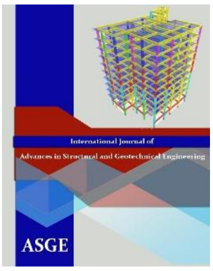

International Journal of Advances in Structural and Geotechnical Engineering

https://asge.journals.ekb.eg/

Print ISSN 2785-9509 *Online ISSN 2812-5142*

Special Issue for ICASGE'19

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ASGE Vol. 03 (02), pp. 38-50, 2019

Uplift Capacity of Single Pile with Wing in Sand-Numerical Study

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ABSTRACT

Designing pile foundations to resist uplift forces is becoming of increasing concern, and is especially prevalent in the design of lightweight steel frame buildings or on sites with residual soils. This paper introduces a modern pile-modification strategy known as winged pile that increases pile-tension capacity by providing an affirmative anchorage close to the pile tip. In this study, a nonlinear 3D analysis with an elastic plastic soil model, an elastic pile material and interface elements are used to model the modified pile–soil interaction. A numerical study using finite element analysis PLAXIS-3D was run on piles without/with wings. Studies were done by changing the wing-width ratio (D_w/d_p = 2, 3, 4 and 5), number of wings (n_w = 0.0, 2 and 4). The effect of sand relative densities were also considered. Results indicated that the adopted wings at the pile end have a considerable effect in increasing the uplift capacity with lesser deformation. It has been found that, for the same wing-width ratio (D_w/d_p), the wing efficiency for uplift capacity increases as the sand relative densities increase. For the wing-width ratio (D_w/d_p of = 5) and number of wings of (n_w =4) the improvement in the uplift capacity are found to be (2.2, 2.33 and 2.45) times of normal pile without wings for sand density of (30, 50 and 80%) respectively. The existence of such wings at the lower part of the piles was provided an ideal anchorage system because of the significant locking-up effect of the soils within the wings, resulting in increased uplift capacity.

Keywords: *Wing pile; Uplift capacity; Plaxis 3d and sand.*

INTRODUCTION

Structures like marine dolphins, dock-fendering systems, tower foundations, submerged platforms, and bridge abutments are constructed on pile foundations, which are subjected to tension loads. Typical piles that can be subjected to tension loads include steel pipe piles, steel H-piles, anchored piles, modified enlarged end, screw piles, bladed piles and finned piles. Therefore, extensive investigations were carried out to find a pile-modification technique that increases pile-tension capacity. These techniques, for example, were aimed at providing a more positive tool at a certain depth along the pile by modifying the pile shape to get a beneficial effect. Enhancing the axial response of piles was investigated by altering the pile shape to be pyramidal or tapered (Appolonia and Haribar 1963; Bakholdin 1971; Kodikara and Moore 1993; El Naggar and Wei 1999; Ghazavi 2008). An alternative method to improve the uplift capacity of a single pile was to use surcharge loading at the top surface around the pile head (Azzam and Al Mesmary 2010). The pullout capacity of earth anchors has been investigated by several researchers; these include: circular plate anchors (Harvey et al 1973; Meyerhof 1973 and Sutherland et al 1983), square and rectangular plate anchors (Hanna et al 1992; Hanna et al 2011; Meyerhof 1973 and Wang et al 1980) and strip and slab anchors (Frydman et al 1989; Kulhawy 1985; Meyerhof 1973). Other investigators studied an alternative technique to improve the uplift capacity of piles using screw-pile technology. Screw pile foundations are usually used to resist tensile loads. A helical anchor/pile consists of one or more helix-shaped bearing plates attached to a central shaft, which is installed by rotating or "torqueing" into the ground. Helical anchors/piles derive their Load carrying capacity through both end bearing on the helix plates and skin friction on the shaft. The performance of screw piles under tension loading has been investigated in several studies (Mitsch and Clemence,1985; Ghaly et al 1991-a; Rao and Prasad, 1993; Ghaly and Clemence 1998; El Naggar and Abdelghany 2007a, b; Sakr 2009; El Sharnouby and El Naggar 2012; Tsuha et al. 2013; Abdelghany and El Naggar 2014 and Sakr et al 2016). These investigations showed that the performance of a single screw pile during installation and pullout procedures depends on the blade diameter, installation depth, and sand characteristics. It is also showed a great improvement in the uplift capacity for a single pile compared with a normal pile. In contrast, underreamed piles (or belled piles) were used to improve the uplift capacity of a pile under tension. Underreamed piles are bored cast in-situ concrete piles having one or more bulbs formed by enlarging the pile stem as discussed by Dickin and Leung (1990). They are used to increase tip strength of compressive piles and the bearing capacity of tensile piles, so they have advantages over uniform diameter piles. The bulbs can be provided at desired depths at which substantial bearing or anchorage is available. The potential benefits of this technique, proving its effectiveness in increasing uplift capacity, were studied by (Balla 1961; MOHAN, et al. 1969; Dickin and Leung 1990; Farokhi, et al. 2014; Hamid Alielahi, et al. 2014; Harris, et al. 2015; George, et al. 2015; Rahman et al. 2017. Other investigators studied an alternative technique to improve the uplift capacity of piles using straight fins at the pile end, around the perimeter named finned pile. Spin finned piles are driven piles with welded fin attachments that modify pile behavior under tension. They can be easily installed in oceanic sites by driving or using a vibratory hammer. Spin-finned piles are a cost-saving alternative in many pile foundation applications. To improve the lateral capacity of monopile foundations, fins at the pile top are used as foundations for offshore wind farms (Lee and Gilbert 1980; Peng 2006). Finned pile is described as a pile that has four plates welded to the top of a traditional monopile at 90° angles to each other. The fins are fixed at the upper part of the pile to improve the lateral pile response under large horizontal load as discussed by Peng et al. (2004, 2010, 2011) and Lutenegger (2012). These studies showed that lateral resistance increases with the increase of fin length ratio (Lf/L). Optimum fin efficiency is attained when the Lf/ L equals 0.5. The importance of the fins relates mostly to both pile stiffness and sand density. In stiff soil, the rigidity of the fins has to be greater than that in soft soil to attain a similar advantage (Duhrkop and Grabe 2008). It has been found that the majority of papers in the literature have focused on only using such fins to progress the lateral piles response. However, studies on the subject of the spin-fin technique in tension are limited, and there is a lack of geotechnical knowledge of such techniques for improving the uplift capacity of piles under tension loads (Azzam and Elwail ,2016).

Based on the paper in literature, it has been found that the regular pile has modified to resist uplift loads. Therefore, the present research aims to investigate an alternative technique to improve the ultimate uplift capacity of single pile under uplift loads in dry sand using wings at a studied depth along the pile. The wing piles under uplift load were modeled using the commercial finite element program PLAXIS 3D Foundation (Plaxis Inc. 2010), and their performance was evaluated in sandy soils. The uplift load responses and load capacities of wing piles embedded in sand were investigated in comparison to regular piles without wings

Three-dimensional finite element analysis and procedure

Recently, Farokhi, et al. 2014; Hamid Alielahi, et al. 2014; George, et al. 2015 presented a three-dimensional (3D) finite element analysis to simulate an uplift load test using the PLAXIS program. The numerical modeling techniques based on the finite element (FE) provide versatile tools that are capable of modeling soil continuity, soil nonlinearity, soil – pile interface behavior, and 3D boundary conditions. Therefore, a series of FE analyses on model-regular piles and winged piles subjected to uplift loading and soil conditions as in the model tests were carried out using the 3D nonlinear computer program PLAXIS 3D Foundation (PLAXIS Inc. 2010).

Finite element mesh and boundary conditions

To perform the finite element calculations, the geometry must be divided into elements. A composition of finite elements is called a finite element mesh. PLAXIS 3D Foundation (PLAXIS Inc. 2010) incorporates a fully automated mesh-generation procedure to create the 3D FE mesh. The 3D mesh was generated into a 3D mesh composed of 15-noded wedge elements. The 15-noded wedge element is composed of 6-noded triangles in the horizontal direction and 8-noded quadrilaterals in the vertical direction. According to Zienkiewicz and Taylor (1994) for the above type of 3D elements, three nodes are located along each edge, which provide a quadratic approximation of the displacement field within the volume of the element. The mesh was automatically generated from the software package and consisted of 6483 elements and 10040 nodes for a regular pile. The typical 3D FE mesh used to analyze a pile subjected to uplift load is shown in figure 2. According to Karthigeyan et al. (2006, 2007), and Nasr 2014, the soil mass dimensions depend on the pile diameter and length. Therefore, the boundary is a cube with sides 50 times the diameter of the pile and a height equal to the pile length (L_P) plus a further $1.0L_P$ below the pile-toe level. These dimensions were considered adequate to eliminate the influence of boundary effects on the pile performance (Wallace et al. 2002). The bottom boundary was fixed (x – y bottom plane) against movements in all directions (x, y, and z), whereas the ground surface was free to move in all directions. Nodes on the end of the (x – z) and (y – z) planes, were restrained in the y and x directions, respectively.

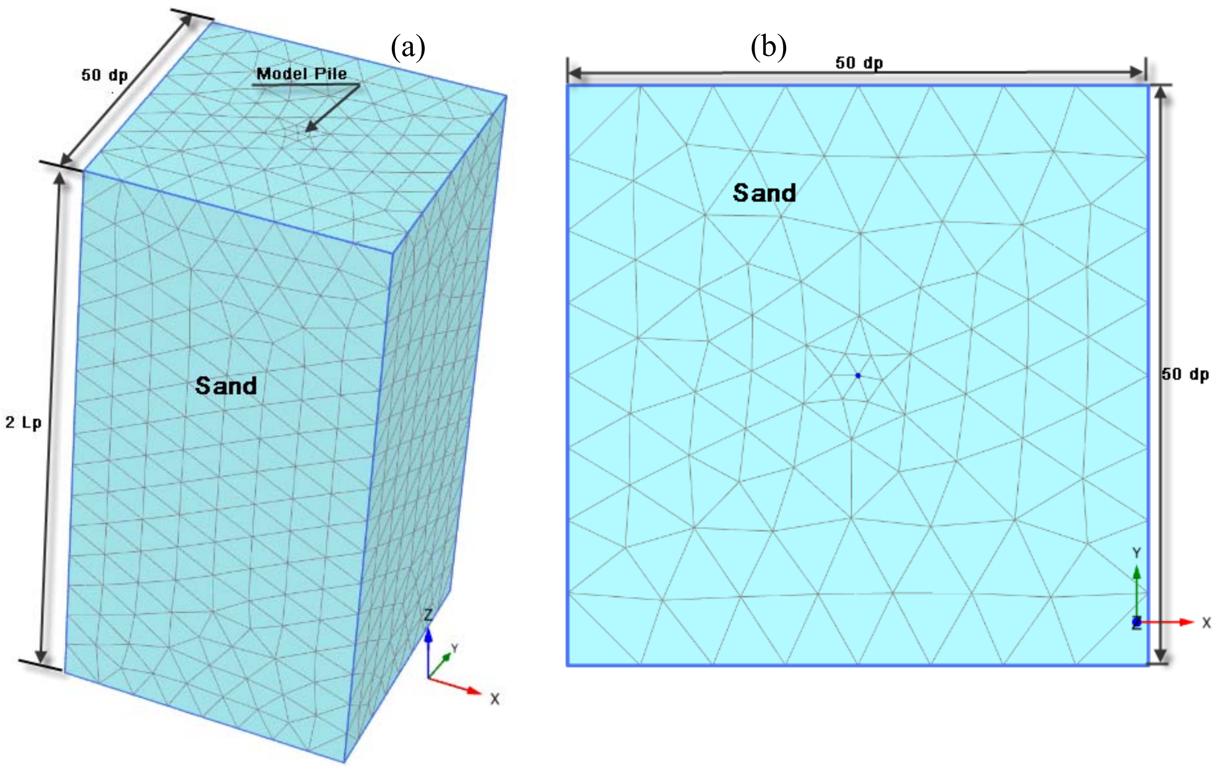

Fig. 2. Finite element used to model the uplift loaded pile showing (a) three-dimensional mesh and (b) plan of the mesh.

Material parameters and interface modeling

The investigations were carried out by varying the wing-width ratio (D_w/d_p), number of wings (n_w). Furthermore, model piles were installed in sand of different relative densities. The advantage of developing such a finite element model is that it can be used to examine various configurations that have not been modeled experimentally in the study. Subsequently, the behavior of these wing piles under uplift loading is discussed.

The soil and pile were modeled with finite elements, which allowed for rigorous treatment of the soil – structure interaction. The Mohr – Coulomb (MC) material model was used to simulate the nonlinear sand behavior because of its simplicity, reasonable number of model parameters, and reasonable accuracy in modeling the behavior of uplift loaded pile problems. The analysis of uplift loaded piles in sand is conducted under drained conditions to model the regular and wing piles. The elastic–plastic MC model involves five basic input parameters: elasticity modulus (E), Poisson's ratio (υ), internal friction angle (φ), cohesion (c), and dilatancy (ψ). The friction angles and elastic modulus of the sand were calculated based on the drained triaxial compression test results for the loose, medium and dense sands. The dilatancy angle (ψ) of the sand was evaluated according to the equation proposed by PLAXIS for quartz sand (ψ=φ– 30˚). The value of the secant elastic modulus (E_{50}) of the sand, in loose, medium and dense sand conditions, was obtained from the drained triaxial compression tests. The value of (c) in the analysis was zero. The initial stress in the numerical modeling was generated using Jaky's formula, which gives the at rest earth pressure coefficient Ko = 1 – sinφ (Jaky 1944). Table 1 summarizes the hyperbolic model parameters used in the analysis.

The piles and wings were assumed to be linear elastic mild steel materials, which have typical properties of Young's modulus E_P and Poisson's ratio υ_P (see Table 1). The pile length is 10.0 m with outer diameter of 0.20 m and thickness of 30 mm. Otherwise the wing length is 2.0 m with variable wing width ratio (D_w/d_p) of (2, 3, 4 and 5) with area cross section of 25 cm^2 see figure 3. The yield of steel was not considered in the study. The modeling of the pile installation process is rather complicated, so the pile is assumed to be in a stress-free state at the beginning of the analysis, and the effect of the pile installation is ignored.

Finally, to model the interaction between the sand and pile an interface element was created along the circumference of the pile. A decreased value of shear modulus is assigned to the interface when a slip mode occurs in the interface element. The decrease of strength for the interface element is represented by a strength reduction factor (R_{inter}) in PLAXIS. The strength reduction factor of the interface (R_{inter}) is set to 0.65 for sand, which is typical of sand–steel interfaces Peng et al 2010 and Nasr 2014. This factor relates the interface properties to the strength properties of a soil layer as follows:

$$\tan \emptyset_{inter} = R_{inter} \tan \emptyset_{soil} \qquad \text{eq(1)}$$

$$c_{inter} = R_{inter}\, c_{soil} \qquad \text{eq(2)}$$

$$\psi_{inter} = \begin{cases} 0.0 & \text{if } R_{inter} < 1.0 \\ \psi_{soil} & \text{otherwise} \end{cases} \quad . \qquad \text{eq(3)}$$

Where $\emptyset_{inter}$, C_{inter}, and ψ_{inter} are the friction angle, cohesion, and dilatancy angle of the interface, respectively.

NUMERICAL PROGRAM AND MODEL VALIDATION

In this study the full-scale pile is simulated using Plaxis 3D program in order to avoid the problem of field study and limited investigated variable. First, the FE analysis was validated with the experimental study of Azzam and ElWkil, 2016 to ensure the program's ability to solve the geotechnical problems of a prototype regular and finned piles in the field. Second, after ensuring the program's capability through the validation process, the analysis further investigated the behavior of a large-scale problem model of regular and wing piles under new parameters. Initially, the numerical model was verified via the results obtained from the experimental test program of Azzam and ElWkil, 2016. Two series of validations were used to validate the results of numerical parametric studies. The first series included uniform cross-section conventional cylindrical piles with (Slenderness ratio (L/D) = 30.0 at relative density, Dr= 50%). The second series included finned piles with (Fin inclination angles (β) = 90˚, Fin-width ratio (b/D) =1.0 and Slenderness ratio (L/D) = 30.0 at relative density, Dr= 50%) and the results of the two series of the present study were compared with the experimental study of Azzam and ElWkil, 2016. The soil was modeled as Mohr–Coulomb (MC) material model with drained behavior. The soil domain is considered according to dimension of tested tank of (750X750mm in length) and 700mm in height. The elastic–plastic MC model involves five basic input parameters: elasticity modulus (E = 9500 kPa), Poisson's ratio ($\upsilon = 0.33$), internal friction angle ($\varphi = 30^{\circ}$), cohesion (c = 0.0), dilatancy (ψ = 0.0) and unit weight, γ = 16.01 kPa. The regular and finned piles were assumed to be linear elastic mild steel materials with Young's modulus E_P = $2.0X10^8$ kPa and Poisson's ratio υ_P = 0.30, unit weight, γ = 78 kPa. The pile length is 30 D_p with outer diameter of 20mm and thickness of 2.0 mm. Otherwise the finned length is 120.0 mm with thickness of 5.0 mm and width of 20.0mm. From figure 1(a and b), it is clear that the ultimate uplift loads obtained from numerical analyses (model regular piles and finned piles) are in close agreement with the results from experimental tests of Azzam and ElWkil, 2016. The difference between the ultimate uplift loads obtained from numerical analyses (model regular piles) and experimental results varies from 3.1% to 8.33%. However, the difference between the ultimate uplift loads obtained from numerical analyses (model finned piles) and experimental results varies from 4.7% to 8.22%. Moreover, it is evident that when the vertical displacement at the top of the pile is less than 0.5% of the pile diameter, the predicted loads from numerical analyses are approximately like that predicted by the experimental model results. On the contrary, when the vertical displacement is more than 0.5% of the pile diameter, the difference between the predicted loads from numerical analyses and the experimental model results increases significantly. Finally, it is concluded that, the numerical results follow the trend of the experimental test results, and acceptable agreement is achieved with a minimum difference around 8 %. Thus, the adopted PLAXIS 3D model was shown to be proficient in predicting the behavior of prototype in the field in comparison with the small model test.

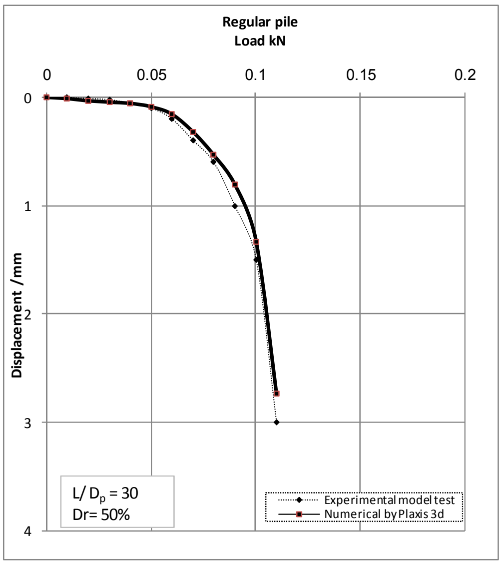

Fig. 1a: Comparison of experimental model test results of of Azzam et al 2016 and numerical study by Plaxis-3D for regular pile.

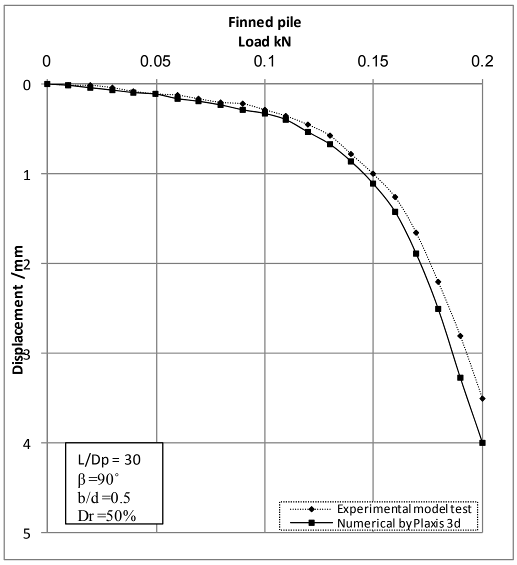

Fig. 1b: Comparison of experimental model test results of Azzam et al 2016 and numerical study by Plaxis-3D for finned pile.

TEST RESULTS AND DISCUSSION:

Load- displacement curves

The behavior of winged piles can better be assessed with the help of the results obtained from the Load-displacement curves for winged piles at different wing width ratio. Due to the limit space, some of the load -displacement curves are exhibited as shown in Figs.(4 to 6). The displacement (S) of the winged pile is expressed in non-dimensional form in terms of pile diameter (d_p) as percentage ratio (S/d_p, %).

Table 1. Material parameters used in the finite element analysis.

Parameter	Loose sand, Dr=30%	Medium dense sand, Dr=50%	Dense sand, Dr=80%	Pile and Wings
Material model **according to Nasr, 2014**	Mohr - Coulomb soil model	Mohr - Coulomb soil model	Mohr - Coulomb soil model	Linear elastic
Type of material behavior, **according to Nasr, 2014**	Drained	Drained	Drained	Nonporous
Secant elastic modulus,E50 (kPa), **according to Bowles, 1996**	21000	26500	32000	2.1×10^8
Unit weight, γ (kPa), **according to Sakr et al 2016**	15.7	16.45	17.68	78
Poisson's ratio, υ **according to Peng et al, 2010**	0.33	0.33	0.33	0.3
Cohesion, C (kPa), **according to Peng et al, 2010**	0.0	0.0	0.0	----------
Friction angle, (Ø) ° **according to Sakr et al 2016**	35.4	37.6	40.2	----------
Dilatancy angle, (ψ) ° **according to Nasr, 2014**	5.4	7.6	10.2	----------
Interface reduction factor, Rinter **according to Nasr, 2014**	0.65	0.65	0.65	----------

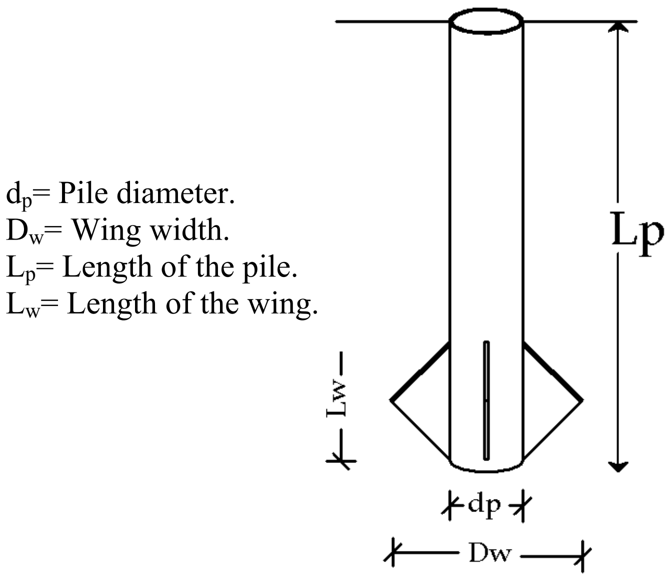

Fig.3. A schematic diagram of a wing pile.

First, the definition of the failure load to obtain the uplift capacity of the pile is considered as the point which the load- displacement curve becomes linear (Ghaly, et al 1998).

The existence of wings can significantly modify the load displacement behavior of regular pile and improve the uplift capacity in accordance of embedment depth and sand density. Figure 4 presents typical load- displacement curves for piles with and without wings at relative density of 30% and number of wings of 4.0. The corresponding uplift capacities were 850, 900, 1000 and 1100 kN for winged pile at (D_w/d_p) ratio of 2, 3, 4 and 5 respectively. While, this value is 500 kN for regular pile without wings. It has been clearly observed that the ultimate uplift capacity of the pile increases with the increase of the wing width ratios (D_w/d_p); however, the regular pile without wings has the least uplift capacity. It is noticed that the maximum normalized displacement at the pile’s failures is increased as the sand relative density increased. This trend is observed for all test results. For the same uplift load, the vertical displacement is decreased significantly as the wing width ratios (D_w/d_p) increased.

Figure 5 shows the typical load-displacement curves for piles with and without wings at relative density of 50% and number of wings of 4.0. The corresponding capacities were 1100, 1200, 1300 and 1400 kN for winged pile at (D_w/d_p) ratio of 2, 3, 4 and 5 respectively. However, this value is 600 kN for regular pile without wings. On the other hand, the load- displacement curves for piles with and without wings at relative density of 80% and number of wings of 4.0 is illustrated in figure 6. It is also noticed that, the corresponding capacities were 1400, 1500, 1600 and 1700 kN for winged pile at (D_w/d_p) ratio of 2, 3, 4 and 5 respectively. But, this value is 700 kN for regular pile without wings. It can be concluded that the ultimate uplift capacity of winged piles was reached to maximum value when the wing width ratio within the range of D_w/d_p = 5 for all test series. But its ultimate uplift capacity is related to number of wings and sand relative density.

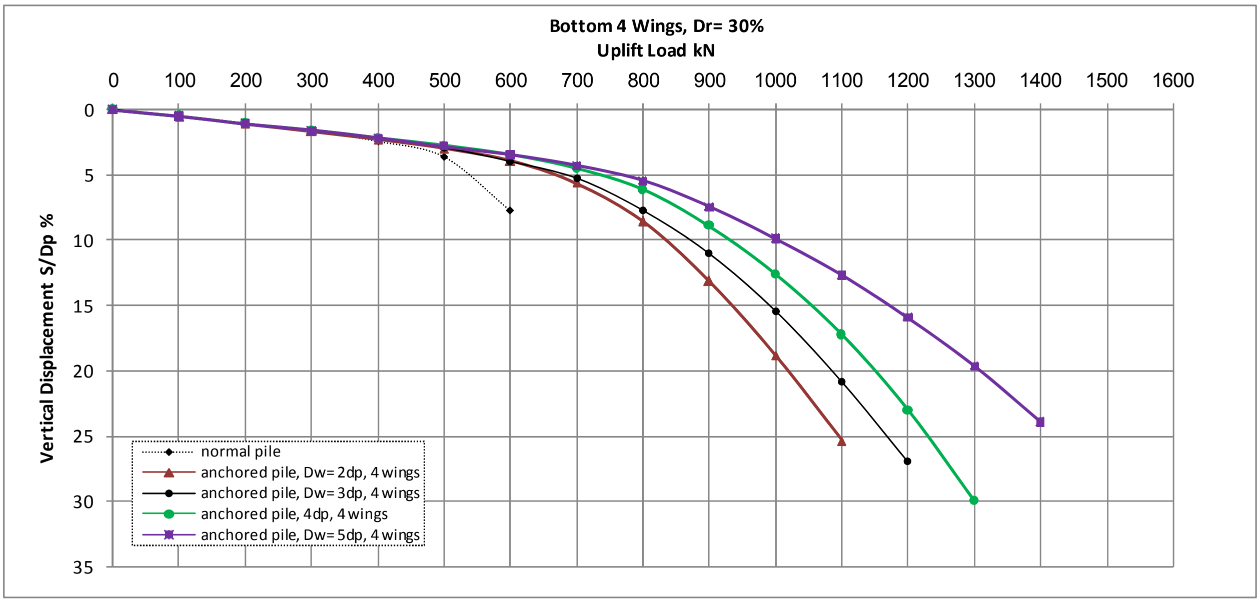

Fig. 4: Variation of uplift load with normalized vertical displacement for Dr =30%, with number of wings of 4.0 in different wing width ratio

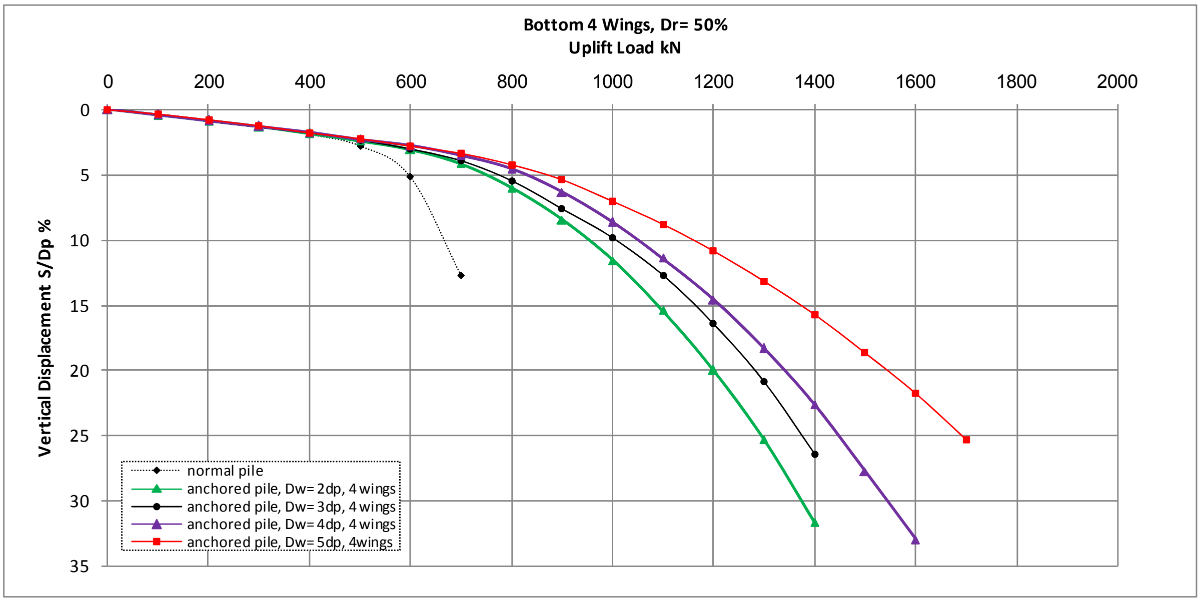

Fig. 5: Variation of uplift load with normalized vertical displacement for Dr =50%, with number of wings of 4.0 in different wing width ratio

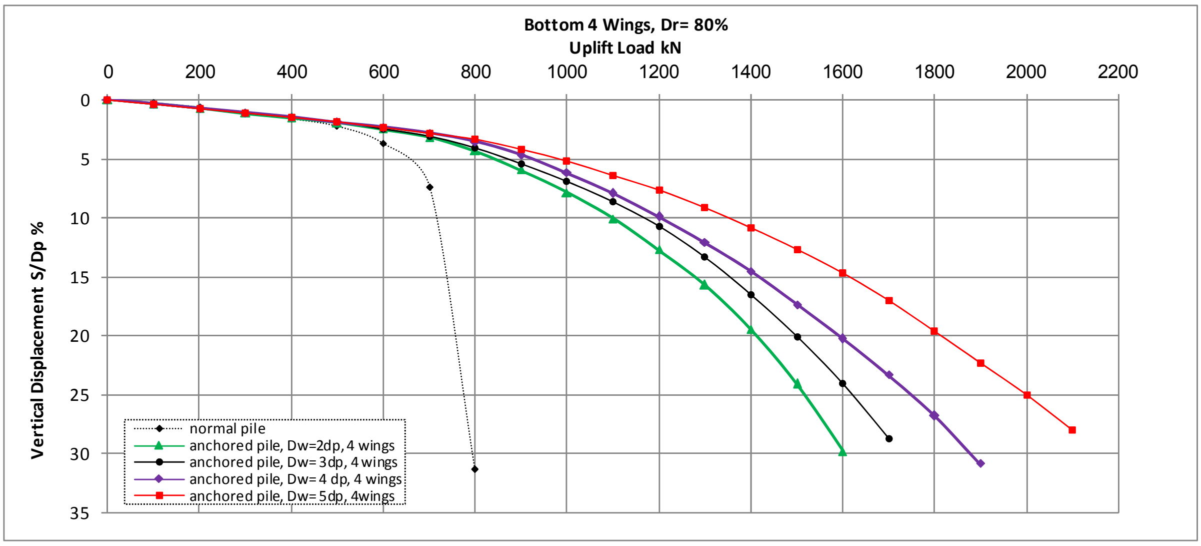

Fig. 6: Variation of uplift load with normalized vertical displacement for Dr =80%, with number of wings of 4.0 in different wing width ratio

Influence of wing width ratio (D_w/ d_p) and sand relative density:

The effect of wing width ratio, (D_w/d_p) on the uplift capacities of wing piles at different sand relative density was studied. Figures 7 and 8 show the significant effect of wing width ratio, (D_w/d_p) on the efficiency of improvement for the ultimate uplift capacity in the form of dimensionless factor (α). This load factor can be expressed as the ratio of Q_{ult} /Q_{ulto} where Q_{ult} is the ultimate uplift capacity for winged piles and Q_{ulto} is the ultimate uplift capacity for regular pile without wing. It is observed that the load factor ratio (α), for ultimate uplift capacities increases as the ratio (D_w/d_p) increased. However, for the same wing width ratio, (D_w/d_p), the load factor for ultimate uplift capacities are increased as the sand relative density increased. Figure 7 confirms and shows that the ultimate uplift capacity of wing pile under vertical loads was reached to 2.30 times of ultimate uplift capacity of regular pile without wing at dense sand. It is noticed that, the percentage of increase in the load factor ratio, (α) for uplift capacities in cases of medium and dense sand compared with loose sand is found to be 6.7 and 23.3 % respectively at D_w/d_p of 2. These percentages were found to be 9.4 & 25.0 % for D_w/d_p of 3. However, these values were found to be 7.6 & 26.5% for D_w/d_p of 4. Finally, these values were found to be 11.11 & 27.8 % for D_w/d_p of 5. On the other hand, Figure 8 again justified that at the range of D_w/d_p of 5, the load factor is obtained 2.45 times of ultimate uplift capacity of regular pile without wing at dense sand.

The improvement in uplift capacity due to such wings which can be resulted due to formation of embedded block at the end of the pile toe. It should be mentioned here that, the soil between wings behaves like one unit and densified zone. This zone is depended on the number of used wings where as the number of wings increased the soil block inside the wings is increased. This can be confirmed by data obtained in figures (7&8) for two and four wings. It can be concluded that using four wings significantly increased uplift load capacity compared with two wings due to soil inside wings interaction which tend to create one block.

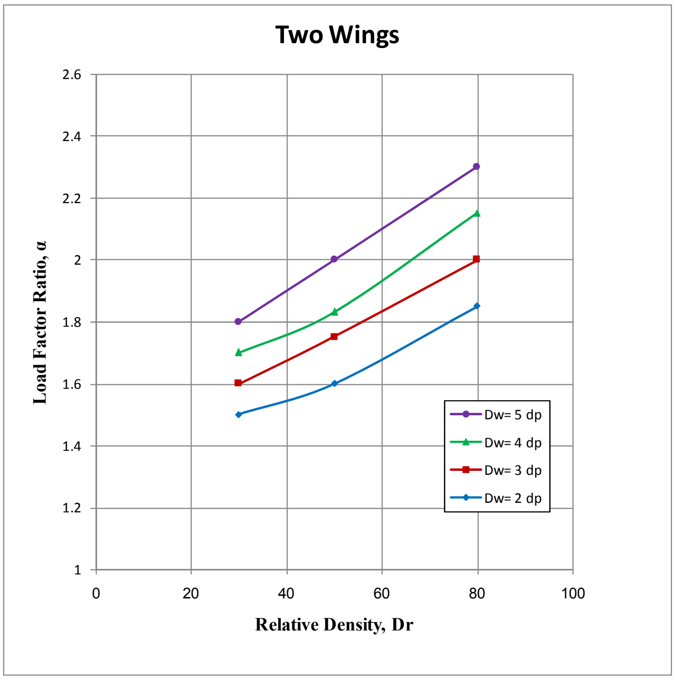

Fig. 7: The relationship between the load factor ratio, (α) and the sand relative density for ultimate uplift capacity at different wing width ratio with Nw of 2.0.

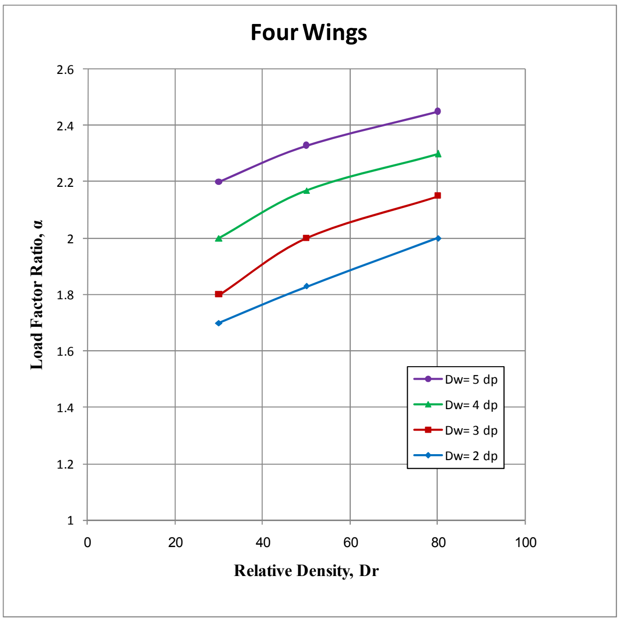

Fig. 8: The relationship between the load factor ratio, (α) and the sand relative density for ultimate uplift capacity at different wing width ratio with N_w of 4.0.

CONCLUSIONS

A numerical program of full scale was undertaken to study the ultimate uplift capacity of vertical winged pile. The study primarily focused on determining the effect of wing width ratio, D_w/d_p. Values of ultimate uplift capacity, of winged pile embedded in different densities of sand are compared with regular pile without wing. This technique can be considered as a novel one to improve the vertical pile response under uplift loads.

Salient conclusions that can be drawn from the present study are as follows:

1. The ultimate uplift capacities for winged piles embedded in different densities of sand are increased with the increase of sand relative density.
2. The uplift displacement of winged pile is decreased as the number of wings and sand density increased
3. As the wing width ratio, D_w/d_p increases the load factor ratio (α) for ultimate uplift capacities of winged piles are increased.
4. The uplift capacity of winged pile with four wings at dense sand is 2.45 times of regular pile without wing. This value is dropped to 2.20 times in loose condition.
5. The uplift capacity of winged pile with two wings at dense sand is 2.30 times of regular pile without wing. This value is dropped to 1.80 times in loose condition.

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