Research Paper

Axial and Lateral Load Test Performance of Steel Fin Piles

Jonathan F. Hubler[1]*, Anthony LaRegina[2], Hannah Iezzoni[3], Sarah McInnes[4], and Alex Ryberg[5]

Abstract: Steel fin piles may offer increased resistance to lateral and torsional loading; however, there is limited experimental data in the literature for steel fin pile performance. This study evaluates the performance of steel fin piles through field load testing and numerical analysis. Axial and lateral load tests were conducted on two fin piles with a diameter of 273 mm and a length of 3.73 m to evaluate their performance and compare with modeling in LPILE. The lateral tests were conducted with the load applied in two orientations, either in line with the fins or rotated 45 degrees to the fins to assess any difference in performance in the fin orientation to the direction of loading. The effect of the direction of loading compared to the fin orientation proved to be small but existent, with the fin pile displacing less from the lateral load when loaded in between the fins. Additionally, the modeled deflected shape of the fin piles in the lateral test closely matched the observed deflected shape recorded by the shape array instrumentation. The models in LPILE provided results consistent with field observations in the lateral testing, bolstering the viability of fin piles as a prospective replacement to conventional deep foundations when lateral loading governs design.

Keywords: load testing, fin piles, shape array, modeling

Introduction

Steel fin piles are modified steel pipe piles that provide enhanced lateral and torsional resistance. These fin piles feature additional straight steel fins that are added to the circumference of a steel pipe pile and extend along some length of the pile, usually in the upper portion of the pile near the ground surface, as shown in Figure 1. These piles differ from spin fin piles, which have angled fins located at the bottom of the pile (Chernauskas *et al*., 2011). The fin piles in this study have been referred to as both wing piles (Durkhop and Grabe, 2008) and fin piles (Pei and Qui, 2022) in the literature. In this study they will be referred to as fin piles. The fins can increase both the lateral and vertical capacity of the pile compared to a pipe pile of the same diameter, resulting in potentially shorter piles with smaller diameters. The versatility of the fin pile has led to their emergence as an alternative in many situations: marine and coastal applications, alternatives to larger diameter piles, solar field foundations, highway lighting, and possible temporary structures (Lutenegger, 2012; McInnes *et al*., 2022). Piles in these applications can be subject to large lateral loads which the fins may be designed to support. Additionally, due to the increased capacity provided from the affixed fins, the length of a fin pile can be reduced greatly in comparison to that of a regular steel pipe pile. This reduction in material can result in potential reduced project costs with improved performance due to the increased lateral and torsional resistance of the fin pile as well as quick installation with vibratory hammers (Chernauskas *et al*., 2011). Despite these advantages, steel fin piles are currently a novel technology and data for field load test performance is sparse.

There are only a few studies that have evaluated the performance of steel fin pile foundations. Many of these studies simulate the performance of fin piles through numerical analysis (Nasr, 2014; Babu and Viswanadham 2019; Pei *et al*. 2020; Pei and Qui, 2022). Pei and Qui (2022) studied the performance of laterally loaded steel fin pile foundations similar to those tested in this study in Abaqus to evaluate the added value of the affixed fins. The study showed that with respect to lateral resistance, steel fin pile foundations greatly outperformed unfinned steel pipe piles. It was found that the improvement in load efficiency decreases as soil relative density increases, and finned piles are capable of reducing maximum bending moment along the pile length. Another numerical study by Babu and Viswanadham (2019), investigated steel fin piles that have fins nearest to the pile top. These piles were similar to the steel fin piles modeled by Pei and Qui (2022); however, Babu and Viswanadham (2019) examined the effects of fin orientation and sand relative density.

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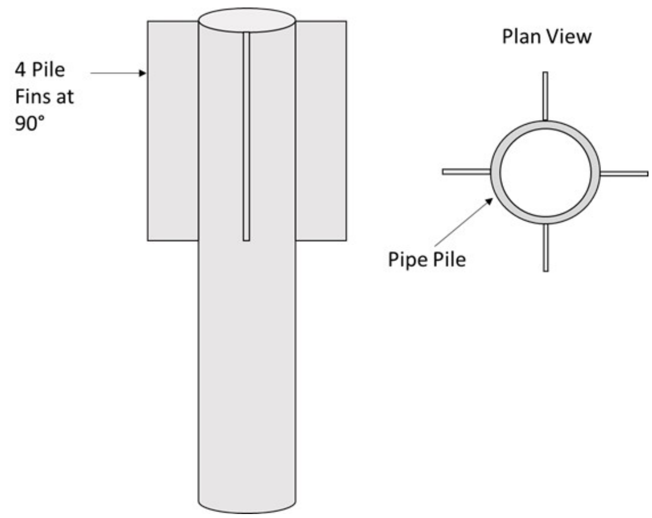

Figure 1. Example of Steel Fin Pile used in this Study

Babu and Viswanadham (2019) observed that the orientation of the fins with respect to the direction of loading has minimal effects on the lateral displacement of the fin pile models. Additionally, Babu and Viswanadham (2019) modeled the location of the fins at various depths along the pile shafts. It was concluded that the highest lateral resistance benefit was achieved with fins beginning near the pile top.

Outside of numerical modeling, fin pile studies have been conducted experimentally at the laboratory scale (Duhrkop and Grabe, 2008; Duhrkop *et al*., 2010; Bienen *et al*., 2012; Nasr, 2014; Assam, 2017). Durkhop and Grabe (2008) performed laboratory testing on wing piles and found that lateral displacements were decreased by 65% compared to non-wing alternatives. Bienen *et al*. (2012) tested monotube piles with wing attachments located near the pile head, which closely resemble the fin piles as described in this work. Results of the study showed a decrease in pile head displacement by 50% for the wing pile. Nasr (2014) performed small-scale model tests on fin piles and found that the fin geometry governed lateral load performance. The lateral resistance was found to increase with increase in fin length until the fin length was equal to 0.40 of the pile length. Few studies (Reinert and Newman, 2002; Lutenegger, 2012; Murphy *et al*. 2016) have performed actual field scale load testing of fin (or wing) piles. Reinert and Newman (2002) performed lateral load testing on two fin piles, one was 2 m in length and the other was 3.4 m in length. Lutenegger (2012) performed fifteen axial uplift tests on three different diameter pipe piles (some with fins) that were 2.4 m in length and found that fin piles had a higher axial capacity than plain pipe piles. Murphy *et al*. (2016) found lateral displacement to decrease by 45 – 60% for wing piles and that wing pile efficiency was greatest at low load levels; however, the piles in this study were only 2 m in length.

As steel fin pile foundations are relatively new compared with conventional deep foundation alternatives, there is a lack of data on performance in the field via proof-of-concept pile load tests. Furthermore, field testing previously performed on fin piles has been completed on relatively short piles (less than 3 m). In this study, pile load tests, both axial and lateral, were performed to add to the body of knowledge for fin pile foundations. In addition to the pile load tests completed in the field, modeling of steel fin piles was also performed using LPILE and compared with the field performance. This enabled calibration of model parameters to mimic field observed capacity and deflections and allowed for study of scenarios that were not tested in the field study.

Test Location and Site Profile

In-situ testing of two steel fin piles was conducted along the Interstate 95 corridor near Philadelphia, PA. The test site was provided by the Pennsylvania Department of Transportation (PennDOT) on a site near the Frankford Creek as shown in Figure 2. Two fin piles were tested for axial and lateral capacity. The fin piles, as pictured in Figure 3 and shown schematically in Figure 4, are steel pipe piles that have a total length of 3.73 m (12 ft 3 inches), with fins starting at the pile top that taper into the pile at 1.83 m (6 ft). The pipe portion of the pile is 12.7 mm thick with a diameter of 273 mm (10.75 inches). The pile fins are 127 mm long and 9.53 mm thick with a spacing of 90° between each fin for a total of four fins on the pile. The piles are covered with a top plate to attach superstructure elements to the pile such as the driving equipment or a light structure (e.g., light pole). The steel used for the top plate of the piles and the fins is ASTM A36 steel with a yield strength

Figure 2. Project Site Location in Philadelphia, PA (Google Maps, 2019; LaRegina, 2021)

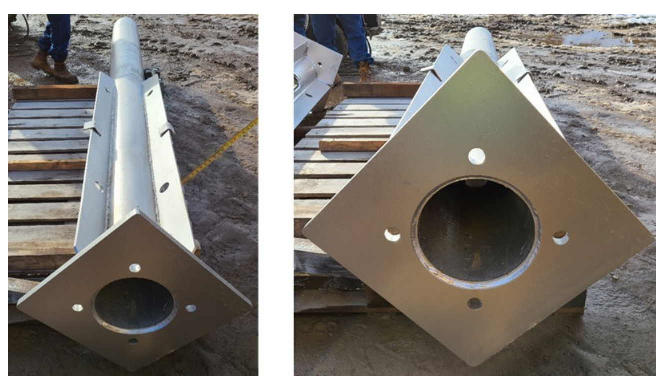

Figure 3. Photographs of Steel Fin Piles Tested in This Study

of 248 MPa (36 ksi). The fins are welded to the pipe portion of the pile, which uses ASTM A500 with a yield strength of 290 MPa (42 ksi).

The soil strata elevations at the test site were estimated using PennDOT-provided boring logs for the general test location area. The soil descriptions, depths, and N values are presented in Table 1 and further discussion of site geology can be found in McInnes *et al*. (2022). The groundwater table is located at approximately 6 m below the ground surface. The soil descriptions and N values in Table 1 were used by the designer of the piles and by the research team to model the performance of the pile using LPILE, which will be discussed in subsequent sections. The governing design criteria for the fin piles is their lateral capacity; therefore, the axial capacity is of secondary consideration and does not typically govern pile design. The fin piles were designed to withstand lateral loads equivalent to an overturning moment of 40.7 kN-m and a shear force of 4 kN. The design criteria met the standards established for a 10.7 m (35 ft) light pole foundation in PennDOT publication 72M (Bureau of Design, 2010). The initial design was completed by the engineering firm that works with the pile manufacturer. The anticipated lateral displacement was approximately 4 mm at the design overturning moment. The tolerable lateral displacement for the service limit state of a pile is capped at 12.7 mm by PennDOT (McAuley, 2013).

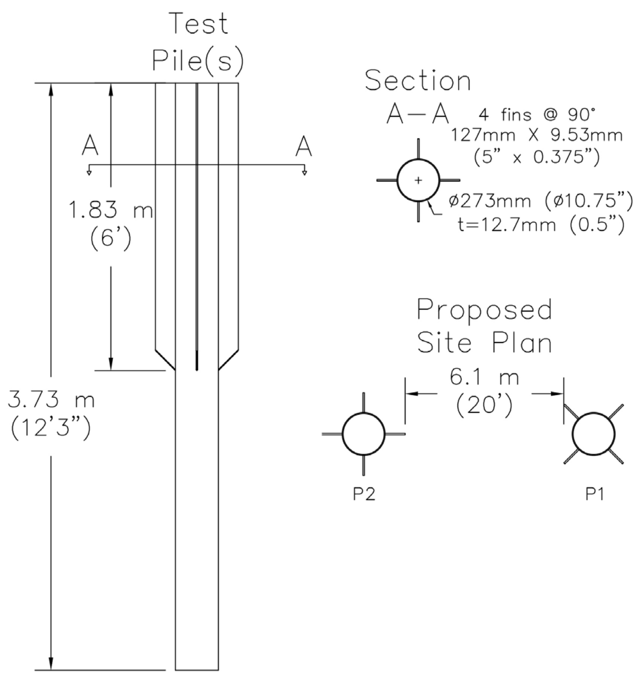

Figure 4. Schematic of Steel Fin Test Pile and Test Setup

Test Procedure

Axial and lateral load tests were performed on the two steel fin piles. The fin piles were installed with a vibratory hammer to depths of 3.58 m and 3.63 m for pile 1 (P1) and pile 2 (P2), respectively, with a Dawson EMV 450 vibratory hammer. The minimum spacing between each pile (i.e., 2.4 m) follows standard procedure as determined by ASTM D1143 (ASTM, 2013a). For the lateral tests, one test applied the load at 45° between the fins (P1) and the other test applied the load in line with one pair of the fins (P2), as shown in Figure 4. The lateral tests were conducted this way to investigate the impact of the orientation of the fins in relation to the direction of the applied lateral force.

Axial load tests were performed according to ASTM D1143 Method A: Quick Test and the setup is shown in Figure 5. The axial pile capacities were significantly higher than the loads applied during the axial load tests. Initial designs of the pile predicted greater pile settlement; however, stiffer soils were encountered at the actual location of the pile tests than predicted on the design boring.

Lateral load tests were performed on both P1 and P2 in general accordance with ASTM D3966 (ASTM, 2013b). An access tube was installed in the pile to accommodate a shape array, which monitored deflection data along the pile length (i.e., curvature). Square plates were welded to the pile extension to provide an area for the jack to load the pile as well as an area to mount the dial gauges. The hydraulic jack was placed horizontally between the square plates on the pile extension and the square plates on the reaction system. The jack was positioned at a vertical distance of 0.61 m above the ground such that a maximum moment of 65.1 kN-m was applied to the fin piles during the lateral test. The reaction system, as shown in Figure 6, consisted of two cuts of H-pile

Table 1. Summary of Subsurface Conditions at Test Site (after McInnes *et al*., 2022)

Soil Layer	Layer Thickness (m)	Soil Descriptions	Average N Value
1	4.27	Loose to medium dense Silty fine Sand fills. Average grain size D_{50}: 0.2 mm, fines content: 30%-35%.	14
2	3.66	Very dense poorly graded alluvial Sand with Silt and Gravel. Average grain size D_{50}: 2 mm, fines content: 10%-15%. Out of 5 CPT borings, refusal was encountered in 3 borings.	43
3	3.05	Stiff alluvial Lean Clay (plastic index less than 15) or non-plastic Silt. Sand content is usually less than 10%.	6
4	6.71	Medium dense alluvial poorly graded Sand and Silt. Average grain size D_{50}: 0.5 mm, fines content: 15-20%.	19
5	8.53	Very dense completely weathered bedrock (saprolite soil). Soils can be classified as Silty Sand with Gravel. Average grain size D_{50}: 1.0 mm, fines content: 10-15%.	Split spoon refusal

Figure 5. Photograph of Axial Load Test Setup

Figure 6. Photograph of Lateral Load Test Setup

supporting a third H-pile laying on both its flanges. This system was reinforced with the weight of 4 concrete barriers, an H-pile, and a stationary bulldozer. As previously mentioned, a shape array (Figure 7) was utilized to measure lateral deflection using accelerometers throughout the length of the pile at 500 mm spacing. The shape array consists of joints connected by rigid metal sections that are dropped to the bottom of the pile. Readings of position are taken throughout the lateral load test using the accelerometers to determine the shape of the pile as it deflects from the load. Nine of the shape array accelerometers measured displacement in the piles. All instrumentation readings were recorded digitally, with an independent reference observing pile movement at the same height as the jack.

The digitized instrumentation recorded lateral pile displacements at the height of the jack, 0.15 m above the height of the jack, and at the connection between the pile and the extension. A tilt meter also monitored the rotation at the top of the pile. The loading schedule followed Method A from ASTM D3966 (ASTM, 2013b). This loading schedule varies from that of the axial compression in that the load increments and the duration of the increments varies throughout the test. The maximum jack load of 106.8 kN was used as the ultimate (200%) load for the lateral tests. All other load increments were determined using 106.8 kN as the desired maximum load. The 106.8 kN, raised 0.61 m from ground surface, created a 65.1 kN-m moment acting on the fin pile. This moment exceeded the expected design load for the fin pile of 40.7 kN-m.

After conclusion of the lateral load testing, high-strain dynamic load testing was performed on pile P2 to further evaluate axial pile capacity. Details are provided in the subsequent section.

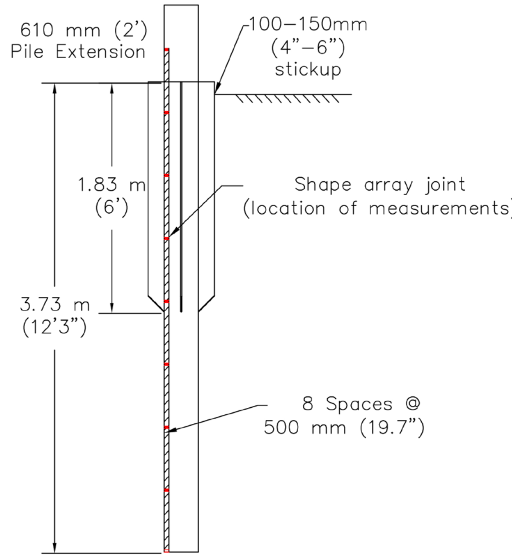

Figure 7. Schematic of Shape Array and Accelerometer Locations within Pile

Results

Axial Load Tests

Axial static and dynamic load test results are shown in Figure 8. The theoretical elastic deformation line was calculated to account for cross-sectional area increases at the location of the fins weighted by length to determine an effective area. The theoretical elastic deformation line and the Davisson offset line are shown in Figure 8. The results of the axial tests showed small displacements, less than expected in design as the dense sand layer in the boring log (Table 1) was encountered shallower than expected. After the conclusion of the static load tests, a dynamic load test was conducted in accordance with ASTM D4945 (ASTM, 2017) to estimate the axial capacity of the fin piles as little movement was observed in the axial test during static testing. Dynamic measurements were obtained with

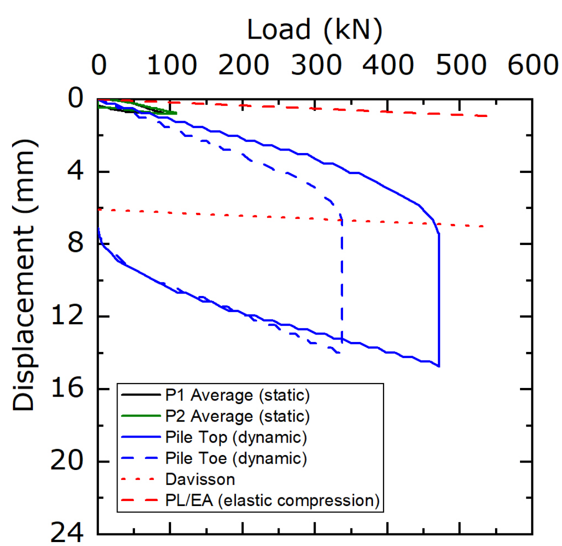

Figure 8. Results of Axial Load Tests on Fin Piles

pairs of piezo-resistive accelerometers and strain transducers attached at opposite sides of the pile, near the pile top. Analog signals from the gages were conditioned, digitized, stored and processed with a Model 8G, Pile Driving Analyzer. Several impacts were applied with an excavator bucket from variable drop heights. Signal matching utilizing the CAPWAP program was performed on the obtained representative data which yielded as a result the shaft resistance and end bearing components and also produced a simulated static load-set graph. The estimate of total pile capacity from the dynamic load test resulted in a total capacity of 468 kN, with the shaft resistance contributing to 133 kN, and the remaining resistance of 335 kN contributed by end-bearing. This data is shown in Figure 8, which also includes the Davisson Offset Limit (Davisson, 1972), the recorded static axial compression load test results, and the elastic compression limit.

Lateral Load Tests

The lateral movements of both piles were monitored at three locations: as close to the ground as possible (true pile head), in line with the hydraulic jack, and 0.15 m above the jack. The lateral displacement at the true pile head for P1 and P2 had maximum lateral displacements of 13.2 mm and 16.8 mm, respectively, as shown in Figure 9. Pile P2, which was loaded in line with one pair of fins, displaced 3.56 mm more at the pile head than P1, which was loaded between the fins. Consistently at all points of measurement, P2 deflected more than P1. The displacement at the pile head for P1 and P2, at an overturning moment of 40.7 kN-m, were 7.37 mm and 9.14 mm, respectively.

The lateral movement monitored with the shape array is shown in Figure 10a for P1 and Figure 10b for P2. Each curve presents the position data for the pile in the direction of the applied load at the end of each load increment. From the shape array data, P1 deflected 18.0 mm and P2 deflected 22.6 mm. The lateral displacement of P1 decreased to approximately zero at the depth 2.44 m. The fin pile(s) are a total length of 3.73 m. The fins on the pile begin at the pile top and taper back into the pile after 1.83 m. The point of zero lateral displacement seen in the shape array results occurs just 0.61 m after the termination of the fins. The same behavior is observed in P2; however, the zero point occurs deeper, around 3.05 m. Pile P2, which was loaded in line with the fins, displaced 16% more than the first pile being loaded in between the fins, suggesting that different load transfer mechanisms are occurring (e.g., P1 creates a different block/wedge of soil that is engaged in load transfer than P2). This is an area of potential future research. Under PennDOT design criteria (McAuley, 2013), the tolerable lateral pile movement for the service limit state is 12.7 mm, a limit these piles

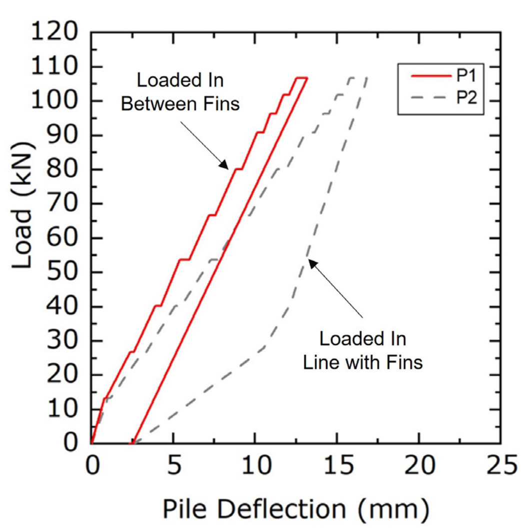

Figure 9. Lateral Pile Deflection Measured at the True Pile Head for P1 and P2

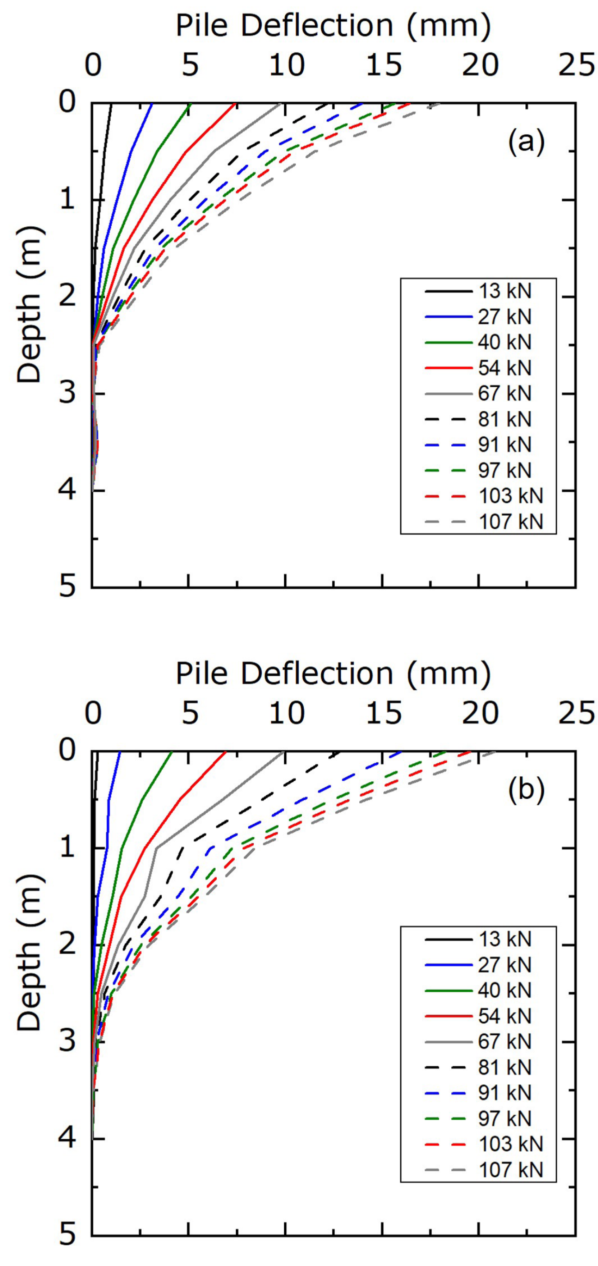

Figure 10. Lateral Load Test Results from Shape Array Measurements for (a) P1 and (b) P2

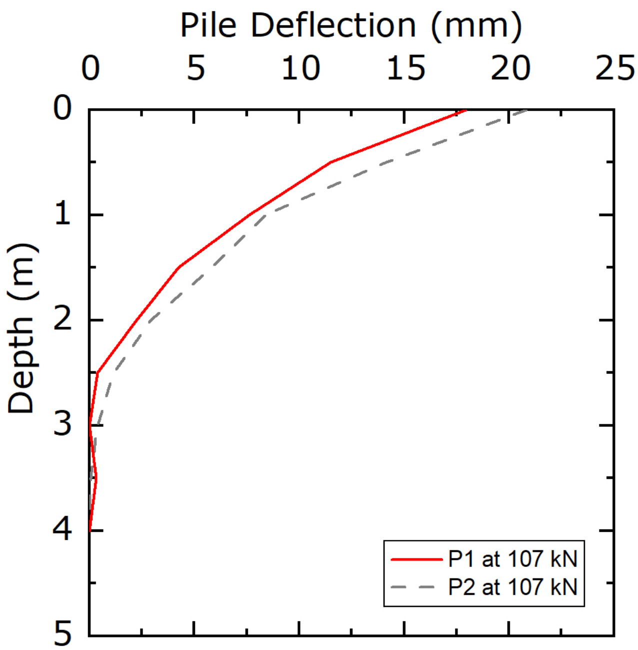

Figure 11. Lateral Load Test Deflection Comparison of P1 and P2

exceeded at the maximum test lateral load but not at the design load. The design moment for a fin pile of this size is 40.7 kN-m, which corresponds to a lateral load of 66.7 kN. The readings in Figure 9 are taken as close to the ground surface as possible. As shown in Figure 9, at a lateral load of 66.7 kN, the pile displacements at the ground surface were approximately 7.6 mm and 10.2 mm for piles P1 and P2, respectively, which is less than the allowable displacement.

For comparison, the shape array results from both piles at the maximum lateral load of 106.8 kN are presented in Figure 10. As shown in Figure 10, P2 deflected more than P1 to depths of approximately 3 m.

Modeling Results

The lateral load tests were subsequently modeled in LPILE, a finite difference beam-column modeling software that evaluates a pile's response under lateral loading using the p-y method (LPILE, 2019). LPILE was used to evaluate the effects of varying several parameters, specifically the fin proportions and the pile type. The model was first calibrated to the lateral load test results. This process did not take many iterations as the initial trial using soil properties from available direct shear tests matched the field results very well as shown in Figure 12. LPILE does not specifically have a finned pile structural section therefore the Elastic (Non-yielding) Section Model was selected to represent the fin piles. The chosen LPILE section allows the user to define the moment of inertia, cross-sectional area, and pile width. The moment of inertia and cross-sectional area were calculated for the finned length for P1 and P2. The moment of inertia was the same for P1 and P2, but the effective width changes. Iterations of the model were run to compare results using the full finned width for P2 (w = 527mm, 20.75in) versus a skewed width for the test orientation of P1 (w = 372mm, 14.65in). Varying the effective width

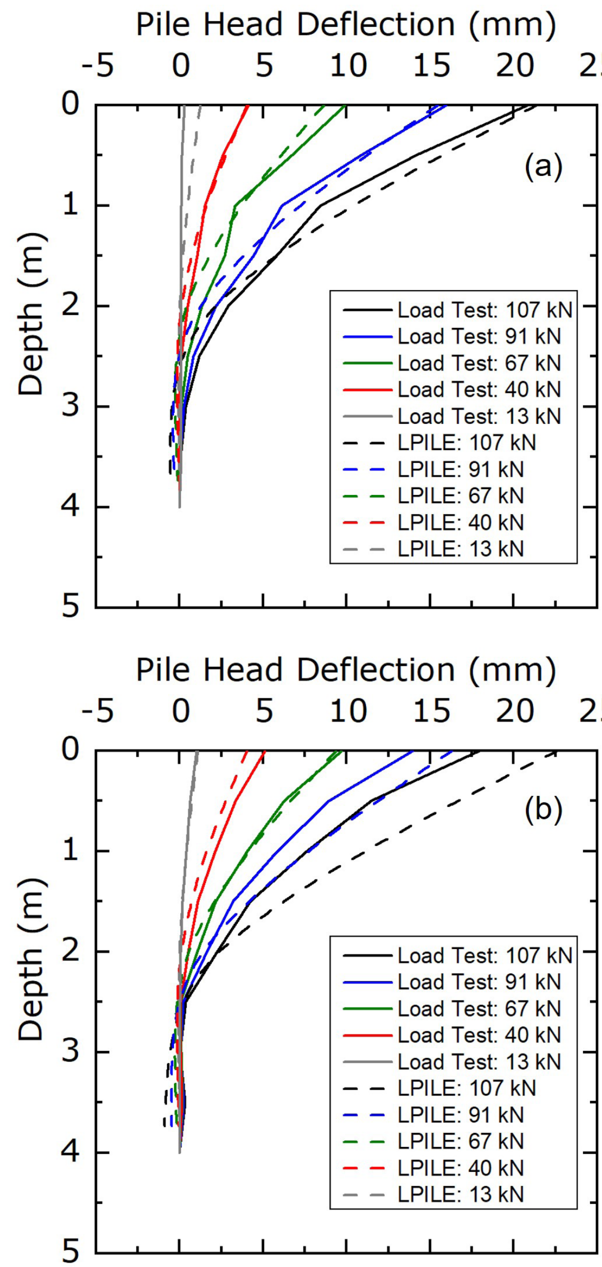

Figure 12. Lateral Load Test LPILE Model Comparison with Measured Deflections for (a) P2 loaded in line with fins and (b) P1 loaded in between fins

did impact the modeled results as shown in Figure 12. Figure 12a shows that lateral deflections estimated in LPILE for P2, which was loaded in line with the fins, matched closely to the field load test results; however, LPILE results for P1, which was loaded in between fins, in Figure 12b show that as load increased LPILE overpredicted lateral deflections compared to the field results. Since the differences in lateral displacement at the maximum load for P1 and P2 were small, but still existent, the full effective width model represents an acceptable prediction for the fin piles, regardless of rotation.

A thorough geotechnical site investigation program was performed, including direct shear test data from the near-surface, silty sand fill material. LPILE contains an elastic silt material model that best captured the laboratory test data. Even though the pile driving records indicated that the test piles most likely refused on the stiff sand layer encountered in the borings, the elastic silt layer was assumed to be infinitely thick as the material below the pile did not affect the lateral response. The load application (steps and geometry) was entered to mimic the setup in the field, with the load applied approximately 0.61 m above the ground surface. The results of the calibration model with no variation from the initial run were found to be sufficiently accurate for the parametric study. The results of the field lateral load test versus LPILE generated deflections can be found in Figure 12.

A parametric study was performed using LPILE to evaluate the effect of several parameters, including fin length and pile type as shown in Figures 13 and 14. For these comparisons the LPILE model for P2 (i.e., full effective width) was used. First, the impact of the finned length was evaluated by varying the percentage of the pile length that was finned. The study considered the actual pile (50% of the length finned) against a 25%-finned length, 100%-finned length, and a traditional 273 mm (10.75”) diameter steel pipe pile (no fins). Considering solely the structural increase in stiffness, a 50% reduction in deflections would be expected using a 100%-finned length pile from a no-fin pile, as the moment of inertia for the fin pile is 2.1 times that of the non-fin pile. From the model results, that reduction in deflection is achieved with only a 50% finned length and a greater reduction in deflection is exhibited with the full-length fins.

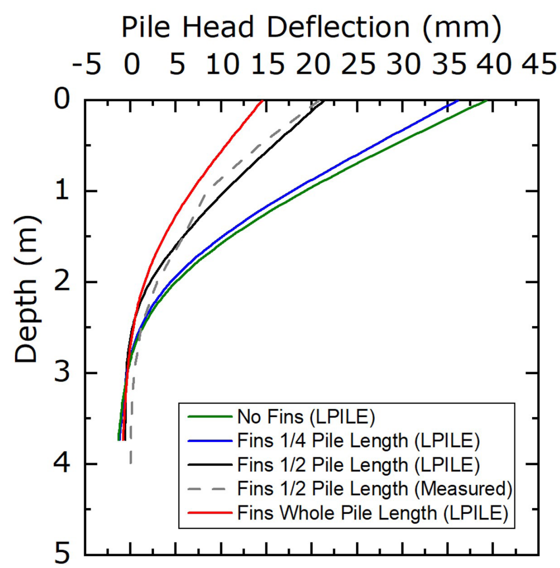

Figure 13. Parametric Evaluation of Changing Fin Length in LPILE

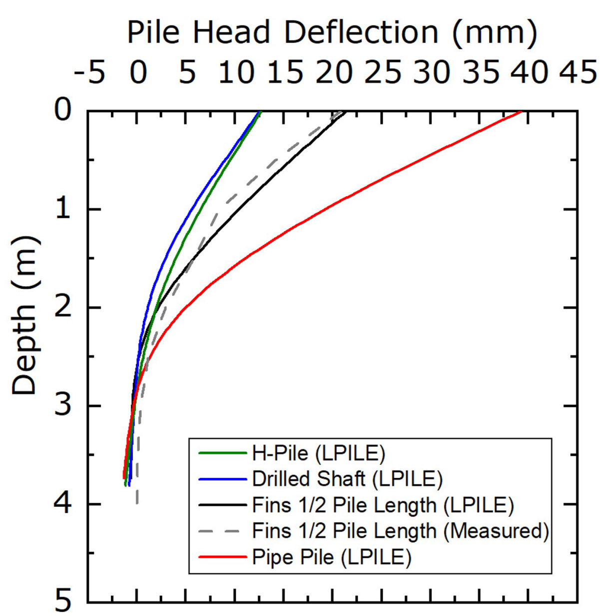

Figure 14. Parametric Evaluation of Pile Type in LPILE

LPILE was used to model the performance of the finned pile and several commonly used alternatives: a 610 mm (2-foot) diameter drilled shaft, a driven HP12x63 pile, and a standard pipe pile. The driven HP pile section was selected as an equivalent steel weight (cost) to the finned pile. As shown in Figure 14, the drilled shaft and HP section had relatively similar stiff responses with pile top lateral displacements of about 12 mm. The finned pile displacement was about 22 mm and the unfinned pipe displacement was about 40 mm. The drilled shaft is commonly selected for sign structures when moment capacity or lateral deflection drives the foundation selection. The selected driven pile is the HP12x63 beam – the section most equivalent to the finned pile in terms of steel weight (the finned pile weighs an average of 92 kg/m (61.1 lbs/ft) for a 3.7-meter length and 50% finned). This section also deflects similarly to the drilled shaft.

Conclusions

Axial and lateral load tests were performed on two fin piles at a test site near I-95 in Philadelphia, PA. Both fin piles had a pipe diameter of 273 mm and a length of 3.73 m. The four fins, oriented at 90° to each other, began at the pile top with a length of 1.83 m, width of 127 mm, and thickness of 9.5 mm. The following conclusions were made:

- Dynamic load testing results showed a total pile capacity of 468 kN with the resistance distribution as 133 kN in shaft resistance and the remaining resistance of 335 kN in end-bearing, which was significantly higher than the initial design.
- The lateral resistance was shown to meet the design criteria for 10.7 m light pole from PennDOT. Load was applied at different orientations to the fins and loading the pile in between the fins resulted in 21% less (4 mm) lateral movement at the pile head. This has implications for design if there is a preferential direction of loading for a particular pile design.
- Shape array data was useful in evaluating the deflected shape of the pile and for comparisons with modeling software. The deflected shape of the fin piles showed a point of zero displacement at approximately 2.44 m for P1 and 3.05 m for P2.
- LPILE was utilized to supplement the field load test data and evaluate scenarios that were not possible in the field testing program. Modeling results showed that the fin pile

can be modeled in LPILE using simplified geometry to mimic the fins. Results showed that using the full effective width more closely captured the field load test results.

- The calibrated LPILE model was used to compare the fin pile to conventional pile alternatives and evaluate the effect of changing fin length and pile type. Results of these analyses showed that fins at one half the length of the pile decreased lateral movement by approximately 50% compared to a pipe pile of the same diameter. Additionally, comparisons of the fin pile with H-pile and drilled shaft alternatives showed that these conventional alternatives had 40% less lateral deflection than the fin pile.

This study adds to the growing volume of information on the benefits of fin pile foundations. The field testing and modeling results provided evidence that fin piles have advantages compared to traditional pile designs. The continuation of the modeling of fin piles and further field testing should be completed to ensure the understanding of lateral and torsional load response of steel fin piles.

Acknowledgments

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