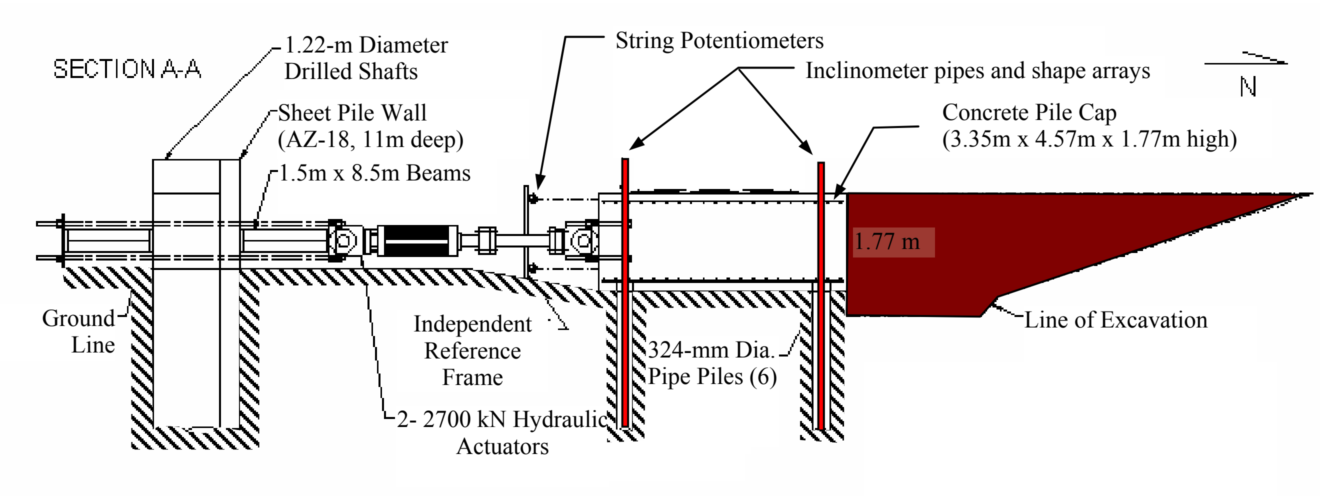

Figure 1 Geometry of pile cap and test piles along with

2.1 *String potentiometers*

During the lateral load test, deflection 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 string pots were located 0.078 m from the top of the pile cap while the bottom 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 12.6 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 pipe extended above the top of the pile cap about 0.6m. 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 0.6 m intervals using a SINCO Digitilt inclinometer probe with a portable data acquisition unit. Inclinometer readings were only obtained at the maximum load for the test so that the time delay for the inclinometer soundings would not interfere with the load-displacement curve. About 30 minutes were required to perform the inclinometer test. During this time, the pile cap displacement was held constant with the two hydraulic actuators. The limit of precision of 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 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 15.25 m below the top of the pile cap. The electrical conduit extended upward through the pile cap and terminated approximately 3 inches above the cap. The PVC pipe was also concreted into the pipe pile.

The accelerometer arrays, (SAAR: Shape Accelerometer Array Research model), are manufactured by Measurand, Inc. They contain MEMS (micromachined electromechanical 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.

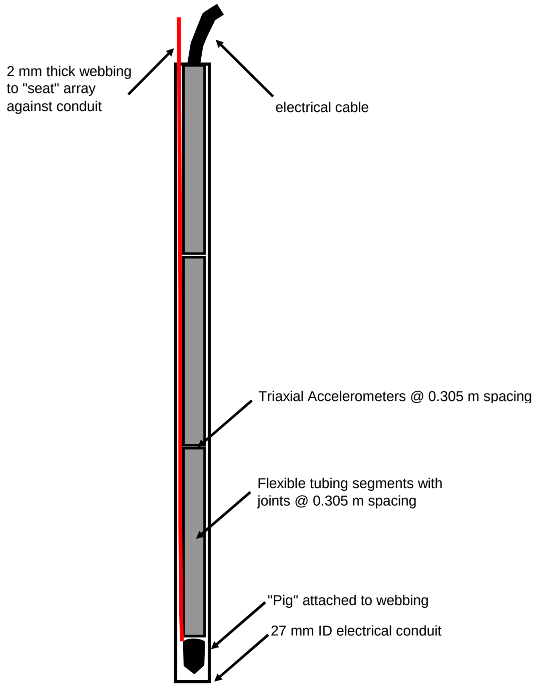

Figure 2. Schematic diagram showing arrangment of shape accelerometer array in 27 mm ID electrical conduit with webbing to seat the accelerometer against the conduit wall.

Each array was connected to 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 slowlychanging deformations, the accelerometers are used to measure tilt angles θ of each segment, according to the equation

$$\theta = \sin^{-1}(ka) \quad (1)$$

where k is a constant and a is the measured acceleration. In this respect the measurement is similar to that of conventional inclinometers; i.e. gravity-referenced tilt. However, azimuth in SAA is resolved by performing 3D joint-angle calculations using the joint construction (bend without twist) as a constraint (refB), 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 but cannot twist. 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 deflection increments to determine the change in deflection. Plots showing the deflection 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 difference 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. Because the displacements are all referenced to the bottom accelerometer, displacement is assumed to be zero at a depth of 7.32 m

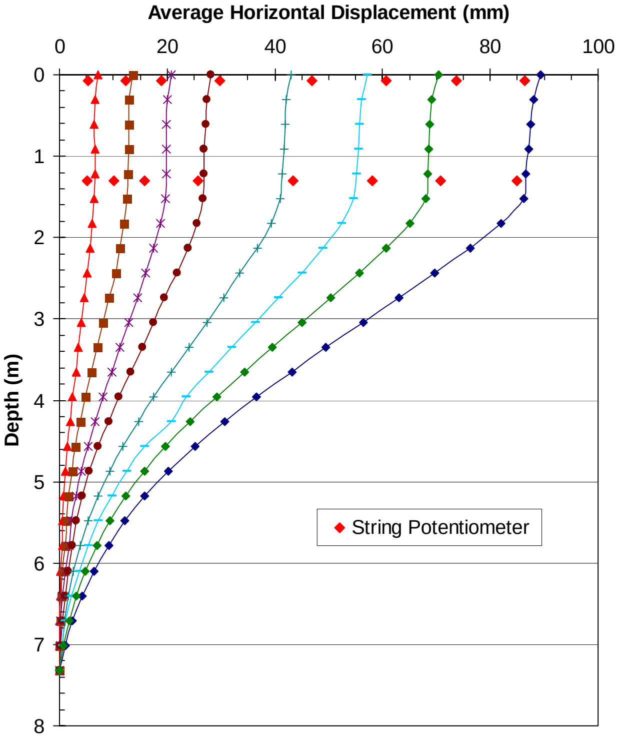

Figure 3. Horizontal displacement versus depth curves obtained with the north and south shape arrays at a number of load increments during the lateral load test.

A comparison of displacement vs. depth curves obtained from the North and South inclinometers and the shape arrays is provided for selected pile head displacement levels in Figure 4. In addition, the average displacements measured by the string potentiometers at two depths along the pile cap 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 reference for the south and north inclinometer readings was located ?? m and ?? m, respectively above the cap and the first inclinometer reading was 1.22 m below this reference point, 0.914 m was subtracted from south inclinometer depths, while 0.884 m was subtracted from the north. Both accelerometer arrays were placed such that the first sensor 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 and 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.

Displacement profiles from the inclinometer and shape arrays were generally in very good agreement suggesting that the two methods provide reasonably comparable accuracy. Typically, the difference in the measured displacement was less than ?? percent. However, comparisons of the pile head displacement from the shape array and a string potentiometer indicate that some inaccuracies occasionally developed due to poor contact between the shape array and the surrounding pipe. This problem also hindered the measurement of dynamic response.

Since early 2008 SAAs have been supplied with joints that swell significantly under axial compression, snugging them into 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 follow-on testing to characterize the effects of these modifications, which are claimed to be tighter, under static and dynamic loading.

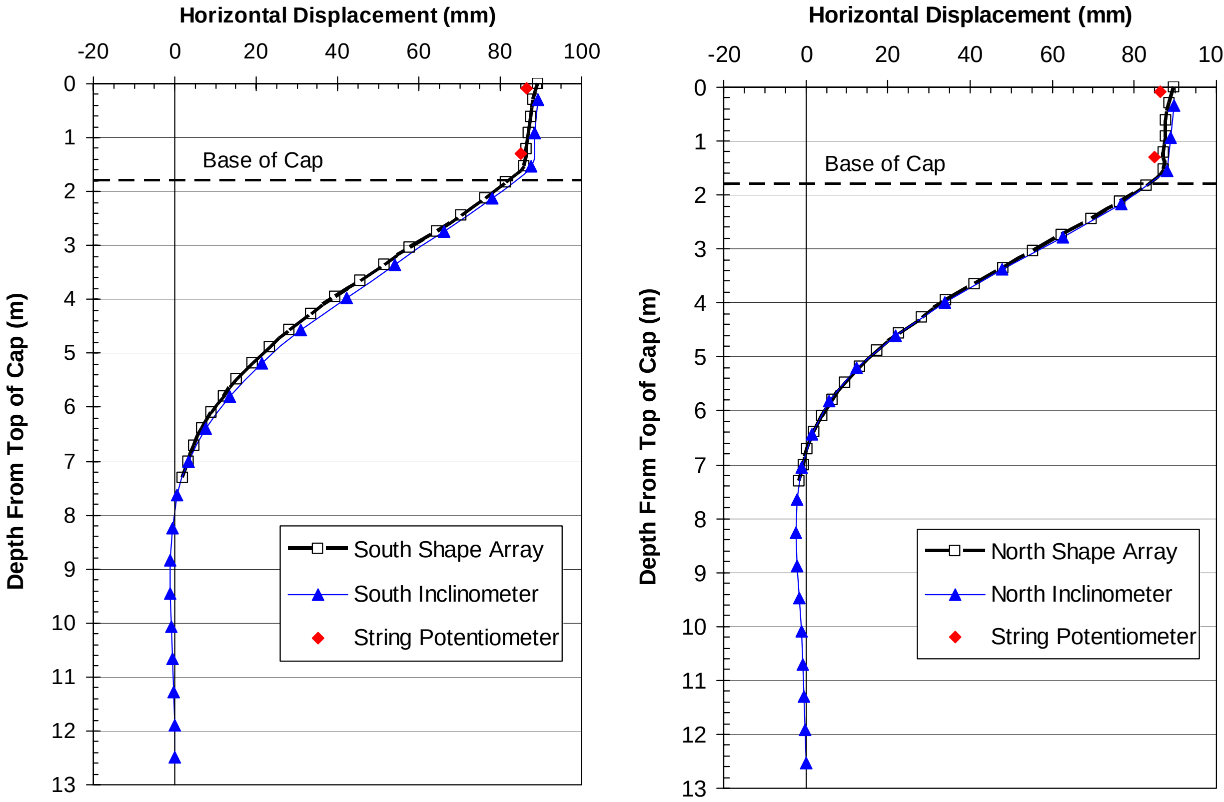

Figure 4. Comparison of horizontal displacement versus depth curves obtained with the shape arrays, inclinometer probes, and string potentiometers at the conclusion of the lateral load test.

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 depth profiles for lateral pile load tests under static conditions, particularly at large displacements.
2. 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 which can adversely influence the pile head load-displacement curve. Results during this study indicate that the difference between inclinometer and shape array displacements were 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.
3. Improved methods of coupling the array to the PVC pipe are needed to improve accuracy during static loading at small displacements and to allow useful measurements during dynamic loading.

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