Experimental and Numerical Evaluation of Plate Modified H-Piles Subjected to Monotonic and Cyclic Lateral Loading

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Paper prepared for presentation
at the Innovation in Geotechnical and Materials Engineering (PS) Session

at the 2020 TAC Conference & Exhibition

Acknowledgments: This project was completed in cooperation with Atlantic Industries Ltd., which provided the tested piles and partial funding for the research.

Introduction and Background

Sound walls (also known as noise barriers or acoustical barriers) are utilized for the mitigation of ambient noise due to traffic or industrial and commercial activities. Sound wall foundations are typically subject to a complex loading system of a small axial load combined with a large lateral load and bending moment produced by wind. Short drilled shafts are conventionally utilized to support sound walls due to their high lateral stiffness which counteracts these forces. However, foundation systems that can provide enhanced lateral capacity, cost-savings, and fast installation and utilization are desirable to further reduce cost and construction schedules of sound walls. Standard steel H piles offer efficient installation and immediate use due to forgoing the need to wait for concrete to cure; however, they lack the required lateral stiffness to adequately support sound walls.

Modifications to H-Pile piles were designed to potentially increase their lateral load-carrying capacity. A preliminary study on this novel pile concept was performed on a limited number of piles in silty clayey soils. The success of these tests provided a basis for a larger comprehensive study of piles performance in clayey till soils which is the primary focus of this paper. The results of additional tests on piles in sandy soils are also presented.

Plate Pile Description

Two similar concepts of novel piles were tested and compared to standard drilled shafts and plain steel H-piles: single plate piles and double plate piles. Structural steel W sections were fitted with steel plates welded to the pile flange for the portion of the pile immediately below the ground surface. Piles with only one plate are designated as single plate piles as shown in Figure 1 (a). The double plate piles were fitted with plates on either side of the outside flange of the pile as shown in Figure 1(b).The purpose of adding the plate is to increase the pile-soil contact area, which in turn increases the area of soil passively resisting the applied load.

The purpose of the double plate pile is to further enhance the pile's resistive capabilities which is based on the assumption that the second plate will give the pile more flexural rigidity, and the soil confined between the two plates will add additional shear resistance along the edge.

Pile Dimensions

The H-pile section selected for the main study was W200 x 36. The total length of the piles was 4850 mm, 3500 mm driven into the ground and 1350 mm of stickup. The stickup allowed loading at an eccentricity, simulating lateral load and moment occurring simultaneously to the pile head. With the loading mechanism in place, the eccentricity was 1.25 m. The plate dimensions were 950 x 420 x 9 mm (length, width, thickness) with a "stinger" extending 210 mm from the bottom of the plate to facilitate pile installation. The piles where installed to a depth of 3.5 m (so that the top of plate was at the ground surface). The dimensions of the piles are illustrated in Figure 1(c) and 1(d). Eight single plate piles and two double plate piles were installed. In addition, four unmodified piles of the same length, and two drilled shafts 711.2 mm (28") in diameter with a W200 x 36 section set in the center and a length of 3.5 m below ground and 1.35 m above ground were installed. The preliminary study performed by AIL was performed on four 4075 mm long (2800 mm embedment, 1275 mm stickup) W150 x 30 piles, two of which included a 950 x 420 x 9 mm plate.

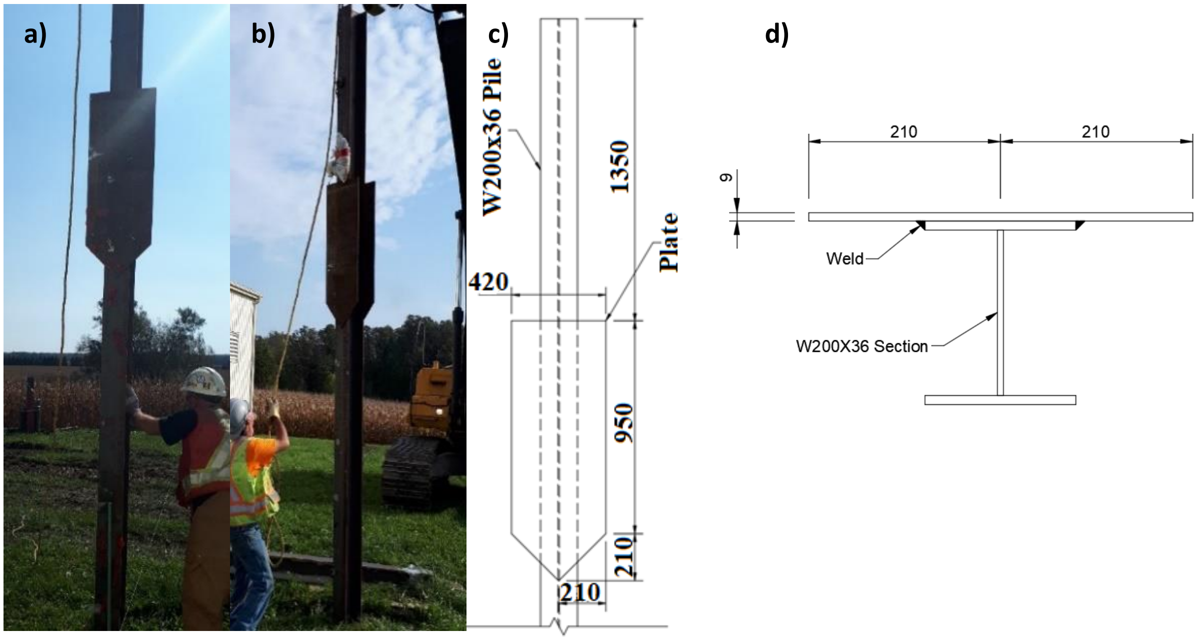

Fig- 1. a) Single plate pile, b) double plate pile, c) dimensions of tested modified H-Pile, d) cross-section of tested pile at plate location (from Mroz, 2019)

Soil Profile and Pile Installation

One borehole was drilled within the testing area to evaluate subsurface conditions. Four additional boreholes that were previously drilled near the site were reviewed to verify results of the most recent borehole. In general, the soil stratigraphy consists of topsoil from 0 to 0.3 m, very stiff grey clay silt till (undrained shear strength, S_u = 110 kPa) from 0.3 to 0.9 m, stiff grey clayey silt till (S_u = 60 kPa) from 0.9 to 2.0 m, very stiff brown clayey silt till (S_u = 125 kPa) from 2.0 to 4.7 m, and stiff grey sandy clayey silt below 4.7 m. The subsoil was noted to contain occasional cobbles or boulders. The preliminary tests by AIL were performed in medium dense sand.

The steel piles were installed via convention vibratory equipment. Cobbles were encountered when driving pile SP-03 and both double plate piles. Since all the double plate piles were poorly installed, the results of these tests could not be compared to other piles.

Testing Setup and Procedure

The piles were tested with monotonic and cyclic lateral loading according to ASTM D3966 / D3966M - 07 (2013) method 6.4: Load Applied by Hydraulic Jack(s) Acting Between Two Test Piles or Test Pile Groups. Figure 2 shows the configuration of the testing mechanism.

Monotonic Load Application

ASTM D3966 standard does not specify a test procedure for quick maintained load tests for laterally loaded piles. However, it allows engineers to adjust the specified test methods. The load was increased and held at regular intervals every 4 minutes until excessive deflection in the pile occurred or until the load could not be maintained.

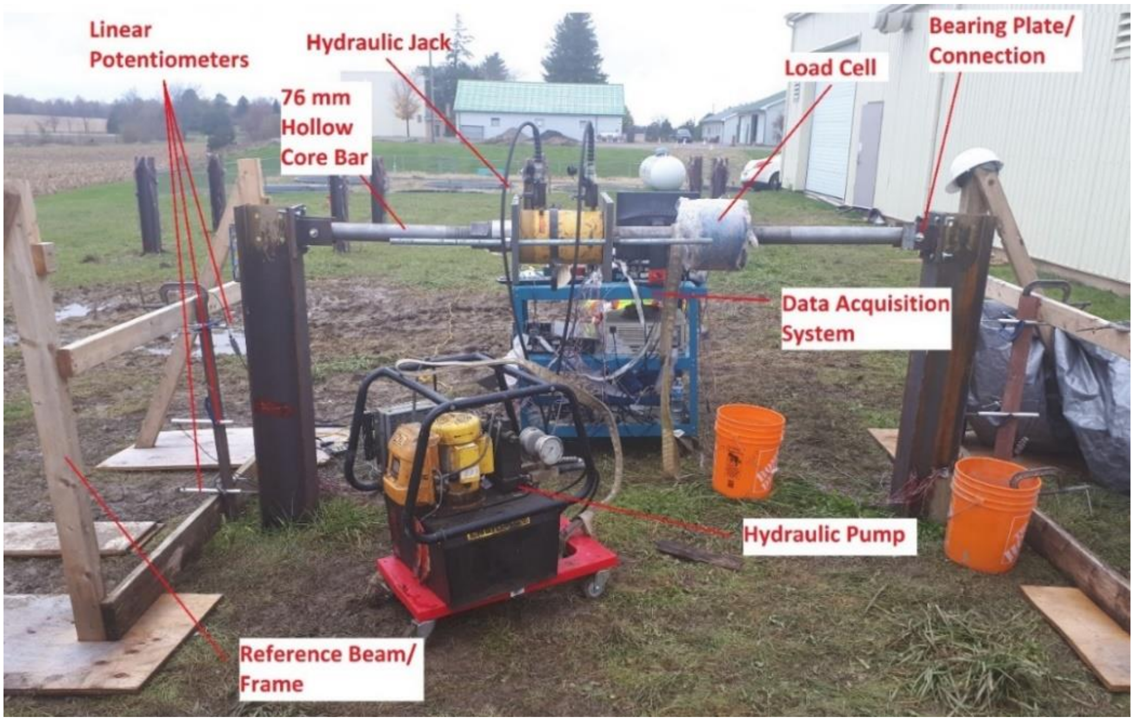

Fig- 2. Configuration of pile loading system (from Mroz, 2019)

Cyclic Load Application

The cyclic load testing procedure in ASTM D3966 was modified to suit the application of the piles. The ideal number of load cycles for wind applications typically ranges into the thousands, but the number of cycles per load increment was limited to 100 cycles of two-way loading for practical reasons when there was no further increase in pile displacement after 100 cycles The highest frequency of the first load cycle ranged from 0.022 to 0.025 Hz and decreased as the number of load cycles increased.

Monotonic Lateral Load Testing

The preliminary testing performed by AIL included monotonic lateral load tests on two unmodified piles (AIL-PP1&2) and two single plate piles (AIL-SP1&2) installed in medium density sand. The load-displacement curves for these tests are shown in Figure 3. The addition of the plate was measured to increase the lateral load capacity by an average of 59%.

For the main study, monotonic lateral load tests were performed on eight piles: four single plate piles (SP-01 to 04), two drilled shafts (DS-01 and 02), and two unmodified (plain) piles (PP-01 and 02). The load-displacement curves for these eight piles are shown in Figure 4, along with a summary of the lateral force required to produce 25 mm of ground level deflection for each pile (H_{25mm}) in Table 1. Due to the limited stroke of the hydraulic jack (the displacement at the loading point was significantly greater than at the ground surface due to eccentricity), the curves were extrapolated to estimate H_{25mm} assuming the rate of change in displacement over increasing increments of load followed the same pattern; this was confirmed with numerical modelling afterwards.

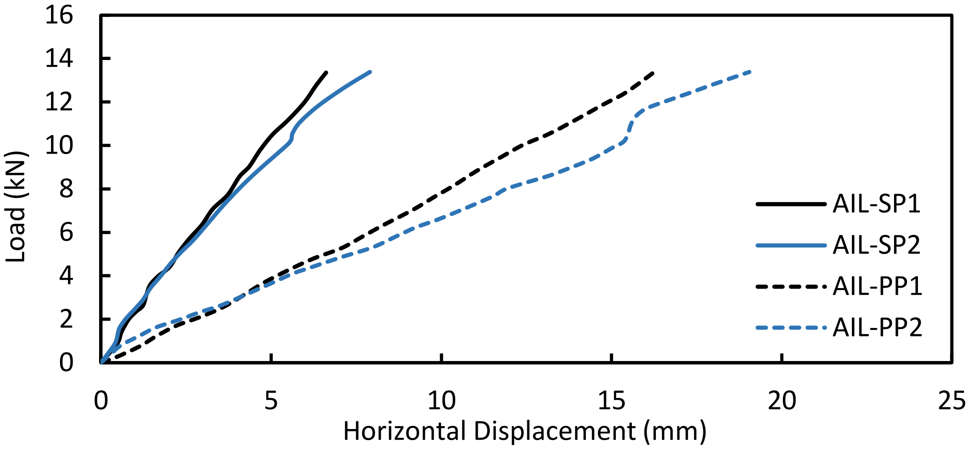

Fig- 3. Results of preliminary pile load tests performed by AIL in sand.

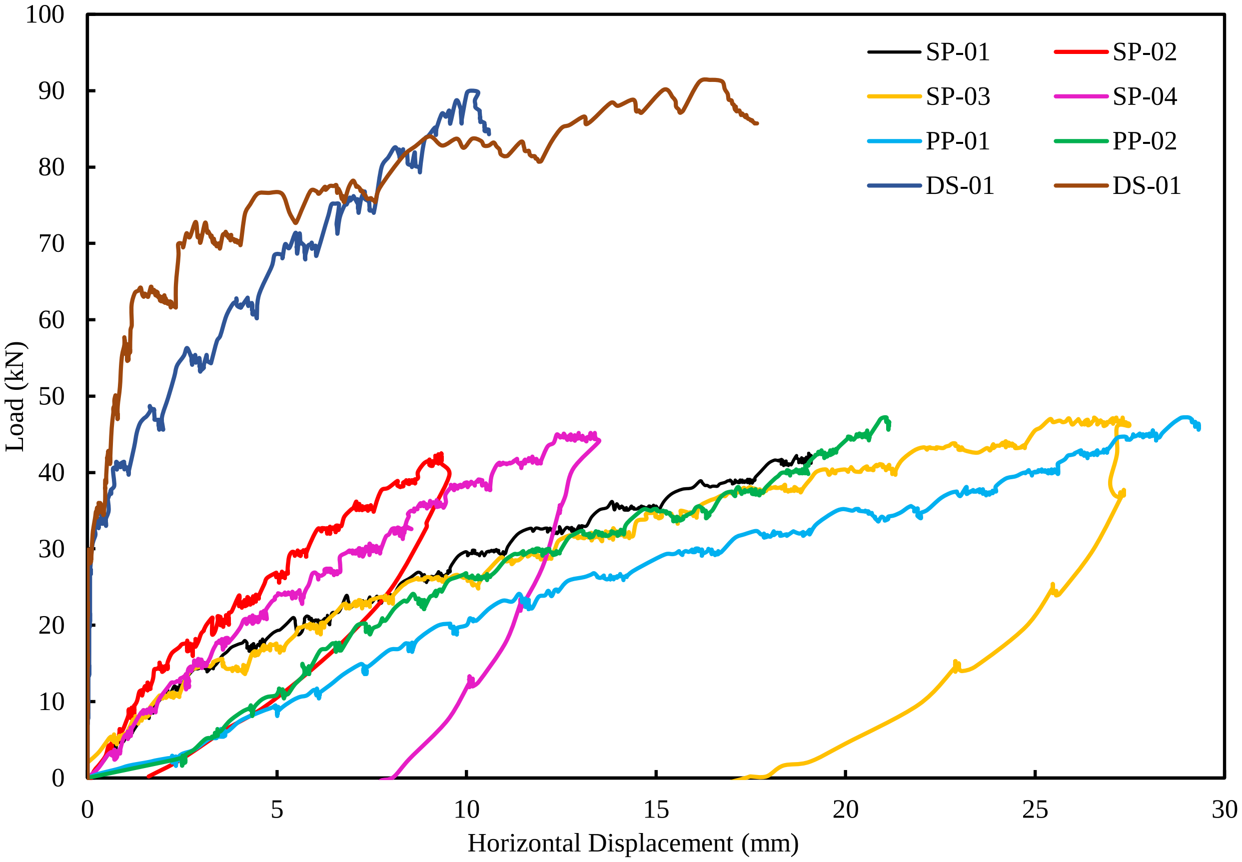

Fig- 4. Results of monotonic lateral load tests from main study.

Table 1. Lateral load required to reach 25 mm of ground level pile deflection (H_{25mm}) for each monotonic laterally loaded pile.

Pile I.D.	H_{25mm} (kN)
PP-01	45
PP-02	51
SP-01	53
SP-02	75
SP-03	46.5
SP-04	62
DS-01	145
DS-02	103

The average load at 25 mm of deflection for single plate piles was approximately 59.1 kN. The initial portion of the curve for all piles was very similar for the first 3-4 mm of deflection, but SP-01 and SP-03 began to deviate as the load increased. Possible explanations for this include variability in the installation quality (especially SP-03), natural variability in the soil, or the effect of uplift testing that was performed prior to lateral testing.

H_{25mm} for DS-01 and DS-02 were approximately 145 kN and 103 kN, respectively (average of 124 kN). It was observed that at low load levels ($P < 28$ kN), the displacement was too small to be detected by the linear potentiometers. The average lateral load capacity of these piles was about two times higher than the single plate piles, which was expected due to the significantly larger size of the drilled shafts. H_{25mm} was 45 and 51 kN for PP-01 and PP-02, respectively (average of 48 kN). The addition of the plate to H-Piles increased the lateral load capacity by approximately 23% on average.

Additional Testing of Piles in Sandy Soils

An additional set of tests was conducted on piles on a different site. The soil conditions consisted of deposits of sands overlying sand and gravel that were compact to dense. The SPT count ranged from 14 to greater than 50 blows per 0.3 m of penetration.

The piles consisted of W6x25 (W150 x 37) sections reinforced with plates on both sides of the flanges. The plates dimensions ranged from 500 mm x 1950 mm to 500 mm x 2450 mm.

The load-deflection curves are presented in Figure 5. Pile 1 had the smaller additional plates and pile 4 had the largest plates. The maximum pile load tests ranged between 80 kN to 140 kN. The ultimate loads sustained by the piles exceed the factored horizontal loads for a typical 5 m high sound wall for a reference wind pressure of 0.46 kPa.

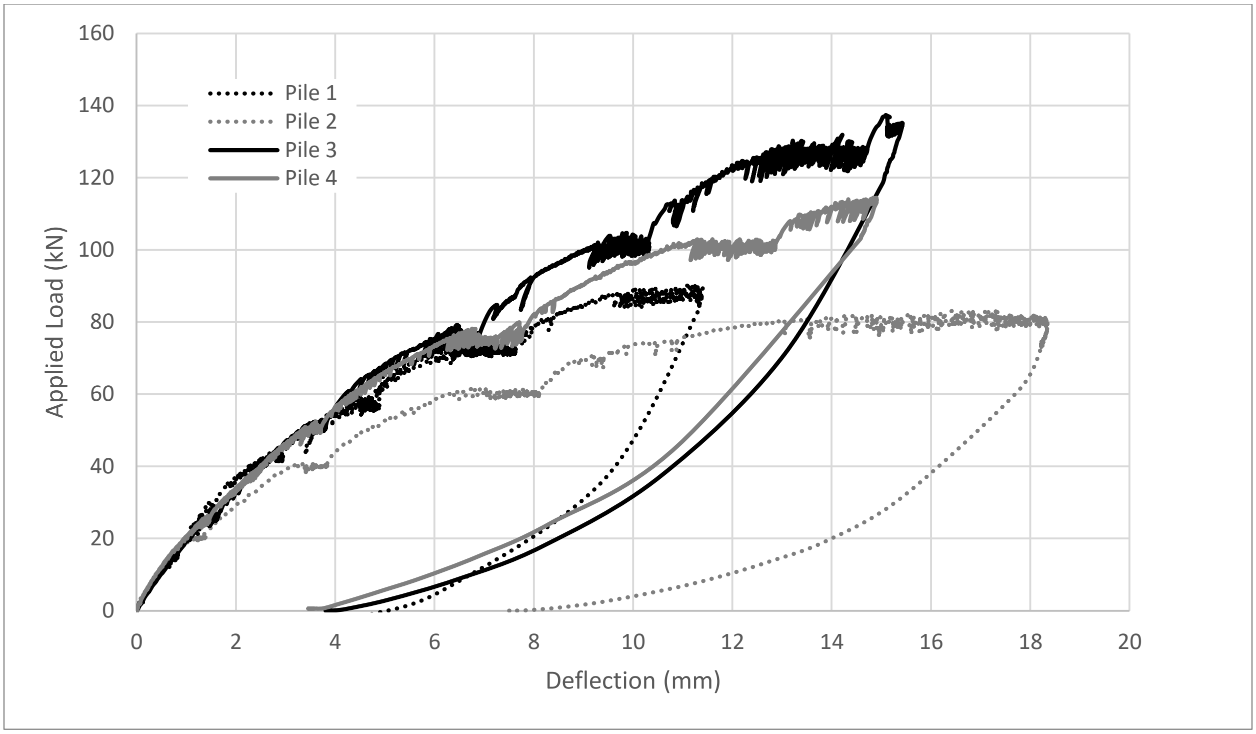

Fig 5. Results for additional monotonic lateral load tests for additional testing in sand.

Numerical Modelling of Monotonic Laterally Loaded Piles

To better understand the performance of plate modified H-Piles, a numerical model was calibrated and validated using the field test data and simulating the pile with different plate dimensions or in a variety of soil conditions; computer software commonly used in industry was used for this purpose. The numerical model was first calibrated using load-displacement curves and bending moment distribution data from the static lateral load tests on single plate piles. Once the model was calibrated, it was validated by predicting the behaviour of the unmodified piles tested in clayey silt till and the preliminary piles tested in sand by AIL.

Soil and Pile Properties

The soil layers were modelled as stiff clay above the water table. The soil modulus, k, was estimated by Equation 1 (Salgado, 2008):

$$k = \frac{9S_u}{5\varepsilon_{50}B} \qquad [1]$$

where ε_{50} is the axial strain at one half of the soil's final shear strength, and B is the pile width. ε_{50} was estimated using correlations with S_u which are provided by Liang (2002). Table 2 shows the selected soil properties obtained for the calibrated model.

Table 2. Soil parameters for lateral load analyses.

Depth(m)	Unit Wt. (kN/m^3)	S_u (kPa)	k (MN/m^3)	ε50
0 – 0.9	19	110	100	0.005
0.9 – 2.0	21	60	95	0.007
2.0+	21.5	125	271	0.005

The piles were modelled as linear elastic sections since the piles were expected to deflect within the elastic region with no yielding of steel. The plated portion of the pile was modelled using its geometrical properties: second moment of inertia (I_x), cross-sectional area, and width, to match the actual pile section physical properties. The unmodified portion of the pile was modelled as a W-section bending about the strong axis.

Model Calibration

The comparison of the results obtained from the calibrated model with experimental data is shown in Figure 6, which shows an excellent match. Only SP-02 and SP-04 were used in the analysis because SP-01 and SP-03 experienced lower capacities due to installation issues or possible variability in soil properties. Because the model compared very well with the field data, this confirms that the method of selecting soil parameters and modelling the pile itself accurately simulate the actual piles that were tested.

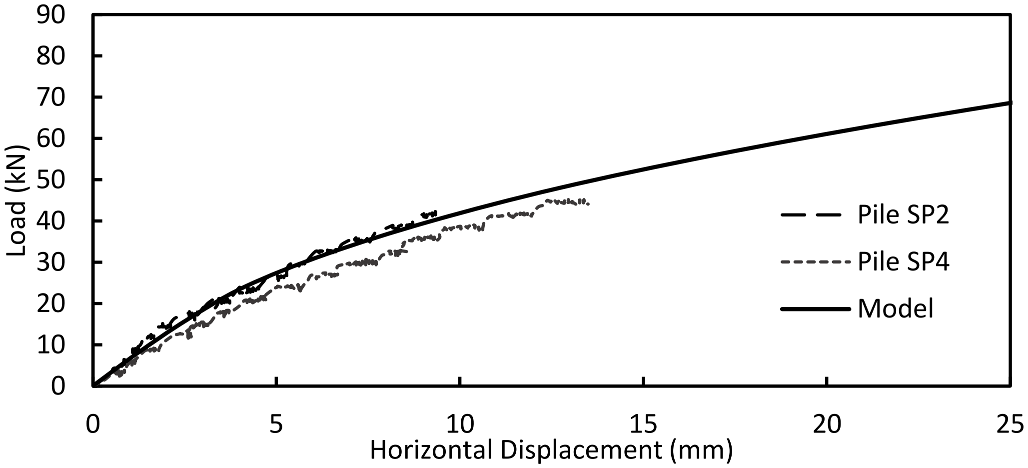

Fig- 6. Comparison of numerical model with field data.

Model Validation

The calibrated model needed to be validated against additional sets of data to ensure the method of soil and pile modelling can reliably predict the load carrying capacity of an actual pile. The model was first validated with the unmodified H piles that were tested in the exact same manner as the single plate piles. A comparison between the second model and field data is shown in Figure 7. A second validation was performed by modelling the response of single plate piles tested by AIL in the preliminary testing phase. The soil profile was comprised of medium dense sandy soil above the groundwater level with an assumed friction angle of 35° and unit weight of 19 kN/m³, the value for k was inputted as 24430 kN/m³ which was correlated from Liang (2002). The comparison between the calculated and measured responses is shown in Figure 8. The second model cannot be a direct validation of the original model since a different soil profile was considered. However, the remainder of the input parameters were consistent with the first model and therefore a successful match with field data does validate the modelling procedures to be appropriate for modelling the modified pile design.

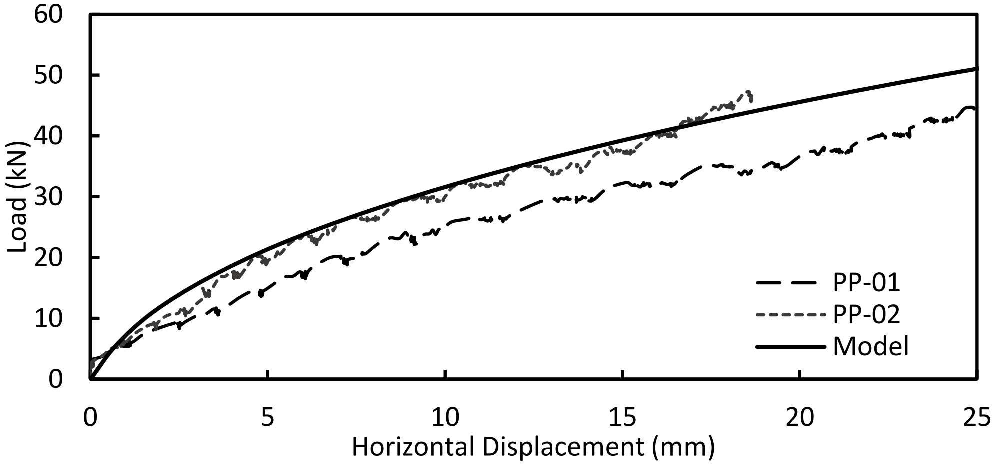

Fig- 7. Validation of numerical model with unmodified H-Piles installed in clayey silt till.

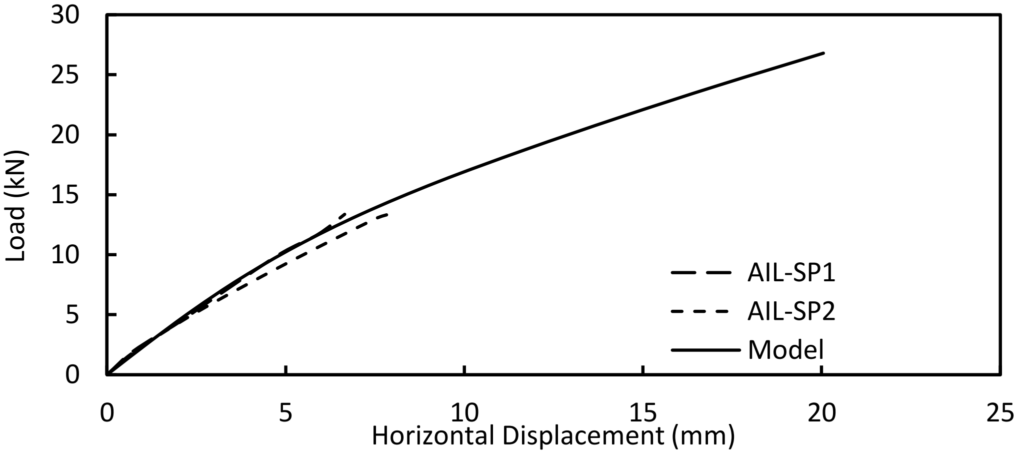

Fig- 8. Validation of numerical model with single plate piles installed in sand and tested by AIL.

As shown in Figures 7 and 8, the results obtained numerical modelling are in excellent agreement with the actual load-displacement curve for both cases. This indicates that the proposed method for modeling the modified pile configuration is suitable for simulating the lateral response of the novel pile and therefore is expected to provide realistic results for the parametric study.

Parametric Study on Single Plate Piles

A parametric study was conducted to evaluate the effects of the geometrical properties of the plate (plate length and width) on the lateral capacity of the pile. The plate widths selected for the analysis were 315 mm, 525 mm, and 630 mm (-25%, +25% and +50% of the original width), all at a constant plate length of 950 mm. The plate lengths selected for the analysis were 712.5 mm, 1188 mm, and 1425 mm (-25%, +25% and +50% of the original length), all at a constant plate width of 420 mm. The parametric study considered a soil profile comprised of clay layers with different levels of strength, and a soil profile comprising sand layers with different levels of compactness. Note that all comparisons are made in terms of the lateral force required to induce a 25 mm deflection of the pile at ground level (H_{25mm}). The total pile length below ground remained at 3.5 m for all cases considered in the parametric study.

Single Plate Piles in Cohesive Soil

A homogenous clay soil profile was modelled at S_u = 25 kPa, 50 kPa, and 100 kPa, which correspond to soft, firm, and stiff clay, respectively. The soil modulus parameter, k, was estimated using Eq. 1 (Salgado, 2008). The soil model selected for generating the p-y curves was the modified stiff clay without free water model, since the water table was assumed to be below the pile toe. A summary of the numerical models considering varying plate dimensions in three levels of clay stiffness is shown in Table 3. Each model was compared at H_{25mm} (each soil strength modelled considers the original plate dimensions and six other dimension configurations).

The results of the parametric study in clay soils show that increasing the plate width is more effective than increasing plate length for increasing the lateral capacity of plated piles. This is expected since the lateral capacity of piles is typically governed by the portion of the pile near the ground surface.

Single Plate Piles in Cohesionless Soil

A summary of the effect of varying plate dimensions in three densities of sand with friction angles equal to 30°, 35°, and 40° sand is also shown in Table 3. The performance of each case is again compared at H_{25mm}.

The results of the parametric study in sand shows that increasing the plate width is more effective than increasing plate length for improving the lateral capacity of a plated pile, however the difference is smaller compared to clay. It was also observed that as the strength of the sand increases, the difference between increasing plate width and plate length becomes smaller. At $\phi = 40°$, changing the plate width and length by the same percentages yields a similar change in capacity.

Table 3. Summary of parametric study considering single plate piles with varied plate dimensions and soil conditions.

Case	Plate Length (mm)	Plate Width (mm)	S_u (kPa)	H_{25mm} (kN)	ϕ (°)	H_{25mm} (kN)
Original Dimensions	**950**	**420**	**25**	**19.5**	**30**	**33**
-25% Plate Width	950	315 (-25%)	25	18	30	29.5
+25% Plate Width	950	525 (+25%)	25	20.75	30	34.75
+50% Plate Width	950	620 (+50%)	25	21.5	30	36
-25% Plate Length	712.5 (-25%)	420	25	19	30	29.75
+25% Plate Length	1188 (+25%)	420	25	20	30	34.25
+50% Plate Length	1425 (+50%)	420	25	20.5	30	35.5
Original Dimensions	**950**	**420**	**50**	**38**	**35**	**46.5**
-25% Plate Width	950	315 (-25%)	50	34.5	35	43.5
+25% Plate Width	950	525 (+25%)	50	40.5	35	49
+50% Plate Width	950	620 (+50%)	50	43	35	51
-25% Plate Length	712.5 (-25%)	420	50	36.75	35	42.5
+25% Plate Length	1188 (+25%)	420	50	39	35	48.5
+50% Plate Length	1425 (+50%)	420	50	40	35	50.25
Original Dimensions	**950**	**420**	**100**	**67**	**40**	**60**
-25% Plate Width	950	315 (-25%)	100	60	40	55
+25% Plate Width	950	525 (+25%)	100	71	40	64
+50% Plate Width	950	620 (+50%)	100	75.5	40	66
-25% Plate Length	712.5 (-25%)	420	100	63.5	40	54.75
+25% Plate Length	1188 (+25%)	420	100	70	40	63.5
+50% Plate Length	1425 (+50%)	420	100	73	40	66

Cyclic Lateral Load Test Results

Cyclic lateral load testing was performed on the eight piles: PP-03, PP-04, SP-05 to SP-08, DP-01, and DP-02. The double plate piles were subjected to cyclic loading to evaluate whether the addition of the second plate leads to better performance under cyclic loads by reducing the degradation of soil strength or gapping at the pile-soil interface (monotonic performance is expected to be approximately the same). The load-displacement curves for PP-03 and PP-04 are shown in Figure 9. Note that the data was reduced for all figures to show only every 10th cycle. These piles were subjected to 100 cycles of two-way loading at 15 kN. The curves remained in the elastic region for approximately the first 5 kN. As the load increased, they exhibited non-linear behaviour. The amount of displacement gradually increased at the maximum load as the number of cycles increased. The single plate piles, SP-05 and SP-06, had similar load-displacement curves to the plain piles as shown in Figure 9, both in terms of stiffness and change in horizontal displacement over 100 cycles. This indicates that adding the plate had little effect on the performance of H-piles subject to small cyclic lateral loads. The single plate piles were also subjected to 70 cycles of loading at 24 kN of force immediately after the first 100 cycles (cycles reduced to 70 due to lack of stroke availability on jack). The load displacement curve showed a similar parabolic shape at 24 kN compared to the curve at 15 kN.

The load-displacement curves for SP-07 and SP-08 are shown in Figure 9. The curves exhibit identical behaviour to SP-05 and 06 in the positive loading direction (push). The change in displacement over 100 cycles was significantly higher in the negative (pull) direction for both piles. This has been observed in other cyclic lateral load tests and is caused by the creation of a gap behind the pile on the opposite direction of loading. When reversing the load in the opposite direction, this gap must first be closed before the soil provides resistance, thus leading to higher displacements in one direction (Abd Elaziz, 2012; El Sharnouby, 2012).

The applied loads were reduced for piles DP-01 and DP-02 to prevent exceeding the stroke limit of the hydraulic jack. Large gaps were identified between the pile and the soil which were created during installation. These gaps would have to be closed during loading before the pile could provide lateral resistance; thus, larger displacements were expected even at low loads. An attempt was made to close the gaps by filling them with drill cuttings from the drilled shaft installation. However, the soil could not be compacted very well manually and therefore did little to remediate the effect of the gap left from the installation. The load-displacement curves are presented Figure 9. The load cell reading displayed large fluctuations (+/- 2kN) during the test. The source of the noise could not be established, and the test was carried out under the current conditions. The second set of load cycles were performed at 15 kN for 50 cycles, at which point the stroke limit was exceeded. Due to the poor installation of some of these piles which affected the results, the expected advantage of adding a second plate could not be established. However, the general shape of the curve was similar to that of the single plate piles. The curve was linear up to approximately 5 kN, at which point the response became nonlinear as the load increased.

The effect of cyclic lateral loading on the piles was evaluated in terms of its lateral stiffness, which can be calculated using Equation 2:

$$k_L = \frac{P_{max} - P_{min}}{y_{max} - y_{min}} \qquad [2]$$

where P_{max} and P_{min} are the maximum and minimum applied load at the specific cycle, and y_{max} and y_{min} are the corresponding deflections to the maximum and minimum applied loads at the specific cycle. To represent the effect of cyclic loading on the tested piles, the ratio of the stiffness (k_L) at increasing cycles to the stiffness of the initial cycle (k_{LO}) is shown for each pile in Figure 10.

The ratio of k_L/k_{LO} stabilizes at a consistent value within 100 cycles of lateral load for all piles. PP-03 and 04 experienced the least degradation, with a k_L/k_{LO} ratio levelling off at 0.70 to 0.86. The ratio was lower for single plate piles SP-05 and 06 with value from 0.68 to 0.74, which is approximately 9% lower than plain piles. The ratio at 100 cycles was significantly lower for the remaining four piles, with values of 0.47, 0.40, 0.64, and 0.41 for SP-07, SP-08, DP-01, and DP-02, respectively. The initial stiffness for these four piles is lower than the plain pile and single plate piles as well. These results clearly demonstrate the need for careful installation of piles, as less than ideal installation leads to a severely reduced pile performance. For the second set of cyclic lateral loading on piles SP-01, SP-02, DP-01, and DP-02, it was observed that the stiffness degradation follows a very similar trend to that of the lower load cycles. The reduction in stiffness between the first cycle of the first load increment and the first cycle of the second load increment is 28% and 18% for SP-05 and SP-06, and 31% and 54% for DP-01 and DP-02, respectively. The reduction in stiffness between load cycles is larger for double plate piles, which is attributed to the installation quality. Because an equivalent assessment could not be performed between single and double plate piles, the effectiveness of adding the second plate could not be properly evaluated and is therefore inconclusive.

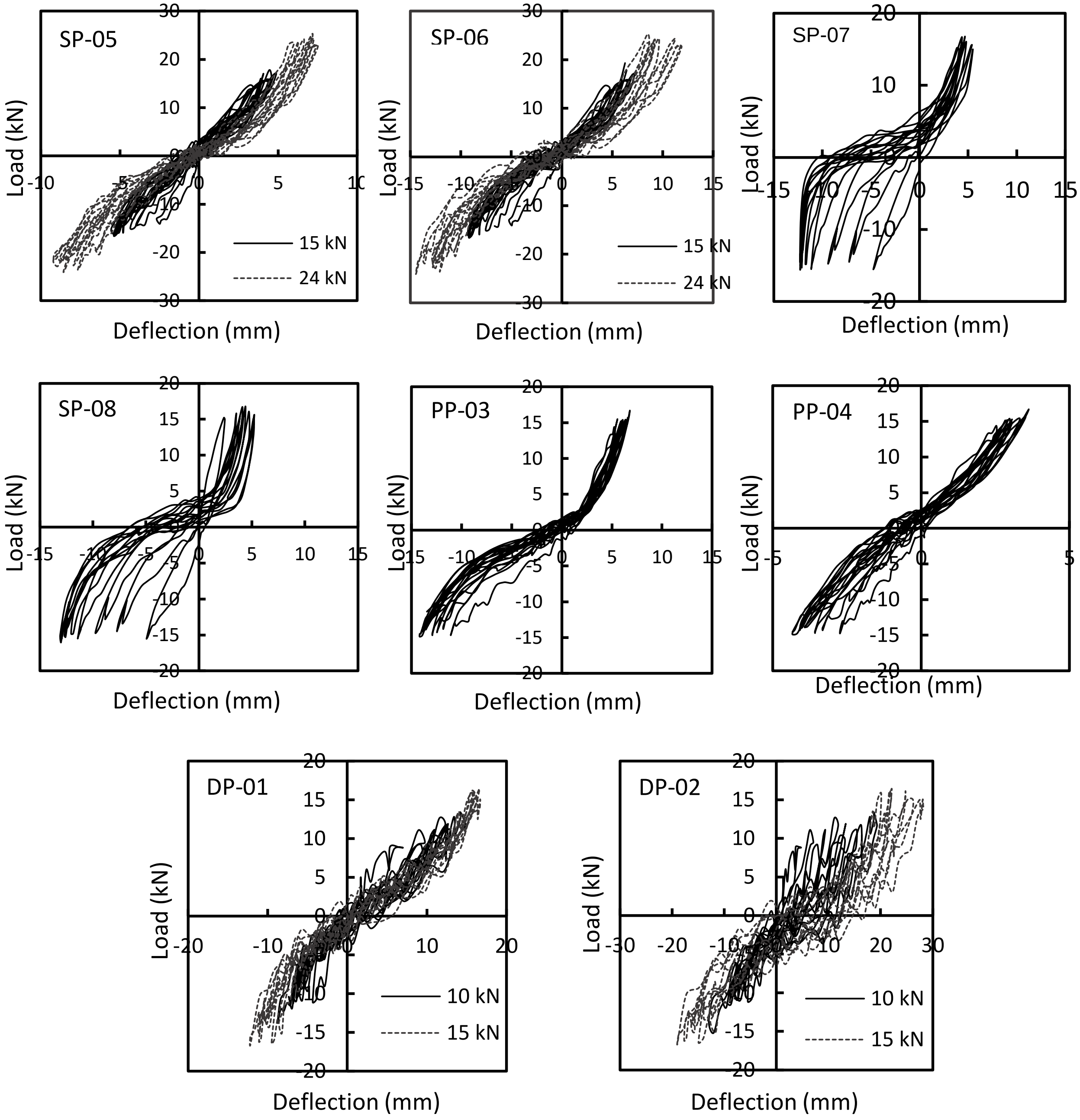

Fig- 9. Results of cyclic lateral load tests.

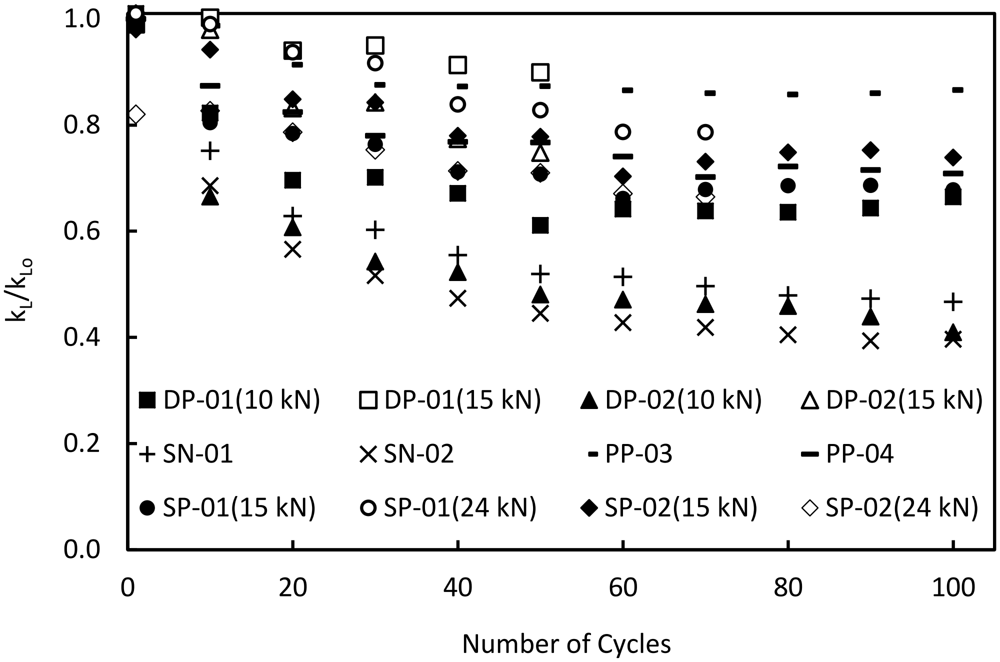

Fig- 10. Degradation of lateral stiffness with an increasing number of cyclic loads.

GSNAP Model of Cyclic Laterally Loaded Single Plate Piles

The performance of single plate piles subjected to cyclic lateral loading was further analyzed with numerical modelling by calibrating a model with the existing data; GSNAP (Geo-Structural Nonlinear Analysis Program) was selected for this purpose. GSNAP incorporates a generalized dynamic beam on nonlinear Winkler foundation (BNWF) soil model and considers key aspects of soil-structure interaction: (El Naggar and Heidari, 2018). GSNAP can simulate the behaviour of piles subjected to many more cycles of lateral loading cycles in a short period of time. Once the model was calibrated with the field results, a limited parametric study was performed with the model considering higher loads and a large number of load cycles to better characterize the novel pile's performance against repeated loading.

Model Calibration

The values of soil undrained shear strength, S_u, soil modulus, k, and ε_{50} used in the GSNAP analysis were the same as the monotonic lateral analysis as shown in Table 2. GSNAP requires five additional inputs which dictate the pile's response when subject to cyclic lateral loading: stiffness and strength degradation factor, stiffness and strength curve shape parameter, and gapping parameter. The range of typical values for clay soils along with the selected inputs for the calibrated model are presented in Table 3. The stiffness and strength degradation factors were > 1 since the stiffness degradation decreased as the number of load cycles increased. The selected gapping parameter was 0.14 which was based on the observation that the soil remained mostly compressed after reversing the load on the pile. The meaning of these parameters is further discussed in Allotey and El Naggar (2008) and Heidari et al. (2014).

The cyclic loading pattern applied to the pile was 100 cycles of 15 kN load follow by 70 cycles of 24 kN load. The model output is compared to the field data in Figure 11(a). In general, the model predicted the pile's response to cyclic lateral loading well. The deflection at the second load cycles match, and the shape of the hysteretic loop are captured in the model. However, there are some discrepancies between the model and field data. The model predicts a stiffer response for the first set of cycles, which is more evident in the positive loading direction. The model also predicts a stiffer response for the second set of cycles in the negative loading direction. However, it is not possible to get a perfect match in both directions due to an uneven stiffness in the tested pile.

Table 4. GSNAP soil parameter range and selection for model.

Parameter	Range	Calibrated Value
Stiffness degradation Factor	>1 hardening <1 degradation	1.45
Strength degradation factor	>1 hardening <1 degradation	1.45
Stiffness curve shape parameter	1.5 – 2.5	1.5
Strength curve shape parameter	0.75 – 0.95	0.75
Gapping Parameter	0 (pure gap) – 1 (entirely confined	0.14

Lateral Cyclic Loading Parametric Study

After calibration, the model was analyzed simulating a load of 26.7 kN and 53.4 kN for 100 cycles each in succession. The results of the simulation are shown in Figure 11(b). The single plate pile experiences 9 mm of deflection at the end of the first set of cycles. The pile deflects less than 25 mm for the first three cycles at 53.36 kN but deflects over 25 mm for subsequent load cycles.

A third analysis was performed considering the effect of 26.7 kN of wind load applied for many cycles to better analyze the pile's performance at the design load. The same model was run with a load of 26.7 kN applied to the pile for 1000 cycles and the results are shown in Figure 11(c). After 1000 cycles, the maximum deflection of the pile was estimated to be less than 10 mm. This indicates that the pile performs well under lower repetitive loading and the stiffness does not degrade excessively after repeated loading for long periods of time.

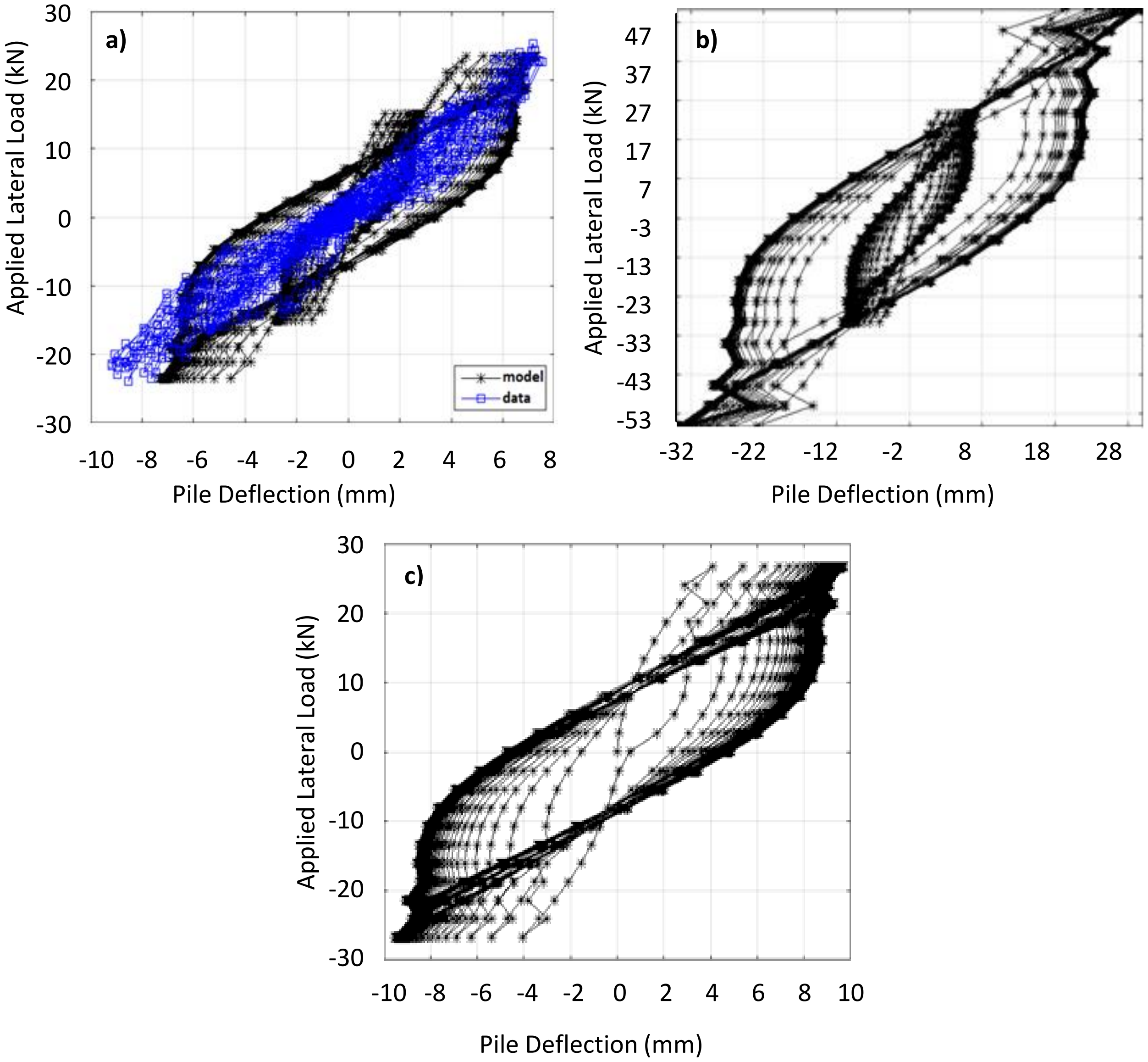

Fig- 11. a) Calibrated GNSAP of a single plate pile subjected to cyclic lateral load, b) model simulating single plate pile subject to 26.7 kN and 53.4 kN for 100 cycles each, c) single plate pile subjected to 1000 cycles of 26.7 kN.

Conclusions

The addition of the plate increased the lateral capacity of the piles by approximately 22% in clayey till and 59% in sand. The drilled shafts lateral capacity was approximately twice the magnitude of the single plate piles.

The installation quality of the pile had a direct effect on its performance when subjected to monotonic and cyclic lateral loads. Piles with an unideal installation typically suffered from reduced lateral capacities and a higher degree of shakedown.

The plate width generally has a greater influence on a pile's lateral capacity compared to plate length, especially in cohesive soils. For cohesionless soils, the different in increase/decrease between plate width and length equalizes as the soil density increases.

The lateral stiffness of all tested piles stabilized within 100 cycles of low-magnitude lateral load. The ratio of kL/kLo was approximately 9% lower for single plate piles compared to unmodified H-piles at the 100th cycle indicating the novel piles experience a minor increase in degradation over unmodified piles.

The limited parametric study using GSNAP indicated that the maximum deflection of a single plate pile will not exceed 10 mm regardless of how many cycles of the design load is applied to the pile. However, the pile was estimated to have excessive deflection after only a few cycles at two times the design load

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