Experimental and Numerical Study on the Winged Pile-Soil Interaction under Lateral Loads

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Abstract. Increasing the cross-sectional area of piles leads to an increase in the lateral bearing resistance and reduces displacements near ground level. This increase compensates for the reduction in soil stiffness at the seabed level. Installing wings near the mudline level is one approach for increasing the area of the pile in mudline level. This research paper discusses a number of small-scale laboratory models and FEM models to study the benefit of adding wings on the variation of bearing capacity of laterally pile loaded embedded in sandy soil. To determine the advantages of adding wings to the pile, four embedded ratios (4, 6, 8, 10) were used to model both flexible and rigid pile types with various wing numbers and dimensions. The results revealed that adding wings to the pile improves lateral load resistance and greatly reduces lateral deflection. So, to achieve better resistance, wings must be linked with the pile shaft perpendicular to the lateral load applied nearer the top of the pile head. Increasing the number of wings results in a large increase in lateral pile capacity. The ultimate lateral applied load is proportional to the rise in relative density at the same (L/D) ratio.

1. Introduction

Pile foundations are often used to support large constructions subjected to lateral pressures such as heavy winds, ocean waves, hurricanes, and earthquakes, such as power transmission lines, high-rise structures, marine structures, bridge abutments, chimneys, and wind turbines [1], [2]. In comparison to onshore facilities, several offshore installations are built on top of piles or are moored with piles to facilitate transfers. In comparison to the applied vertical load, there are significant horizontal loads. As a result of these loads, the pile experienced significant deflection/movement, which could result in major foundation failure. Piles must be built to withstand the impacts of horizontal or lateral loads to avoid failure hazards. A pile's lateral capacity is determined by three factors: soil type, loading direction, and pile geometry. As a result, several types of piles, such as (tapered, tripod, and helical piles), must be employed to improve pile capacity and resistance to lateral loads. [3], [4]. As a result, several researchers have tried a variety of strategies to improve a pile’s lateral reactivity when subjected to such forces. The "winged-pile" concept, first introduced by [5], is a unique foundation approach for increasing the diameter of the pile. Other traditional approaches like reinforcing shallow soils or increasing pile diameters have been proven to be less effective than winged or finned piles [6], [7]. Steel plates serve as wings that are connected to the outside of the pile at an angle of (90°) to the pile to increase resistance on the seabed near the surface (mudline) and so increase the pile's efficacy, [8], as seen in Figure (1). The pile's wings (fins) will give additional bearing capacity, allowing it to be used in deeper water or allowing the designer to lower the size of the pile to save money on steel and manufacturing, Manufacturing, transportation, and installation costs, as well as drive times and operating site dangers [9].

The following are the precise objectives of this investigation:
• Assessing the performance of winged piles buried in sand and subjected to lateral loads.
• Looking at how the relative density of sandy soil affects the behavior of a laterally laden pile.
• Investigating the effect of the length-to-diameter (L/D) ratio on winged pile behavior.
• Examining the impact of the size and number of wings on the behavior of winged piles under lateral stresses.
• Proposing Numerical models by PLAXIS-3D that can predict the pile-soil deformation, ultimate horizontal load, and bending moment.

Figure 1. Winged Pile Model

2. EXPERIMENTAL PROCEDURE AND SETUP
To analyze the winged pile-soil interaction under lateral loads, a series of laboratory model and finite element model tests have been utilized on steel pipe piles implanted in sandy soil beds.

2.1. THE SOIL’S CHARACTERIZATION
In this experiment, dry river sand was employed, and several tests are used to establish the physical and mechanical properties. Modeling on a small scale, which is linked to the production of shear zones right beneath the footing in the active region, and to reduce the particle size effect, which is recommended, scale effects are taken into account by [11] for a small model, who stated that the D/D50 ratio must be not less (100), the D/D50 ratio is 142.8, which fulfills the scaling law requirement. There are three relative densities are used: 35% in loose, 60% in medium, and 75% in dense sand. The characteristics of the sandy soil utilized are listed in Table (1). The Unified Soil Classification System (USCS) classifies the soil as poorly graded sand (SP), as shown in Figures (2).

Table 1. The characteristics of the sand.

| Property                                | Value          | ASTM Standard |
|-----------------------------------------|----------------|---------------|
| Specific gravity (Gs)                   | 2.67           | D 854 [8]     |
| Active sizes: D10, D30, D50, D60        | 0.15, 0.23,0.35, 0.48 |               |
| Coefficient of uniformity [Cu]          | 3.2            | D 422         |
| Coefficient of curvature [Cc]            | 0.73           | D 2487        |
| Soil classification                      | SP             |               |
| Maximum dry unit weight [kN/m³]         | 17.7           | D 4253 [11]  |
2.2. MODEL PILES AND WINGS

A closed-ended hollow steel winged pile model was used. It has a 50 mm outer diameter and a 2 mm wall thickness. The strain gauges are Model BF350 strain gauges with a resistance of (350 Ohm), a 2.1 sensitivity factor, and dimensions of 7.1mm in length and 4.5mm in breadth. They begin at the top of the winged pile, where the strain gauges are attached to the axis of the winged pile, as seen in Figure (3) (a & b). As shown in Table (2), the Location of strain gauges shown in Table (3).

**Table 2. Properties of model piles and wings.**

| Material                      | Steel |
|-------------------------------|-------|
| Modulus of elasticity, [GPa]  | 200   |
| Pile embedded length [cm]     | 20 , 30 , 40 , 50 |
| Diameter of pile [mm]         | 50    |
| Thickness of pile [mm]        | 2     |
| Length of wing (Lw) [mm]      | 56 , 112 |
| Width of wing (bw) [mm]       | 37    |
| thickness of wing [mm]        | 2     |

**Figure 2.** The sand's grain size distribution
2.3. PREPARATION OF THE SOIL

A container made of steel. The container's internal dimensions are as follows: (750x750x750 mm). According to ASCE (1990), pile behavior can be achieved using lateral boundary effects ranging from 13D to 30D. Its utilization in this investigation was divided into five layers, each 5 cm thick, to ensure that the desired relative density of sand was attained. The following is the application for soil layers with three different configurations:

- **Loose Sand State**: Each layer of sand is tossed from a height until the container is completely full to RD%=35 percent.
- **Medium Sand State**: With a 60% RD, soil rains from a constant height of 5 cm to the container's top.
- **Dense Sand State**: RD%=75 percent, river sand was pushed down from a height, and each layer was compacted until the necessary depth was reached.

2.4. INSTALLATION OF A WINGED PILE

The loading point at the pile cap is 50 millimeters above the ground's surface. The pile model is anchored in the middle of a 25 mm square hollow steel section for pile installation. The steel tube is secured to the top of the container and is used to level the pile vertically [11]. The soil deposit must be produced after the pile model has been vertically positioned. The hollow steel rod component was removed and the top surface of the sand layer was flattened when the soil level in the container reached a certain level. Finally, the dial gauges were installed, along with two 0.01 mm dial gages. The winged pile's horizontal and vertical displacements were measured, as illustrated in Figure (4), which were attached and fixed using two magnetic stand base holds. The pile cap has a load cell affixed to it zero reading of load, as well as the static reading, are shown on the plate.
2.5. THE HORIZONTAL MOVEMENT SYSTEM

After the sandbed has been prepared and the piles have been put, the lateral system is being worked on. For the test, the device created by [12] is being prepared and a system that is integrated. The logger and the load cell are linked, while the strain gauge is connected to the pile shaft. As shown in Figure (5), Two dial gages are fixed to the pile cap, one on the top surface to read vertical displacement and the other on the thin side to measure lateral displacement. The AC drive then adjusts the speed of movement. The horizontal jack's frequency is 1.5Hz to meet the task requirements, as well as the shaft moving in reaction to the jack's movement, giving incremental load readings for the digital weighing indicator to record, which shows which load cell was detected while the jack was moving. When the lateral dial gauge reading exceeds a 12mm displacement measurement, the loading is stopped [13].

Figure 4. (a, b, & c) Steps for installation of the winged pile.
2.6. TESTING PROGRAM AND STRATEGY
This research looked at numerous factors of wing shape and numbers to see how they affect lateral capacity and single pile load deformation using a parametric technique. Table (4) lists the variable parameters in both the constant and issue statements. The piles’ models without wings were tried in the early stages of research on the behavior of piles under lateral pressure. Winged piles were utilized as a reference since they are a form of pile with wings. The wings were erected perpendicular to the applied static loading direction at the upper portion of the pile, close beneath the soil surface of the buried pile depth. This is the best site for increasing ultimate load capacity by a large amount.
2.7. Numerical Analysis Results
A study was conducted to understand more about how the addition of wings influences the behavior of laterally loaded monopiles. A finite element model generated with the PLAXIS 3D computer tool is now being used to lay the groundwork for the testing. To account for three-dimensional interactions between pile and soil in the current condition, a 3D FE-analysis can be applied. Shear forces, soil-pile interaction, layered soil, coefficient of lateral earth pressure, and soil dilatancy are all taken into consideration in the FEM.

2.7.1 Boundary Conditions and Finite Element Mesh
The sand was supposed to be a linear elastic property that was entirely flexible. The soil behavior was supposed to be governed by a non-associated Mohr-Coulomb constitutive model with well-established material characteristics in geotechnical engineering practice.

Five main input parameters are used in the elastic-plastic Mohr-Coulomb model: internal friction angle (\(\varphi\)), elasticity modulus (E), cohesion (c), dilatancy (\(\psi\)), and Poisson's ratio (\(\nu\)). The friction angles were calculated using the direct shear results for loose, medium, and dense materials and the elasticity

| Pile type | Pile length [mm] | Wing number | Wing length [mm] | Pile type | Pile length [mm] | Wing number | Wing length [mm] |
|-----------|------------------|-------------|------------------|-----------|------------------|-------------|------------------|
| RP20      | 200              | -           | -                | WP3..30..56 | 300              | 3           | 56               |
| RP30      | 300              | -           | -                | WP3..30..112 | 300              | 3           | 112              |
| RP40      | 400              | -           | -                | WP3..40..56 | 400              | 3           | 56               |
| RP50      | 500              | -           | -                | WP3..40..112 | 400              | 3           | 112              |
| WP2..20..56 | 200              | 2           | 56               | WP3..50..56 | 500              | 3           | 56               |
| WP2..20..112 | 200              | 2           | 112              | WP3..50..112 | 500              | 3           | 112              |
| WP2..30..56 | 300              | 2           | 56               | WP4..20..56 | 200              | 4           | 56               |
| WP2..30..112 | 300              | 2           | 112              | WP4..20..112 | 200              | 4           | 112              |
| WP2..40..56 | 400              | 2           | 56               | WP4..30..56 | 300              | 4           | 56               |
| WP2..40..112 | 400              | 2           | 112              | WP4..30..112 | 300              | 4           | 112              |
| WP2..50..56 | 500              | 2           | 56               | WP4..40..56 | 400              | 4           | 56               |
| WP2..50..112 | 500              | 2           | 112              | WP4..40..112 | 400              | 4           | 112              |
| WP3..20..56 | 200              | 3           | 56               | WP4..50..56 | 500              | 4           | 56               |
| WP3..20..112 | 200              | 3           | 112              | WP4..50..112 | 500              | 4           | 112              |

Note: All wings have the same width = 37 mm
Total Number of Tests = 84
(28 Tests) Loose, (28 Tests) Medium and (28 Tests) Dense
RP: Reference Pile, WP: Winged Pile
WP2..50..112: Two Wings, Embedded Length 50cm, Wing Length 112 mm
modulus was determined using the direct shear results for (loose, medium, dense) materials [14]. The dilatancy angle ($\psi$) for soil type quartz sand ($\psi = \varphi - 30$) was computed using the equation supplied by PLAXIS program.

The value of (c) was zero in the analysis. At rest, the coefficient of earth pressure $K_0= 1 \cdot \sin \theta$ [15] was utilized to construct the beginning stress in the numerical simulation using Jaky's formula. Table (5) lists the hyperbolic model parameters used in the investigation, and the mesh was set to medium (element:8448 and node:13851). The piles and wings utilized in the numerical analysis are the same dimensions as those used in the experimental tests. Figure (6) shows a common 3D FE mesh for calculating the horizontal load on a pile.

![Figure 6](image)

**Figure 6.** The lateral loaded winged pile was modelled using a finite element.
(a) Three-dimensional mesh, (b) a mesh in a plan, and (c) winged pile model.

| Parameter                      | Loose Sand Dr=35% | medium Sand Dr=60% | Dense Sand Dr=75% | Pile and Wings |
|-------------------------------|-------------------|-------------------|------------------|----------------|
| Material Model                | Mohr-Coulomb soil model | Mohr-Coulomb soil model | Mohr-Coulomb soil model | Linear elastic |
| Type of material behavior     | Drained           | Drained           | Drained          | Nonporous      |
| dry unit weight $\gamma_d$ (kPa) | 15.7              | 16               | 16.5             | 78             |
| Effective friction angle ($\phi$) | 34.65            | 36.45            | 40.6             | ............ |
| Effective cohesive strength(c) (kPa) | 0               | 0                | 0                | ............ |
| elasticity modulus (E) (MPa)   | 0.75              | 4.4              | 9                | 200x10³       |
| Poisson's ratio ($\nu$)        | 0.33              | 0.33             | 0.33             | 0.3            |
| Dilatancy angle ($\psi$)       | 4.65              | 6.45             | 10.6             | ............ |
| strength reduction factor (Rinter) | 0.65             | 0.65             | 0.65             | ............ |
3. ANALYSIS OF THE RESULTS

These are the load-displacement relationships for experimental winged pile and reference pile. The ultimate lateral load is indicated as Pult, and (Ux) the horizontal displacement is provided as a proportion with no dimensions to the diameter of the pile (D) as an Ux/D for P-Y curves. Failure occurs when the lateral load equivalent to a horizontal displacement exceeds 10% of the pile diameter [16]. The upper section of the soil surrounding a laterally loaded pile is the most significant [17]. As a result, in all test series, the wings were placed at the top of the pile beneath the ground level. This was the most advantageous location for getting a significant improvement in ultimate load capacity. In each test series, the acting incremental loads are delivered perpendicular to the wing plan.

3.1. EFFECT OF WING LENGTH ON THE LATERAL CAPACITY OF WINGED PILE

Throughout the testing, the wing width (bw/D = 0.74) was kept the same for varying wing lengths. To determine the effective wing lengths, experiments were conducted with various pile stiffeners (L/D). Figures (7) and (8) show the curves of lateral load capacity and horizontal displacement ratio, and they demonstrate that increasing wing length results in a significant improvement in lateral capacity. The lateral pile capacity at a failure was enhanced by 1.33 %, 1.40 %, 1.55 %, and 1.79 % for Lw equal 112 mm and 1.12 %, 1.17 %, 1.26 %, and 1.49 % for Lw equals 56 mm L/D = 10, 8, 6, and 4 for pile stiffness, respectively and Dr equal to 35 % and three wings as comparison to a regular pile. In lateral force resistance, the embedded length of the pile and the area of the wings are the two most important features. As a result, the space behind the wings has a significant influence on the passive resistance produced. The maximum bending moments were recorded near the ground surface, implying that the wings give additional pile fixity there, as shown in Figure (9). The maximum positive bending moment has happened near the midway of the pile shaft in all of the models investigated in this work, whereas the maximum negative bending moment has occurred beneath the rotating point. When it comes to the laterally laden pile in cohesionless soils, Broms [18] agrees with this tendency.

![Figure 7. The P-Y curve for different wing lengths [L/D=10 & 8]](image1)
![Figure 8. The P-Y curve for different wing lengths [L/D=6 & 4]](image2)
3.2. EFFECT OF WINGS NUMBER ON THE LATERAL CAPACITY OF WINGED PILE

One of the tests' goals was to determine how increasing the number of wings in the pile's upper section affected the resistance of laterally loaded piles while maintaining \( L_w = 112 \text{ mm}, \, b_w/D = 0.74 \) as well as utilizing \( Dr = 35\% \). P-Y curves show that the pile capacity against lateral load increases as the wing numbers grows and the loading direction acting on the greatest response surface changes, as illustrated in Figures (10) and (11).

The capacity of the lateral piles at failure was increased by (1.25 percent, 1.33 percent, 1.44 percent, and 1.56 percent) for two wings, (1.33 percent, 1.40 percent, 1.55 percent, and 1.79 percent) for three wings, and (1.33 percent, 1.44 percent, 1.58 percent, and 1.77 percent) for four wings when compared to the reference pile for pile stiffness.
3.3. EFFECT OF LENGTH TO DIAMETER RATIO L/D ON THE LATERAL CAPACITY OF WINGED PILE

The length to diameter ratio (L/D) of the piles is modified (4, 6, 8, and 10) to demonstrate the wings efficiency associated to short and long piles (pile stiffness) [19] [20]. As shown in Figure (12), The slenderness ratio boosts the load-carrying capability of winged piles significantly. The higher the (L/D), the greater the gain in lateral capacity.

![Figure 12. P-Y curves for different length to diameter ratio (10, 8, 6, 4)](image)

3.4. EFFECT OF RELATIVE DENSITY ON THE LATERAL CAPACITY OF WINGED PILE

As a result, several tests were carried performed, encompassing a wide range of relative densities (35, 60, and 75%). Winged piles' lateral load capacity is affected by relative density, as shown in Figure (13). A stronger lateral load capability is associated with a higher relative density. This is due to the fact that as sand becomes denser, its shear strength increases [21], [22]. For wing length of 112 mm with three wings, and (L/D =10), tThe capacity of the lateral piles at failure was increased by 1.16% for dense, 1.18%t for medium, and 1.33% for loose. Additionally, when the relative density of sand increases from 35 to 75%.

![Figure 13. P-Y curve for (Dr=35, 60 and 75%)](image)
3.5 Verification Between Numerical and Experimental Results

To see if the process of the study yielded an acceptable result, laboratory testing was compared to the results of numerical research on laboratory scale piles. The head of the pile load-displacement curves was compared to a model test utilizing PLAXIS-3D computational assessments of a winged pile, revealing that the numerical technique may be used to estimate pile height while enhancing precision at displacements. Figure (14) shows the lateral load at the end of the test (12 mm) 195 N and 259.6 N for RP50 and WP4..50..112, respectively, which is similar to what the numerical studies predicted 200 N and 264.6 N for RP50 and WP4..50..112, respectively. This indicates that the numerical model of flying pile behavior is appropriate.

![Figure 14](image)

**Figure 14.** Lateral load versus horizontal displacement for a single winged pile model with a relative density of 35%.

3.6 Pile-Soil Deformation

The motions of the pile WP4..50..112 and the dirt in the model are depicted in Figure (15)(a, b, c, and d). A significant soil movement around the pile, notably near the pile’s front, is depicted in Figure 15(a). The soil movement occurred synchronously with pile movement, with the maximum lateral displacement occurring immediately behind the pile. The soil in the vicinity of the trailing wing flowed forward to fill the void left by the trail wing’s movement. There was a significant soil displacement near the ground surface, notably in the zone behind the pile head.
CONCLUSION
Based on the collected data and after comparing the reactions of winged and traditional heaps, as well as reviewing the goals of selecting the appropriate settings for the best performance, the following points can be summarized: The lateral load magnitudes of winged piles increase by an average of 16, 19.8, and 35.8 % for experimental results and 15.7, 19, and 33.2% for numerical results when compared to reference piles with relative densities of 75, 60, and 35 %, respectively, for length to diameter ratios (L/D) 4, 6, 8, and 10 and wing length 56,112mm and wing number 2, 3 and 4. The final lateral applied load is proportional to the relative density increase at the same length to diameter ratio (L/D). As the relative density rises, the vertical displacement rises with it. The vertical displacement reduced as the length to diameter ratio (L/D) increased. Increasing sand density from loose to medium, then dense, affects the bending moment significantly. It enhanced the bending moment's magnitude. For long-winged piles with length to diameter ratios (L/D) of 8 and 10, the maximum positive bending moment occurred near ground level in the pile shaft's upper section. For L/D of (8) and L/D (10) correspondingly, the negative bending moment occurred below 300 mm and 400 mm. The bending moments along the pile shaft indicate that adding wings to the pile shaft increased the pile's fixity near the soil surface. Increasing the wing length would significantly increase the pile's lateral capacity in comparison to the standard pile, the capacity of the lateral piles at failure was increased by an average of (52.3%) for length of the wing (112 mm) and (26.3%) for wing length (56 mm) for length to diameter ratios [L/D= 10, 8, 6, and 4], [Dr = 35 %] and [wing Number=3]. Increasing number of wings on a pile would significantly increase its lateral capacity. The capacity of the lateral piles upon failure was increased with an average

![Figure 15](image-url). Pile- soil deformation (a and b) at total lateral displacement (c and d) lateral displacement for x-direction only.
of 40, 52.3, and 53.4 % for two, three, and four wings, respectively, for length to diameter ratios (L/D) = 10, 8, 6, and 4 and Dr = 35 %, as compared to the normal pile.

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