An Experimental Study on Laterally Loaded Winged Pile in Sandy Soil

T. K. Mahdi1a, M. A. Al-Neami1b*, and F. H. Rahil1c
1Civil Engineering Department, University of Technology-Iraq, Baghdad, Iraq. 
*a.bce.19.67@grad.uotechnology.edu.iq, b40008@uotechnology.edu.iq, c40029@uotechnology.edu.iq.

Abstract. Many offshore facilities such as offshore wind turbines and other engineering structures, including floating offshore facilities (FPSOs), are founded on or anchored with piles to transfer large horizontal loads relative to the imposed vertical load compared to onshore installations. The subgrade reaction of the soil surrounding the pile shaft mobilized when the lateral loading is applying on the pile to resist the applied loads. Since the soil at the midline is often weak and tends to have a poor subgrade reaction, resulting in large pile displacements near ground level. The lateral bearing capacity of pile foundations can be increased, and pile displacements near ground level can be decreased by expanding the piles' cross-sectional area near the seabed level to compensate for the lower soil stiffness in the seabed level. One method of expanding the pile area in the lower soil stiffness zone is the addition of wings (or fins) near the seabed level. This paper presents a series of laboratory small-scale model tests that were conducted to laterally loaded piles with/without wings in sandy soil with different densities. The Piles slenderness's ratio (L/D) is varied from 4, 6, 8, and 10 to simulate the behavior of both flexible and rigid pile designs, with different wings geometry and numbers. This study indicated that the lateral pile capacity increased, and the horizontal deformation of the pile decreased after mounting wings compared to the regular normal pile without wings. It has been found that the optimum geometry and number of adopted wings is found to be three wings, and its length equals (0.22) of the embedded pile length. The existence of wings improved the bearing capacity of the winged pile by 1.33, 1.18, and 1.16 for piles of L/D=10 in the case of loose, medium, and dense soils, respectively, compared to regular piles in the same condition.

Keywords: Winged pile; laterally loaded; model tests; slenderness's ratio; river sand; pile foundation.

1. Introduction
Several offshore facilities are founded on or are anchored with piles to which the structure transfers large horizontal loads relative to the imposed vertical load when compared to onshore installations. Monopiles are the most widely used foundation structure to support offshore wind turbines (OWTs). Currently, more than 79 percent of the constructed offshore turbines have been supported on the Monopile [1], and the expense of the foundation system exceeds 30 percent of the capital investment in offshore wind projects [2]. Usually, pile foundations are liable to the axial load or lateral load or a combination of them. Laterally loaded piles behavior is one of the major issues concerned with the soil-structure interaction [3].

The monopile diameter can be increased at locations where water depths are greater than 30 m to provide additional rigidity to resist extra-large loads. However, the increase in the cross-sectional...
monopile area would result in considerably higher processing and handling costs, thus reducing the potential gain of increased size. However, moving from single piles (monopiles) to jacket systems usually entails a considerable cost increase. Therefore, to meet the changing design requirements, new foundation systems are required to provide cost-effective support structures.

An innovative foundation solution for increasing the pile diameter is called the "winged-pile" concept, originally proposed by[1]. winged piles have been discovered to be a better option than other traditional procedures such as strengthening shallow ground or increasing pile diameters [4,5]. The wings are steel plates attached to the exterior of the pile shaft at the top of the pile at (90°) to the pile [6] to mobilize additional resistance in the near seabed (midline) to improving foundation efficiency, as shown in Figure 1. The wings will give additional bearing capacity to the pile to allow pile foundations to be deployed in deeper waters or allow the designer to reduce the pile dimensions resulting in reduced steel and fabrication costs, driving times and operational site risks, and the cost of manufacture, transport and installation could be reduced by using wings [7].

In light of the foregoing, the purpose of this research is to identify, analyze, and evaluate the potential benefits of adding wings to a pile to improve its performance under lateral loading. In comparison to standard regular piles, the lateral load responses and load capabilities of winged piles embedded in the sand were examined. The investigations were carried out by varying geometric and wings for different slenderness ratios (L/D) and different soil densities.

![Figure 1. Winged pile.](image)

2. Experimental setup and procedure
A series of laboratory model tests with steel pipe piles embedded in sandy soil beds were conducted to meet this study's main goal and investigate the wing pile-soil interaction under lateral loads. This section describes the investigations that were conducted and the pertinent observations that were made in order.

2.1. Soil preparation
Three relative densities are used (35, 60, and 75%). The application for soil layers with three types of configuration is as follows:
- Type one: throwing the sand from height per layer until the container is filled with RD = 35%.
- Type two: raining the soil from constant height per (5 cm) to reach the top of the container with RD=60%.
- Type three: throwing down the sand river from height and compacting each layer to reach the desired depth with RD=75%. Where a steel container was divided into (5 cm) thickness layers with specific weight to each layer to verify the required relative density of sand.
2.2. The winged pile installation

The level of loading point at pile cap with respect to the ground surface (e) is equal to 50 mm. for pile installation, a 25 mm square hollow section made of steel with a dimension of 60 mm and 860 mm length is used, the hollow steel section used for leveling the pile vertically and fastened at the top of the container, and the pile model is tied at mid-point of it. The soil deposit must be prepared after the pile model is located vertically at its position. At a specific level of the soil in the container reached, the hollow steel rod section is removed, and the top surface of the sand layer was leveled. Finally, the sensor was put in its position, and the container is completely filled with sandy soil. After the soil preparation was taken place, and the container had been filled with soil, and the top surface layer is leveled; two dial gauges were used of 0.01 mm accuracy to measure the lateral and vertical displacements of the winged pile, which were fixed and installed with two holders of the magnetic stand base. The zero reading of load for the load cell connected to the pile cap is recorded, and static reading was recorded, as shown in Figure 2 (a, b, c, and d).

![Figure 2. Installation steps of the winged pile.](image)

2.3. Device of Lateral loading system

After the sand bed had been prepared and the piles installed, the lateral system is being worked, where the device manufactured by [8] is prepared and installed with the system for the test. The load cell is connected to the shaft of the hydraulic jack and the strain gauge linked to its logger by using wire. Two dial gauges are attached to the pile cap, one is attached to the upper surface of the pile cap to read a vertical displacement, and the second dial gage is connected to the thin side of the pile cap to read the lateral displacement, which is facing the load cell at the other side of pile cap as shown in Figure 3. Then the Ac drive operates to run the hydraulic jack and control the rate of movement according to the required work, and thereafter the shaft starts to move subsequently to the jack movement giving the incremental load readings which are recorded by digital weighing indicator, i.e., what load cell had been sensed during jack moving. The loading stops when the reading of the lateral dial gauge reaches 12mm displacement reading [9].
The load and strain gauge logger data are recorded and analyzed to give the proper results. The lateral loading system includes a horizontal hydraulic jack system and screw steel shaft connected to exert a horizontal load applied on the load cell from one side. The second side of the load cell is linked with a steel shaft with a penetration cone to apply a point load on the cap for the winged pile. The load cell is connected to the weighing indicator to read the applied load from the hydraulic jack, and the frequency of the horizontal jack is equal to 1.5 Hz.

2.4. Steel container
The inner dimensions of the container are (750×750×750 mm). It was made from five separated parts, one for the base and the four sides. Each part of the container was made by using a 6 mm thick steel plate, as shown in Figure 4. The boundary effects in the lateral direction for pile behavior is achieved from 13D to 30D according to ASCE (1990).

![Figure 3. System of lateral loading diagram.](image)

![Figure 4. Steel container.](image)

2.5. Soil characterization
The dry river sand is used in this study was brought up from the banks of the Tigris River. Many tests are carried out according to the standard specifications to clarify and identify both physical (Sieve analysis, Specific gravity, maximum and minimum dry density) and mechanical (Direct shear test) properties of sand used. The scale effects for the small-scale model are considered, which is related to the shear zone formation in the active region directly beneath the footing. Taylor [10] recommended that a model with a ratio of D/Ds should be at least (100) is used to avoid the particle size effect. In this study, the ratio of D/Ds is 142.8 matching the scaling law criteria. Three relative densities are used, 35% for loose sand, 60% for medium sand and, 75% for dense sand. The properties of sandy soil used are listed in Table 1. The soil is classified as poorly graded sand (SP), according to the Unified Soil Classification System (USCS).

2.6. Model piles and wings
The winged pile model used is made from hollow steel with closed-ended, and The model of strain gauges used is BF350 with a resistance of (350 Ohm). The length of each gauge is 7.1 mm and 4.5 mm width with a 2.1 sensitivity factor. The strain gauges are fixed corresponding to the winged pile axis with a distance between them is 150 mm starting from the top of the winged pile, as shown in Figure 5 (a and b). It has an outer diameter of (50 mm) and wall thickness equal to (2 mm). The wings are also made from steel and have a thickness equal to (2 mm) as shown in Table 2.
Table 1. Properties of the river sand used.

| Property                          | Value          | ASTM Standard |
|-----------------------------------|----------------|---------------|
| Specific gravity (Gs)             | 2.67           | D 854 [8]     |
| D10 D30 D50 D60 (mm)              | 0.15, 0.23, 0.35, 0.48 |             |
| Coefficient of uniformity, (Cu)   | 3.2            | D 422         |
| Coefficient of curvature, (Cc)     | 0.73           | D 2487        |
| USCS Soil classification          | SP             |               |
| Maximum dry unit weight [kN/m³]   | 17.7           | D 4253 [11]   |
| Minimum dry unit weight [kN/m³]   | 15.0           | D 4254 [12]   |
| Void ratio, (emax.)               | 0.6            |               |
| Void ratio, (emin.)               | 0.37           |               |
| Natural dry unit weight at R.D = 30, and 60% [kN/m³] | 15.7 and 16 |               |

Table 2. Properties of model piles and wings.

| Material                        | Steel   |
|---------------------------------|---------|
| Modulus of elasticity [GPa]     | 200     |
| Pile embedded length [mm]       | 200, 300, 400, 500 |
| Outer diameter [mm]             | 50      |
| Wall thickness [mm]             | 2       |
| Wing length (Lw) [mm]           | 56, 112 |
| Wing width (bw) [mm]            | 37      |
| Wing thickness [mm]             | 2       |

Figure 5. Schematic dimensions of examined winged piles.

2.7. Preparation of experimental setup
Three relative densities are used (35% of loose sand (L), 55% of medium sand (M), and 75% of dense sand (D)). The pouring of the sand river from height and after that compacted each layer to reach the
desired depth with \( RD = 75\% \). A steel container of \((750 \times 750 \times 750\text{mm})\) dimensions was divided into \((5\text{ cm})\) thickness layers with specific weight to each layer to verify the required relative density of sand. A uniform distribution of blows by a steel tamping hammer is employed to get the necessary relative density. A ruler of the sharp edge is used to get a flat surface as near as possible. Figure 6 (a and b) represent the steps of the sand soil preparation.

![Figure 6. Sandy soil preparation](image)

### 2.8. Testing program and strategy

This study used a parametric approach to analyze different aspects of wing geometry and numbers to assess their influence on the development of lateral capacity and single pile load deformation. Both the constant and the problem statement in Table 3 lists the variable parameters. Initial research into the behavior of under lateral load, model piles without wings were tested as a reference for comparison with winged piles are a type of pile with wings on it. For all examined piles, the wings were constructed perpendicular to the applied static loading direction at the upper part of the pile just beneath the soil surface of the embedded pile depth. This referred to an optimum location to gain a significant improvement on the ultimate load capacity.

### 3. Results and analysis

The pile load-displacement relationships of the experimental model pile with or without wings are plotted here. For \( P-Y \) curves, a horizontal displacement \( (U_x) \) for the pile head is expressed as a dimensionless ratio to pile diameter \( (D) \) as \( U_x/D \), and the ultimate lateral load is presented as \( P_{ult} \). Failure of piles took place when the lateral load corresponding to a horizontal displacement exceeds more than \( 10\% \) of the pile diameter [11]. In the case of a laterally loaded pile, the upper part of the soil around the pile is the most critical [12]. As a result, the wings were built at the top of the pile underneath the soil surface in all test series. This was a reference to the best position for gaining a large increase in ultimate load capacity. The application of the incremental acting loads is perpendicular to the wing plan in every test series.

The improvement ratio in lateral resistance due to wings is represented by the dimensionless factor \( (Ir) \). This factor is expressed as the ratio of the lateral load resistance of a winged pile compared to that of a regular pile.
Table 3. Parameters of model piles and wings.

| 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

3.1. Effect of wing length

Tests were conducted for various wing lengths by keeping the wing width (Ww/Dp = 0.74) is constant. The tests were carried out for different piles stiffens (L/D) to get the effective wing lengths. Figures 7 and 8 show that a great improvement in the lateral capacity is achieved by increasing the wing length. Results show that for pile stiffness of L/D = 10, 8, 6, and 4 and Dr = 35% and wing No.=3, the lateral pile capacity at failure was increased by (33.8, 40.7, 55.8, and 79%) for Lw = 112 mm, respectively as compared to the regular pile. The length of the pile and the area of the wings are the two most essential parameters in lateral force resistance.

In reality, the most effective location for soil resistance is the region perpendicular to the load direction. The effective area of a regular pile, for example, is the pile diameter multiplied by the pile length. However, the region above the wingtip of a winged pile has an effective area equal to the pile diameter plus the wings area (width of the wings multiplied by the length of the wings). As a result, the area behind the wings can greatly impact the induced passive resistance: the recorded strain readings and the bending stiffness of the pile. The bending moment profile can be used to calculate the P-y curves along the pile shaft and determine the soil-pile interaction response. Results show that for long piles (L/D = 10) with wing No.= 4 as shown in Figure 9. These graphs illustrate that the larger bending moments were measured in the piles fitted with wings. For the reference pile, the maximum moment was developed at approximately 180mm below ground level.

However, in the case of the winged piles with Lw = 56 mm, the maximum moment was found at approximately 145mm below ground level, and for Lw = 112 mm, the maximum moment was found at approximately 112mm below ground level. The maximum bending moments were found near the ground surface, and this is mean that the wings provide the additional fixity to the pile near the ground level. For all investigated models in this study, the maximum positive bending moment along the pile shaft occurs near the pile's midpoint, while a negative bending moment is generated beneath the rotation point. This behavior is agreed with Broms [13] about the laterally loaded pile in the cohesionless soils.
3.2. Effect of wings number
Tests focused on exploring the effect of a number of wings to increase the resistance of laterally loaded piles by keeping \( L_w = 112 \text{ mm}, \frac{W_w}{D_P} = 0.74 \) constant and using \( D_r = 35\% \), and change the number
of wings in the upper part of the pile by using two, three and four wings. The plot of the (P-Y) curves shows that as the number of wings increases and the loading direction acting on the largest reaction surface, that leads to an increase in pile capacity against lateral load, as shown in Figures 10 and 11. Results show that for pile stiffness of L/D = 10, 8, 6, and 4 and Dr = 35% and Lw = 112 mm, the lateral pile capacity at failure was increased by (25.2, 33.4, 44.9, and 56.9%) for two wings, respectively as compared to the regular pile, was increased by (33.8, 40.7, 55.8, and 79%) for three wings, respectively as compared to the regular pile and was increased by (33.1, 44.8, 58.4, and 77.5%) for four wings, respectively as compared to a regular pile.

Figure 10. P-Y curve for various wing numbers (L/D = 10 and 8).

Figure 11. P-Y curve for various wing numbers (L/D = 6 and 4).

3.3. Effect of slenderness's ratio L/D
The Pile slenderness's ratio (L/D) is varied from 4, 6, 8, and 10 to represent both short rigid and long flexible piles, respectively (pile stiffness) [14,15]. The slenderness ratio (L/D) greatly affects the lateral load capacity of winged piles, as confirmed by Figure 12, which shows that the higher stiffness improves lateral capacity. Results showed that for wing length 112 mm, wing No. 3, and pile stiffness of (L/D = 10), the lateral pile capacity at failure was increased by (33.8%), for (L/D = 8). The lateral pile capacity at failure was increased by (40.7%), for (L/D = 6), the lateral pile capacity at failure was increased by (55.8%), and for (L/D=4), the lateral pile capacity at failure was increased by (79%).
3.4. Effect of the relative density \((Dr\%)\)

The relative density \((Dr\%)\) was the last parameter to be assessed in this laboratory study. So, series of testing for different relative densities were carried out (Loose, Medium, and Dense). The relative density \((Dr\%)\) has an effect on increasing the lateral load capacity of winged piles, as confirmed by Figure 13, which shows that the higher relative density provides more improvement in lateral capacity. This is due to the fact that the shear strength of sand increases as it became denser \([16,17]\). Results showed that for wing length 112 mm, wing No. 3, and pile stiffness of \((L/D =10)\), the lateral pile capacity at failure was increased by \((16.6\%)\) for Dense sand, \((18.6\%)\) for medium sand, and \((33.8\%)\) for loose sand.

![Figure 12. P-Y curve for various slenderness ratios \((L/D=10, 8, 6\), and \(4)\).](image_url1)

![Figure 13. P-Y curve for various relative densities \((Dr=35, 60, \) and \(75\%)\).](image_url2)

4. Conclusion

In addition to vertical stresses, piles must be designed to withstand horizontal or lateral loads. Winged piles are innovative piling that improves the response to lateral loads. The performance of lateral loaded winged piles on sandy soil is investigated in this work. From the obtained results and after the comparisons between the response of winged and regular piles, and evaluating the objectives of determining the optimum conditions for the highest performance, the points below can be summarized:

- The use of wings on the pile in the foundation design greatly improves lateral load resistance and reduces lateral deflection. As a result, the total length and diameter of the pile will be reduced.
- Wings must be placed toward the top of the pile head to acquire higher resistance, and wings orientation must be perpendicular to lateral load in case of lateral loading.
• With the increasing length of the wings, the lateral resistance increases.
• For both long and short piles adjusting wings increases the lateral pile capacity by as much as (33.8 % and 79%), respectively.

References
[1] Grabe, J., Mahutka, K.P. and Dührkop, J., 2005. Monopilegründungen von Offshore-Windenergieanlagen–Zum Ansatz der Bettung. Bautechnik, 82(1), pp.1-10.
[2] Murphy, G., 2015. Experimental testing and finite element modelling of hybrid foundation systems for offshore wind turbines. Geotechnical Research Group, University College Dublin, Dublin, Ireland.
[3] Al-Neami, M.A., Samueel, Z.W. and Al-Noori, M.M., 2019, July. The influence of pile groups configuration on its stability in dry sand under lateral loads. In IOP Conference Series: Materials Science and Engineering (Vol. 579, No. 1, p. 012043). IOP Publishing.
[4] Nasr, A.M., 2014. Experimental and theoretical studies of laterally loaded finned piles in sand. Canadian Geotechnical Journal, 51(4), pp.381-393.
[5] Grabe, J. and Duhrkop, J., 2007. Improving of lateral bearing capacity of mono-piles by welded wings. In Proceedings of the 2nd international conference on foundations. HIS BRE Press, Garston, UK (pp. 849-860).
[6] Lee, P.Y. and Gilbert, L.W., 1980. The behavior of steel rocket shaped pile. In Symposium on Deep Foundations (pp. 253-273). ASCE.
[7] Allen, P.G., Digeo Inc, 2002. Remote control device for video and audio capture and communication. U.S. Patent 6,489,986.
[8] Shlash, K.T., Al-Neami, M.A. and Al-Lami, A.S., 2017. Behavior of single pile subjected to lateral soil movement in different rates. Journal of Scientific and Engineering Research, 4(5), pp.51-58.
[9] Al-Neami, M.A., Baqir, H.H. and Hameed, S.H., 2021. Behavior of Single Micropile Under Different Lateral Load Rates. Engineering and Technology Journal, 39(2A), pp.27-63.
[10] Taylor, R.N., 1995. Geotechnical Centrifuge Technology. First ed, Chapman and Hall, London.
[11] Mohamedzein, Y.E., Nour Eldaim, F.A.E. and Abdelwahab, A.B., 2013. Laboratory model tests on laterally loaded piles in plastic clay. International Journal of Geotechnical Engineering, 7(3), pp.241-250.
[12] Zhang, L., 2009. Nonlinear analysis of laterally loaded rigid piles in cohesionless soil. Computers and Geotechnics, 36(5), pp.718-724.
[13] Broms, B.B., 1964. Lateral resistance of piles in cohesionless soils. Journal of the Soil Mechanics and Foundations Division, 90(3), pp.123-156.
[14] Broms, B.B., 1964. Lateral resistance of piles in cohesive soils. Journal of the soil mechanics and foundations division, 90(2), pp.27-63.
[15] Boominathan, A. and Ayothisraman, R., 2007. An experimental study on static and dynamic bending behaviour of piles in soft clay. Geotechnical and Geological Engineering, 25(2), pp.177-189.
[16] Salini, U. and Girish, M.S., 2009. Lateral Load Capacity of Model Piles on Cohesionless Soil. Electronic Journal of Geotechnical Engineering, 14, pp.1-11.
[17] Rahil, F.H., Al-Neami, M.A. and Al-Zaho, K.A.N., 2016. Effect of relative density on behavior of single pile and piles groups embedded with different lengths in sand. Engineering and Technology Journal, 34(6 Part (A) Engineering).