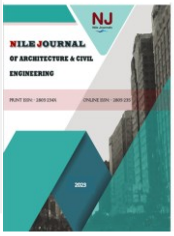
Nile Journal of Architecture &Civil Engineering

Journal Webpage: https://njace.journals.ekb.eg

Volume 1, Jan. 2024



# Numerical Investigation of the Behavior of Group-Finned Piles in Sandy Soil Subjected to Tensile Loads

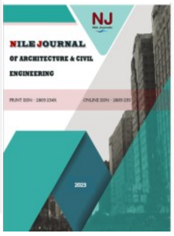
Maher T. EL-Nemr[1]. Waseim R. Azzam[2]. Ehab K. Gaber[3]. Omar Ashour[4]

1. Prof. of Geotechnical Engineering, Civil Engineering Department, Menoufia University, Egypt,
**E-mail:** yos_el_nemr@hotmail.com.
2. Prof. of Soil Mechanics and Foundation, Structural Engineering Department, Tanta University, Egypt,
**E-mail:** azzam_waseim@yahoo.com, wassim.rajab@f-eng.tanta.edu.eg
3. Lecture in Civil Engineering Department, Menoufia University, Egypt,
**E-mail:** ehabkhirt@gmail.com, ihab.khairt@sh. eng.menofia.edu.eg
4. Lecture in Civil Engineering Department, Sinai University, Egypt,
**E-mail:** Omar.Moustafa@su.edu.eg, omar.ashour@sh-eng.menofia.edu.eg

## Abstract

Numerous towering structures such as dock-fendering systems, abutments, marine dolphins, transmission towers, and high-rise platforms, which experience substantial uplift loads, rely on deep foundations for support. In this research, we have introduced an innovative pile modification technique aimed at enhancing traditional piles, known as the "finned pile." This modification involves the addition of four fins, welded around the lower circumference of the pile, to augment its tensile capacity. Numerical simulations were conducted to subject various pile groups and spacing configurations to axial static tension loading. Throughout all test scenarios, consistent parameters such as fin width, fin length, number of fins, embedment depth, and pile diameter were maintained to assess the effectiveness of this pile modification strategy. The analysis utilized the PLAXIS 3D Foundation as its numerical modeling program. The findings demonstrated a noteworthy enhancement in the uplift capacities of pile groups with fins when compared to traditional piles without fins. For finned pile groups featuring different L/d ratios of 10, 20, and 26, the respective capacities reached 450 Kg. Conversely, the normalized displacement ratio exhibited an uptick with higher L/d ratios, measuring 0.4, 0.9, and 4.4, respectively. Consequently, there was a marginal performance improvement in finned pile groups with increasing ratios. Moreover, the performance of the pile groups saw a significant enhancement as the soil Dr (Relative Density) increased. For varying $W_f$ (Finned Pile Width), the ultimate load of finned pile groups showed a slight rise with increasing $W_f$ while keeping the fin length constant. In contrast to single fin piles, $W_f$ exhibited an increase as the ultimate load rose.

**Key words:** Tension load; Group finned piles; Pile cap; Sand.



| **Dp** | **Diameter of the pile;** | **Lp** | **Length of the pile;** |
|---|---|---|---|
| $D_r$ | Relative density of soil; | $E_b$ | Modulus of Elasticity of material |
| G | Specific gravity for the soil; | C | Cohesion of soil; |
| L/d | Length/diameter ratio; | $D_{10}$ | Particle size at 10% finer.; |
| Lf | Fin length; | $D_{30}$ | Particle size at 30% finer.; |
| SW | well-graded sand | $D_{60}$ | Particle size at 60% finer.; |
| Cu | Uniformity Coefficient; | Cc | Coefficient of curvature; |
| $K_{ST}$ | relative stiffness of the soil-foundation system | $E_s$ | Modulus of Elasticity of soil |
| $R^2$ | Coefficient of determination; | ***Greek letter*** | |
| $R_{inter}$ | Rigidity; | $\gamma$ | Unit weight of soil; |
| S/D | Spacing/Diameter ratio; | $\varphi^\circ$ | Angle of internal friction; |
| $W_f$ | Fin widths; | $\psi$ | Dilation angle; |

***Abbreviations***

| | | | |
|---|---|---|---|
| **FEM** | Finite element modeling; | **SPSS** | Statistical Package for the Social Sciences; |
| **RMSE** | Root Mean Square Error; | **USCS** | Unified Soil Classification System. |
| **RMSD** | Root-mean-square deviation | | |

## 1. Introduction

Piles serve as elongated structural elements that facilitate the transfer of loads from upper structures to deeper, more robust soil layers with enhanced load-bearing capabilities, thus avoiding the weaker, shallow strata. The primary materials employed for constructing piles are wood, steel, and concrete, and on occasion, composite piles combining two or more of these materials are employed. Piles are installed in the ground using methods such as driving, drilling, or jacking, and they are affixed to caps at their upper ends. [4]

The findings from an extensive experimental study involving the testing of screw piles featuring single, double, and triple cylindrical screw helices installed in the respective soil were presented by [5] . In his research, the load tests encompassed a range of assessments, including uplift tests on both pile groups and individual piles. All these tests maintained a constant helix spacing, pile embedment depth, number of helixes, and helix diameter. However, the number of piles and their spacing varied to assess the effectiveness of pile groups.

The test results illuminated several key findings. Firstly, they indicated that the helical resistance of piles to axial uplift increases as the embedment ratio (H/dh) rises. Similarly, for a given H/dh ratio, the axial uplift resistance of the piles increases as the relative density (Dr) of the surrounding soil increases. Additionally, as the helix diameter expands, so does the axial uplift capacity. Furthermore, the rate of increase in uplift capacity accelerates as the soil's Dr increases.

In loose soil conditions, the group efficiency approaches 100% when the spacing between helices is three times their diameter, while for two-helix-diameter spacing, it falls below 100%, and for three-helix-diameter spacing, it surpasses 100%. However, in medium and dense soils, the efficiency of pile groups was found to be lower than that observed in loose soil conditions.

Lastly, the study noted that group efficiency decreases as the relative density of the sand (Dr) increases. Simultaneously, group efficiency rises with both increased piles spacing and a greater number of piles within the group.

The performance of screw piles has been investigated in several studies under tension loading [3.9.12.16 and 22]. The utilization of screw-pile foundations was chosen to counteract tensile loads. These investigators adopted the screw-pile method as an avenue for exploring an alternative approach to enhance the uplift capacity of piles. Screw or helical piles find diverse applications, offering robust protection against axial and tensile uplift forces. They typically consist of circular screw plates affixed to a steel shaft.

In their study, [17] employed PLAXIS 3D Foundation as their finite element (FE) software to analyze the group configuration of under-reamed piles. They subjected different groups comprising 3, 5, and 7 piles, with spacing-to-diameter (S/D) ratios ranging from 4 to 12, within pentagonal, square-like, and triangular layouts.

The investigation yielded significant findings. Specifically, the pentagonal arrangement, when compared to the square arrangement with an equal number of piles and the same area, exhibited a notable 16% improvement in bearing capacity. Furthermore, the triangular arrangement, while maintaining the same area, proved to be more effective than a symmetric square arrangement.

In their study, (32) presented an innovative pile modification approach known as "finned piling." This technique is designed to improve the efficiency of pile tension by creating a stable anchorage point near the base of the pile. This modification involved attaching four welded fins around the lower perimeter of the pile. The outcomes of this modification demonstrated significant improvements in the piles' uplift capacity when fins were incorporated at the pile's tip.

When the fins were installed with an effective width (Wf) equivalent to the pile diameter (D) and positioned at an inclination angle (b) of 90° relative to the soil, with a soil relative density (Dr) of 50%, remarkable uplift capacity enhancements were observed. Specifically, uplift capacity improvements of 1.82, 3, and 6 times greater than that of a standard pile were achieved, considering different pile length-to-diameter (L/D) ratios of 15, 20, and 30, respectively. The findings underscored that, for substantial uplift capacity gains, the fins should be installed with an inclination angle (b) of at least 45° or greater.

The installation of these fins at the pile's base underwent testing and demonstrated their effectiveness as anchorage devices. This was attributed to the significant soil locking effect within the fins, resulting in a notable increase in uplift capacity.

A novel approach to enhance the uplift capacity of piles has been put into practice. The study involved examining the uplift capacities of individual vertical piles with anchor wings, constructed in various densities of dry soil. The test series involved consistent pile diameter and embedment depth modeling. Furthermore, the investigation explored the effects of varying wing dimensions installed at the pile's base, including diameter and length.

The test findings demonstrated that the uplift capacity of anchor finned piles increases as the relative soil density rises. When the wing-to-pile length ratio (Lw/Lp) was 0.5, and the maximum wing diameter-to-pile diameter ratio (Dw/Dp) was 3, remarkable enhancements in uplift capacity were observed. Specifically, at sand densities of 30%, 50%, and 80% (Dr), the uplift capacity efficiencies were 2.0, 2.38, and 2.77 times greater than those of wingless piles, respectively. The installation of these wings at the tip of the monopile created an effective anchoring mechanism, owing to the significant soil-locking effect of the wings. This, in turn, led to increased uplift capacity and reduced pile displacement. Additionally, the presence of these wings substantially augmented skin friction and earth pressure along the pile shaft.[23].

Prior research has not explored the concept of using groups of finned piles to improve the uplift capacity of pile foundations exposed to tension loads. Consequently, the primary objective of this study is to analyze the load-displacement characteristics of finned pile groups installed in sandy soil when subjected to varying uplift loads.

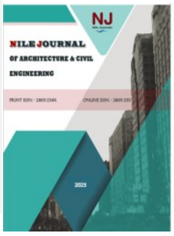
## 2. Research objective

Given the various varieties of tension piles available, this paper specifically concentrates on a single type, namely, the tube pile with fins affixed to its toe. In this configuration, four fins are evenly distributed and welded around the perimeter at the base of the pile.

Hence, the objective of this study was to conduct a numerical investigation of the impact of employing groups of finned piles. These finned piles, characterized by fins located at specific depths along the pile, have been shown to enhance pile-tension efficiency by establishing secure anchorage near the bottom tip of the pile group. Specifically, the analysis focused on their performance in sandy soil under axial uplift loads applied to the pile cap. To achieve this, finite element modeling (FEM) and PLAXIS 3D Foundation software were utilized to comprehensively assess the response of these modified piles under varying uplift loads. Additionally, the study aimed to identify the failure patterns associated with this technique.

## 3. Numerical Modeling

A FEM was established for the finned pile groups using sandy soil. Before adopting the model, a parametric study comprising a numerical verification of the model was tested and validated as compared to the data results provided from the experimental prototype laboratory pile test.



One of the most powerful approximate solutions that can be applied to solve geotechnical problems is the FE method [18]. In this research, numerical simulations were performed using 3D FE software. All the FE calculations were based on six-node triangular elements using a three-point Gaussian integration rule to calculate the element stiffness matrix. The shear stress parameters were used to define the failure behavior of the soil. The Mohr–Coulomb model comprised five main parameters and was employed to simulate the elasto-plasticity of the soil. The model is prevalent among most geotechnical engineers and can be employed in basic tests on soil samples.

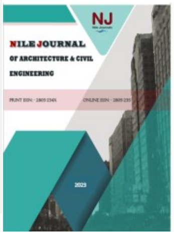
In this research, the finned pile groups were simulated using PLAXIS 3D Foundation. The geometry of the FE model adopted for this analysis was set to have the same dimensions as the experimental model. The displacements were proposed to be zero in both the x- and y-directions at the bottom and x-direction at the sides. An interfacial element of the interaction between the soil and both the pile and finned sections was adopted for all the embedment pile depths.

A preliminary elastoplastic model was used in describing the interfacial behavior before modeling the soil-structure interaction. The interface strength (Rinter) of 0.65 was taken as actual interfacial strength between the soil and steel piles. Three pairs of nodes were connected to the soil interfacial elements. A stiffness matrix was obtained for the interfacial elements using the Newton–Cotes integration points. By assigning an appropriate value for the strength reduction factor at the interface corresponding to the strength of the soil, a model for evaluating the interaction between the interface friction angle, adhesion, and the contact surfaces was developed. The Coulomb criterion was used to distinguish between the elastic behavior, where small displacements can occur with the interface, and plastic interface behavior otherwise known as slip. There are three means of obtaining modulus of soil:

- laboratory triaxial tests (from a calculation based on the tangent modulus of soil)
- pile-load test
- empirical correlations based on previous experience.

In this research the elastic modulus of soil was chosen according to empirical correlations based on previous experience [2,15,32].

The pile and soil specifications, material modes (optional for the behavior of materials in PLAXIS program software), interfaces, and stiffness characteristics are presented in Table (1) for the verification model.



### Table (1): Materials Specifications, considered in the FE models (PLAXIS 3D Foundation)

| **Specification** | | **Pile** | **Loose sand** | **Medium sand** | **Dense sand** |
|---|---|---|---|---|---|
| **Material model** | | **Linear elastic** | **Mohr Coulomb** | **Mohr Coulomb** | **Mohr Coulomb** |
| **Material properties** | $\gamma$ (kN/m$^3$) | 78 | 16 | 16.6 | 18.4 |
| | $\gamma_{sat}$ (kN/m$^3$) | 78 | 16 | 16.6 | 18.4 |
| | Dr (%) | - | 30 | 50 | 80 |
| **Stiffness** | E (kN/m$^2$) | 2.8 E7 | 4.5E4 | 7.5E4 | 10E4 |
| | $\nu$ (nu) | 0.3 | 0.35 | 0.35 | 0.35 |
| **Strength** | C (kN/m$^2$) | - | 1 | 1 | 1 |
| | $\varphi$ (Phi) | - | 30 | 36 | 40 |
| | $\psi$=($\varphi$-30$^o$) (dilation angle) | - | 0 | 6 | 10 |
| **Interface** | Rigidity (R$_{inter}$) | - | 0.65 | 0.65 | 0.65 |

## 4. Results of Numerical Analysis

### 4.1 Verification of the Finite Element Model

The numerical analysis was used to validate the laboratory model test results. It was also employed in measuring the different parameters that cannot be investigated in the laboratory. First, the model analysis was validated with the experimental model test results to ensure the numerical model can solve the geotechnical problems of a prototype finned pile groups in the field. Second, after the validation process, the analysis was performed to further investigate the behavior of a large-scale problem model under new parameters.

Initially, the numerical model was verified via the results obtained from the experimental test model.

A good consistency was achieved between the experimental results and the FE modeling calculations for the case of 1 × 1 × 1 m, L/d = 10, Wf = 0.5Dp, Lf = 2Dp, spacing = 4Dp, No. of piles = 4, and Dr = 30%. There are roller fixities on the boundaries. Figure (1) shows a 3D mesh generated by PLAXIS 3D Foundation; it is necessary to generate the 3D mesh before the calculation phase [7]. The similarity between the load-displacement curves for the experimental and numerical analyses is illustrated in Figure (2).

Also, Figure (2) illustrates the comparison between the experimental and numerical analyses of the load-displacement curve. The numerical results follow the trend of the model test results, and an acceptable correlation was achieved with a minimum difference of about 2.5%. Thus, the adopted PLAXIS 3D model was demonstrated to be proficient in predicting the behavior of finned pile groups in comparison with the small model test.

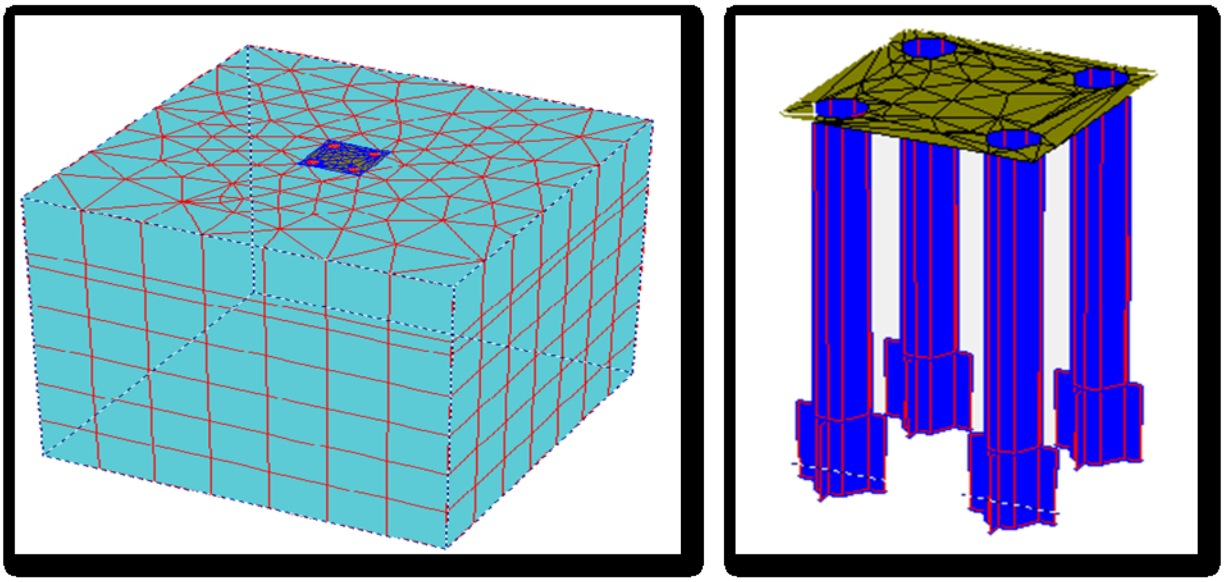


**Figure (1):** 3D Mesh for pile group, generated by PLAXIS 3D Foundation software.

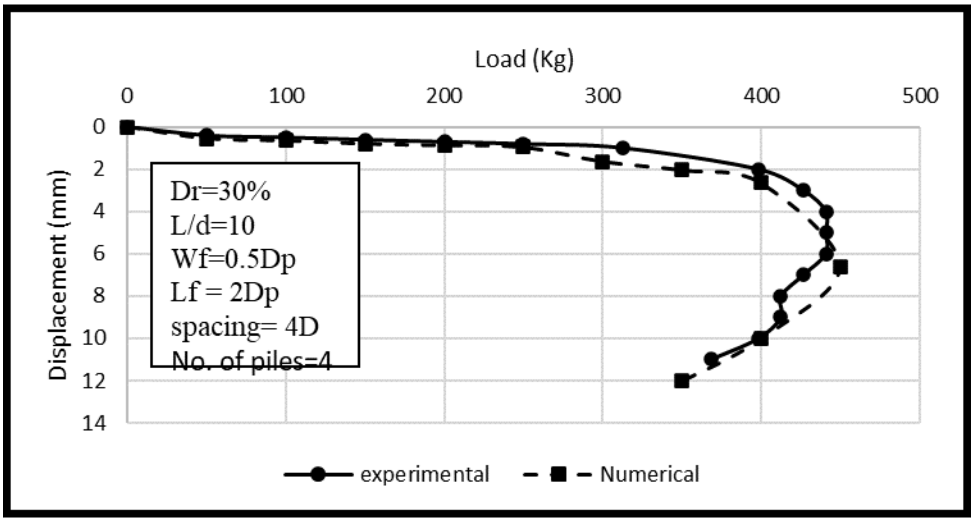


**Figure (2):** Load displacement curve for the Experimental and numerical model

To analyze the results from the numerical modeling and the experimental modeling we use Root Mean Square Error (RMSE).

Root Mean Square Error (RMSE) is the standard deviation of the residuals (prediction errors). Residuals are a measure of how far from the regression line data points are; RMSE is a measure of how spread out these residuals are. In other words, it tells you how concentrated the data is around the line of best fit. “Root mean square error” is commonly used in climatology, forecasting, and regression analysis to verify experimental results.

RMSE is always non-negative, and a value of 0 (almost never achieved in practice) would indicate a perfect fit to the data. In general, a lower RMSE is better than a higher one.

The formula can be written with the following, slightly different, notation [8]:

$$RMSE_{f0} = \left(\sum_{i=1}^{N}(Z_{fi} - Z_{oi})^{2}/N\right)^{1/2} \qquad \textbf{(2)}$$

**Where:**
Σ = summation (“add up”)
(zfi – Zoi)2 = differences, squared
N = sample size.

From the results in Figure 10, Root Mean Square Error (RMSE) was calculated for both the numerical and experimental results, and it was discovered that RMSE = 0.005631 and 0.002251 for the numerical and experimental results, respectively. These results for RSME are very good since they are very small, close to 0.0.

Also, the results from the numerical model were closely comparable to those of the experimental model in the laboratory.

For more confirmation another validation was done on the other model test results. Where, prior to adopting the test for the parametric study, a verification test held by [32] were tested and validated in comparison with the data results provided from there experimental prototype finned single pile test.

The soil used was medium-sized sand of minimum dry unit weight of 14.65 kN/m3, maximum dry unit weight of 17.65 kN/m3, uniformity coefficient of 2.60, effective diameter of 0.19 mm, specific gravity of 2.56, and percentage of fins of 1.8%. After pile erection, the sand bed was formed in the soil bin in layers 100 mm thick. To ensure homogeneity of sand formation, a designed weight of sand, with an accuracy of 0.001 kN, was formed into a certain volume within the soil bin by compaction to give the specified relative density. The formed sand was levelled using a straight steel plate.

A hammer weighing 40.0 N and 200mm in diameter was used to compact the sand. Three aluminum boxes measuring 50*50*30 mm were embedded into the sand to recheck the relative density after performing the experiment. The drained triaxial tests of sand in dense, medium, and loose conditions were carried out to evaluate the shear parameters of tested soils. In this work, three different relative densities were studied, 50, 65, and 85%, to give corresponding angles of internal friction form triaxial are, Ø of 30, 36, and 40° respectively. Before preparing the sand bed, the pile was positioned at a predetermined depth and the sand was installed to cover the pile length as mentioned above. This method can be called the quasi-non-displacement technique for pile installation, as stated by [13, 32]. As presented in Figure (3).

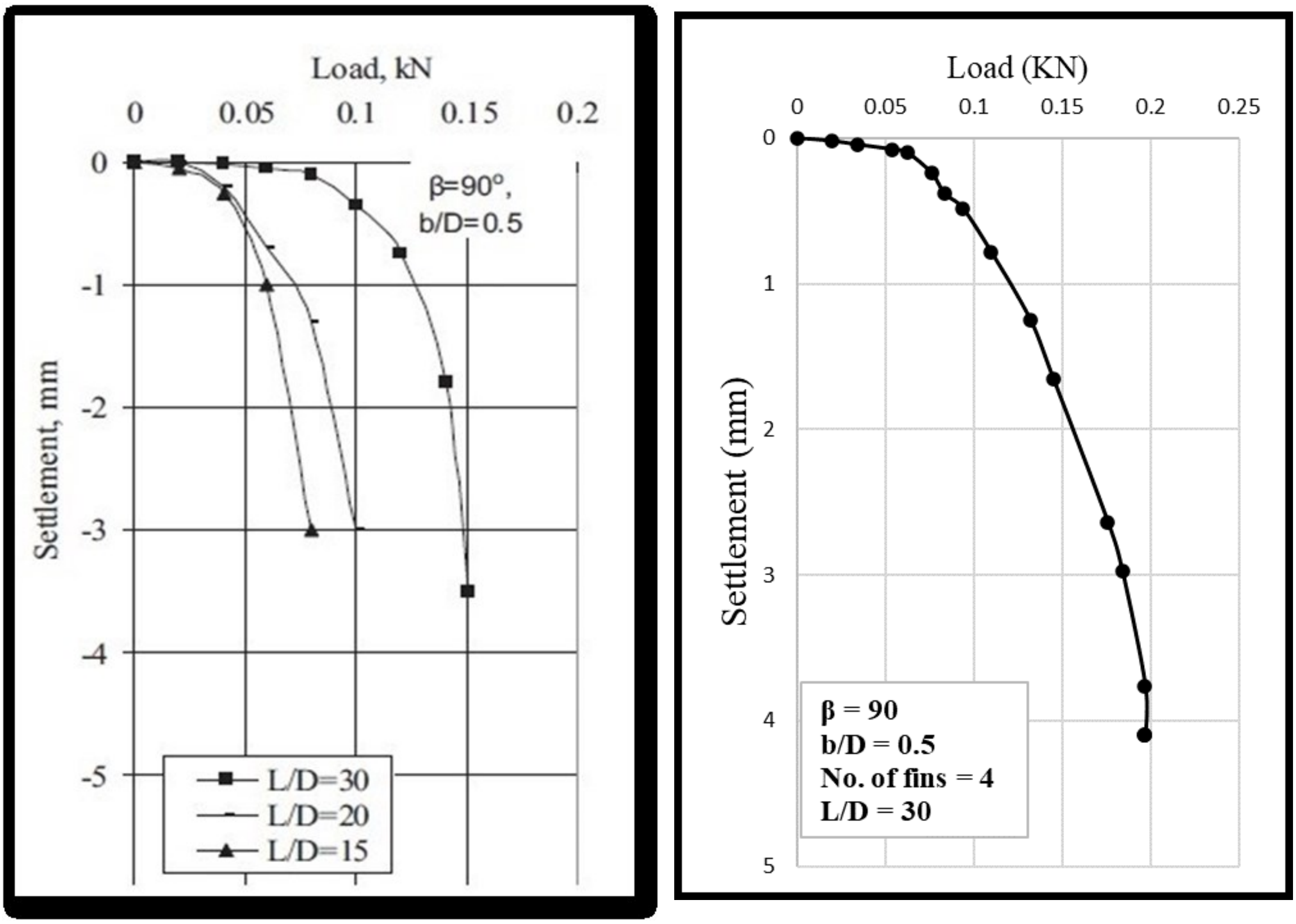
**Figure (3):** Test Tank and Finned Pile.

All test series were carried out at a constant pile diameter (D) of 20 mm and fin length (Lf) (Lf = 6D = 120 mm) as mentioned previously, whereas fin width (b), embedded length of pile L, and the inclination angle (b) varied.

In this research, single finned pile was chosen to validate the experimental model. Same parameters (same pile type, very close sand type, fin inclination angle (900), number of fins (4) and fin-width diameter Ratio (0.5)), as shown previous, was modelled to validate the results. The test results for the model were verified using the PLAXIS 3D Foundation as a numerical program.

The comparison results, in term of pile/settlement response between this model and [32] model showed good agreement. With considering the simple difference. Figure(4) (a and b) shows the results of this model, Pile load versus settlement curves, comparing with [32] results.

It can be seen that the finite element results follow the trend of the laboratory results, and a moral agreement is achieved. Therefore, in view of the fact that the adopted Plaxis 3d version is reliable for predicting the behavior of finned group piles under tension loads. It was decided to adopt this package for the analyses proposed in this manuscript.



**A: experimental model test results** **b: finite element analysis**

**Figure (4):** A comparison between load-settlement curves from experimental models of (32) and Pile load versus settlement curve for single finned pile model in PLAXIS 3D.

The parameters were varied to evaluate their effects on the uplift capacity of finned pile groups. All the details of the numerical models are presented in Table (2).

### 4.2 Effect of Length per diameter ratio

The displacement (S) of the anchor winged pile was expressed in a non-dimensional form in terms of S/Dp [2.23].

The definition of the failure load to obtain the uplift capacity of the pile was considered as the point at which the curve attains a peak or maintains a continuous displacement increase with a decrease in the pullout load [15.16].

**Table (2) Studied series in numerical analysis**

| Series | Constant parameters | Variable parameters |
|---|---|---|
| **1** | Dr = 30%<br>Dp = 2.5 cm<br>Wf = 0.5 Dp, Lf = 2Dp<br>No. of piles = 4<br>Spacing = 4Dp | Length per diameter ratio (L/d) = 10, 20 and 26 |
| **2** | Dp = 2.5 cm<br>(L/d = 10) for pile<br>Wf = 0.5 Dp, Lf = 2Dp<br>No. of piles = 4<br>Spacing = 4Dp | Relative Density (Dr) = 30%, 50% and 80% |
| **3** | Dr = 30%<br>Dp = 2.5 cm<br>(L/d = 10) for pile<br>Lf = 2Dp<br>No. of piles = 4<br>Spacing = 4Dp | Fin Width (Wf) = 0.5Dp, 0.75Dp and 1Dp |

Where (Dr) relative density of sand, (Lp) length of the pile, (Dp) diameter of pile, (Wf) fin width, (Lf) length of the fin and (L/ d) length per diameter ratio.

Three models were employed to analyze the steel circular piles with tension load. The modeling of the steel pile/soil system was performed with different L/d values of 10, 20, and 26 with the same pile caps for each case, the same pile spacing of 4Dp, and the same Dr = 30%. All types of the piles have the same Dp of 25 mm and thickness of 3 mm as previously mentioned, for comparison with each other, and all pile types also have the same fin geometry and number of piles (4 piles). The pile load-normalized displacement relationships determined with the numerical model at different length-per-diameter ratios of the fined pile groups are illustrated in Figure (5). The FE output will provide for this observation, presented in Figure (6) (a-c). Figure (6(a)) illustrates deformed FE mesh for L/d = 20, pile spacing of 4Dp, and the relative density Dr = 30%.

From figure (5), it was noticed that the corresponding uplift capacities were 450 Kg for each finned pile group with different L/d ratios of 10, 20, and 26. However, the normalized displacement ratio increases with an increase in the L/d at 0.4, 0.9, and 4.4, respectively. Thus, the finned pile group’s performance slightly improved with an increase in the L/d ratio.

This is primarily due to an increase in the pile surface area, which resists the tension force, with an increase in the length of the piles though this may result in a large area disturbance of the soil around the pile.

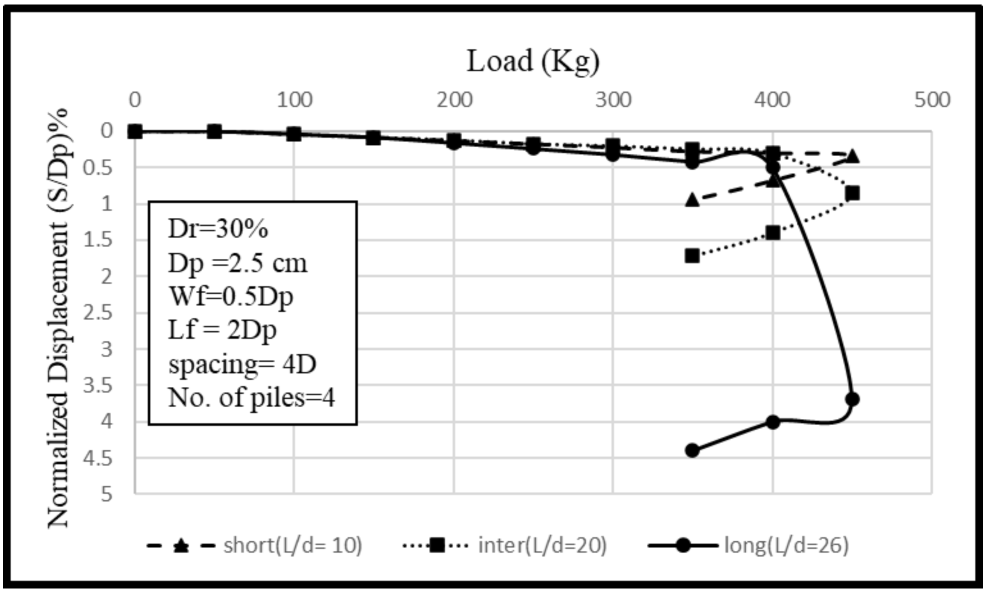
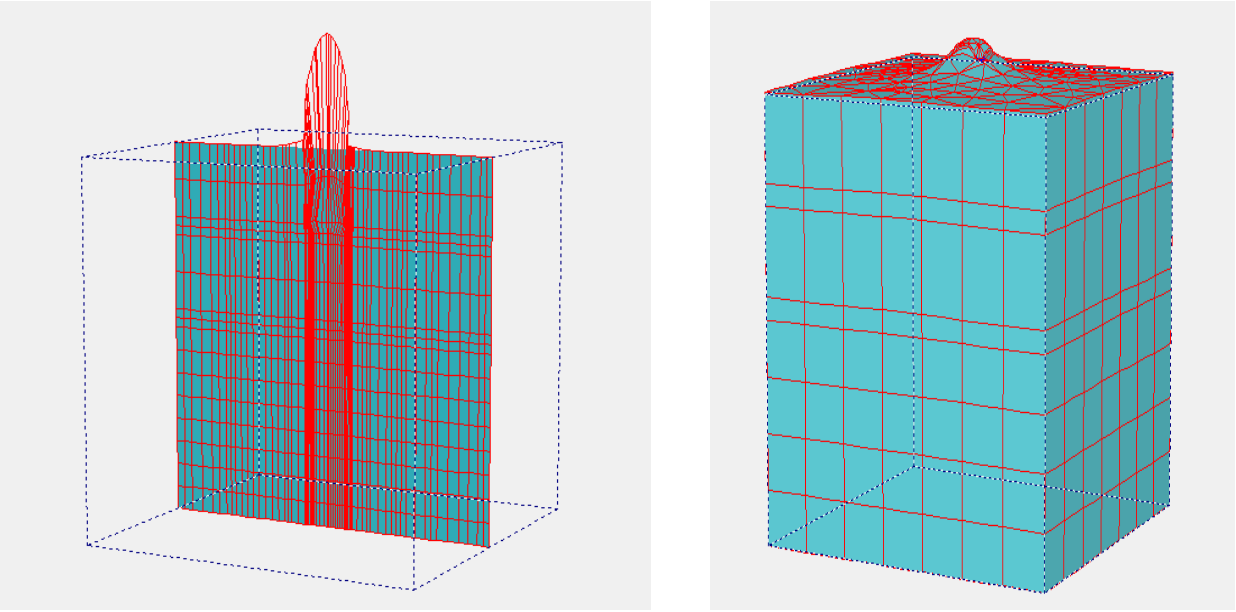
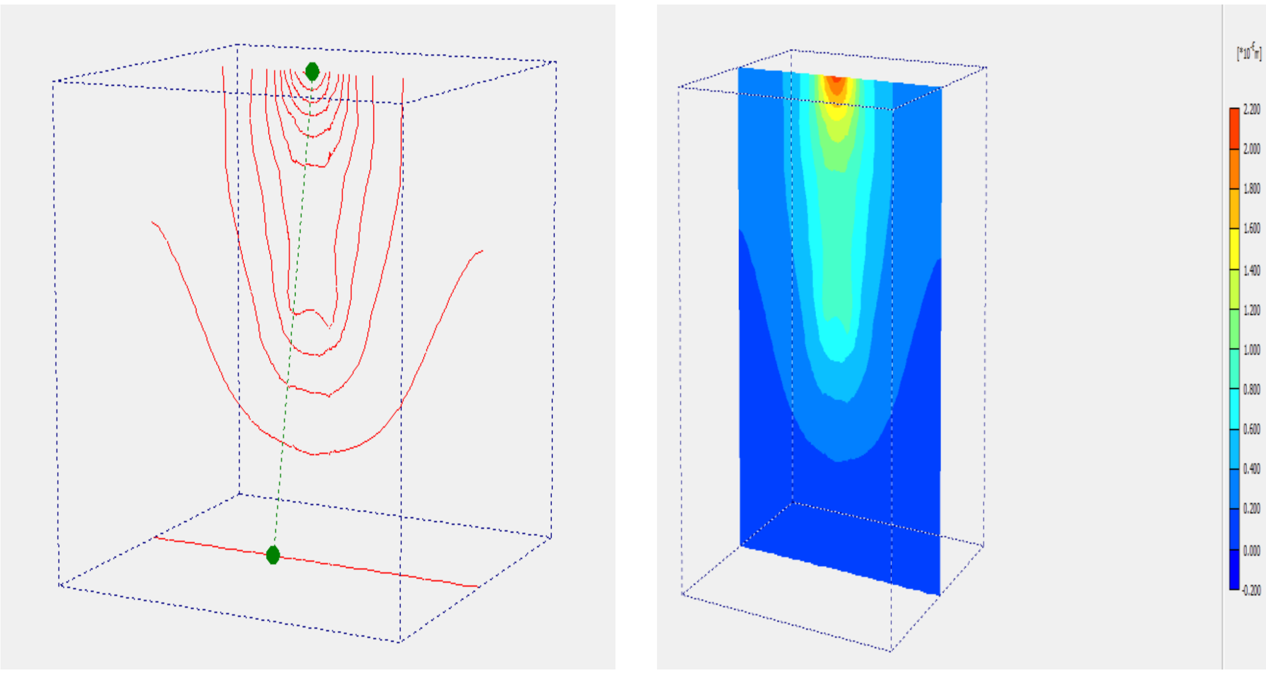


**Figure (5):** Normalized Displacement versus Load for different (L/d) ratio



(a)



(b) (c)

**Figure (6):** Output for L/d = 20, pile spacing of 4D, and the relative density Dr = 30%. (a) deformed mesh; (b) contour lines for total displacement; (c) total displacement shading.

### 4.3 Effect of Relative Density

To study the effect of Dr on the finned pile groups response, three models were analyzed on steel circular piles with tension load. The modeling of the steel pile/soil system was subjected to different Dr values of 30, 50, and 80% with the same pile caps for each case, the same inter-pile spacing of 4Dp, and the same L/d of 10. All types of the piles have the same diameter of 25 mm, length of 250 mm, and thickness of 3 mm as mentioned previously, for comparison with each other. They also have the same fin geometry and number of piles (4 piles). The pile load- normalized displacement relationships determined with the numerical model at different relative densities of the finned pile groups are illustrated in Figure (7).

From Figure (7), it was observed that any increase in Dr leads to an increase in the load uplifting capacity of the pile group. The pile-group performance greatly improved with an increase in Dr. When Dr increases from 30 to 50% and 50 to 80% the load to failure increases about 33 and 34%, respectively. Additionally, an increase in Dr from 30 to 50% and 50 to 80% leads to an increase in the normalized displacement ratio from 2 to 12% and 12 to 38%, respectively.

This increase leads to an increase in the shear resistance of the pile surface through the interfacial friction between the soil, pile, and fins.

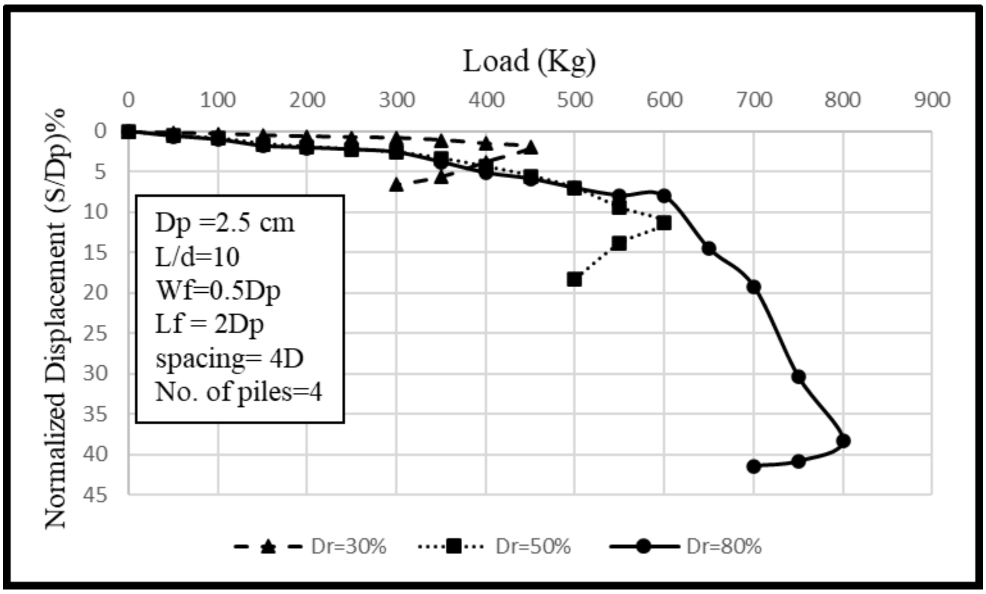


**Figure (7):** Normalized Displacement versus Load for different relative density (Dr).

### 4.4 Effect of Fin geometry

The most critical region of the pile/soil system under tension load is the bottom zone of the soil around the pile [8.9] because the overturning moment is maximum, and the uplift deformation starts from this zone and propagates until reaching the slippage failure. Therefore, different investigations have been conducted to study the improvement of the uplift capacity using plate anchors, screw helices, belled pile shapes, and fins [8.10.3.31]. Consequently, a sequence of the model tests has been performed for different Wf of 0.5, 0.75, and 1Dp. The normalized displacement versus load for different fin widths are illustrated in Figure (8). All the models have the same inter-pile spacing of 4Dp, the same L/d of10, the same number of piles (4 piles), and the same Dr of 30%). Also, all types of the piles have the same Dp of 25 mm, length of 250 mm, and thickness of 3 mm as mentioned previously, for comparison with each other.

The results clearly indicate that for different $W_f$, the ultimate load for the finned pile groups slightly increases with increasing $W_f$ at a constant fin length. Unlike the single fin pile, the Wf increases with increasing ultimate load [31]. Thus, the $W_f$ has little effect on the finned pile-group capacity.

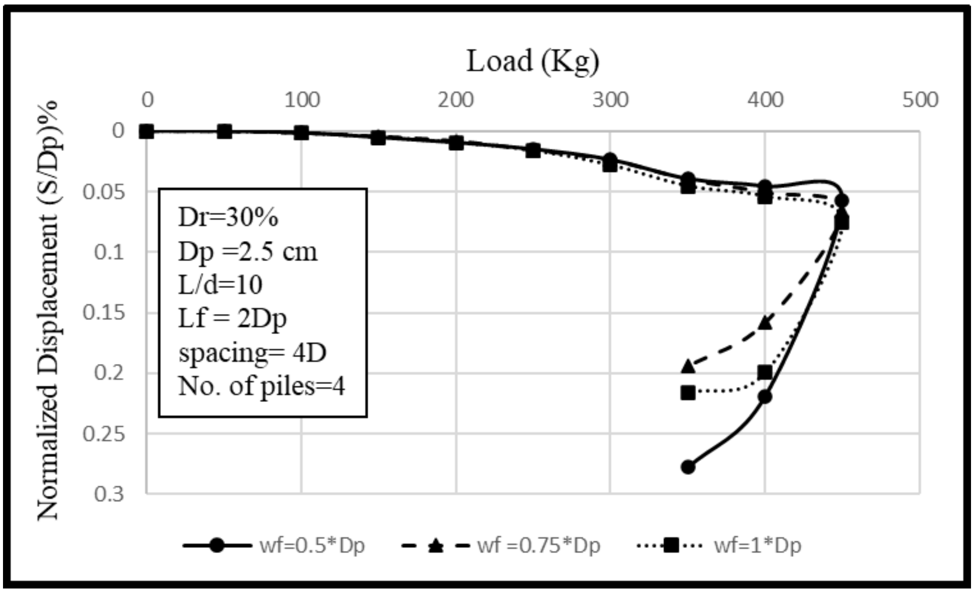


**Figure (8):** Normalized Displacement versus Load for different fin width ($W_f$).

## 4.5 STATISTICAL ANALYSIS

### 4.5.1 SPSS program

Statistical Package for the Social Sciences (SPSS) is the set of software programs that are combined together in a single package. It was originally launched in 1968 by SPSS Inc. and was later acquired by IBM in 2009. The basic application of this program is to analyze scientific data related to the social science. SPSS's Modeler program enables researchers to build and validate predictive models using advanced statistical procedures. In the SPSS program, some of the results are chosen randomly while the others are used to make validations using equations derived from the program.

In this research, the formulas were derived between parameters affecting the pile capacity. These formulas mainly aim to find the load for the (L/d) ratio, soil Relative Density (Dr), Spacing between piles (S), Number of piles (N) and fin width (Wf).

The formula can be written with the following:

$$\mathbf{Load = 362.21*(L/d)^{0.022}*(Dr)^{0.04}*(S)^{0.005}*(N)^{0.021}*(W_f)^{0.186}} \tag{3}$$

The curve in Figure (9), represent the load observed and load predicted for the results of the models.

Also, from curve at Figure (9), it was found that (R2= 0.96). where R-squared (R2) is a statistical measure that represents the proportion of the variance for a dependent variable that's explained by an independent variable or variables in a regression model.

Whereas correlation explains the strength of the relationship between an independent and dependent variable, R-squared explains to what extent the variance of one variable explains the variance of the second variable. So, if the R2 of a model is 0.50, then approximately half of the observed variation can be explained by the model's inputs. R2 is an element of [0, 1] and represents the proportion of variability in Yi that may be attributed to some linear combination of the repressors (explanatory variables) in x.

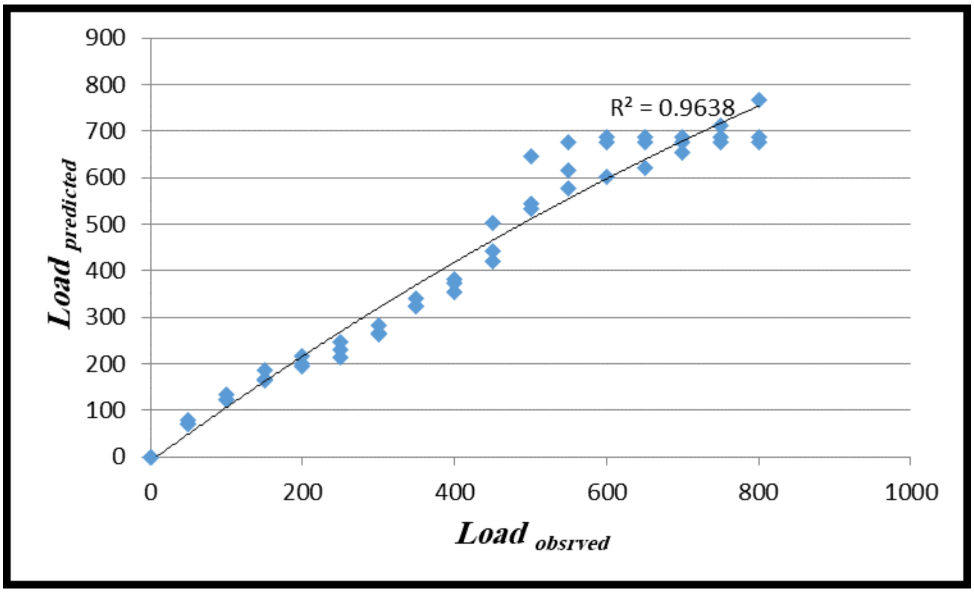


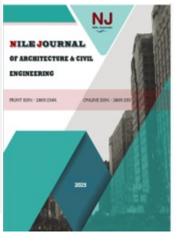
**Figure (9):** Load observed Vs Load predicted curve for models.

So, from the results and the value of (R2), it was a very good result as it near to (1) or (100%) and is a good indication that the fitted model explains all variability in y.

From the results in Figure (9), Root Mean Square Error (RMSE) was calculated for both load observed, and load predicted results, and it was discovered that RMSE = 0.04973 load observed, and load predicted results. These results for RSME are very good since they are very small, close to 0.0.

The Root-mean-square deviation (RMSD) is a frequently used measure of the differences between values (sample or population values) predicted by a model, or an estimator and the values observed. The RMSD represents the square root of the second sample moment of the differences between predicted values and observed values or the quadratic mean of these differences. RMSD is always non-negative, and a value of 0 (almost never achieved in practice) would indicate a perfect fit to the data. In general, a lower RMSD is better than a higher one.

From the results in Figure (9), Root-mean-square deviation (RMSD) was calculated for both load observed, and load predicted results, and it was discovered that RMSD = 0.04924 load observed, and load predicted results. These results for RSMD are very good since they are very small, close to 0.0.



## 5. Conclusion

This research focused on determining the effect of finned pile groups, which comprised welded fin plates at the bottom tip of the pile, and the pile caps were made of steel plates with different dimensions to ensure adequate rigidity. Numerical modeling was performed under tension load with different parameters.

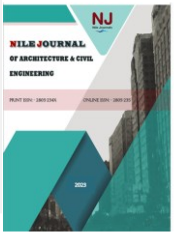
Based on both analyses in investigating the pile's group behaviors, the following conclusions were made:

- RMSE was calculated for both numerical and experimental results. It was realized that the RMSE = 0.005631 and 0.002251 for the numerical and experimental results, respectively. These results for RSME are very good as the values are very small, close 0.0.
- The corresponding capacities were 450 Kg for finned pile groups with different L/d ratios of 10, 20, and 26. However, the normalized displacement ratio increases with an increase in the L/d at 0.4, 0.9, and 4.4, respectively. Thus, the finned pile groups' performance slightly improves with an increase in the ratio.
- The pile-group performance significantly improved with an increase in the soil Dr. When Dr increases from 30 to 50% and 50 to 80% the load to failure increases about 33 and 34%, respectively. Additionally, an increase in Dr from 30 to 50% and 50 to 80% leads to an increase in the normalized displacement ratio from 2 to 12% and 12 to 38%, respectively.
- For different $W_f$ the ultimate load for the finned pile groups slightly increases with increasing $W_f$ at constant fin length. Unlike the single fin pile, Wf increases with increasing ultimate load.
- R-squared ($R^2 = 0.96$) for the load determined versus load predicted curve of the models, and this is a good indication that the fitted model adequately explains all variability in y.
- It was discovered that (RMSD = 0.04924) and (RMSE = 0.04973) for load observed and load predicted results. These results for RSMD are very good since they are very small, close to 0.0.

## References

1 A. Nasr, Canada, Geotech, **Experimental and theoretical studies of laterally loaded finned piles in sand**, (2014) J. 51 -381–393.

2 A. Sallam, A THESIS Submitted for the Degree of Master of Philosophy in Civil Engineering (Structural Engineering), **Behavior of Grouted Screw Piles Under Inclined Loads in Sand**, Faculty of Engineering - Tanta University, (2016).



3 Abdelghany, Y., and El Naggar, M. H., Soil Dyn. Found. Eng., **Full-scale field investigations and numerical analyses of innovative seismic composite fiber reinforced polymer and reinforced grouted helical screw instrumented piles under axial and lateral monotonic and cyclic loadings,** (2014), Adv., 414–424.

4 Abebe A. and Smith I., School of the Built Environment, Napier University, Edinburgh, **PILE FOUNDATION DESIGN**, www.tumcivil.com, (1999).

5 Ads A., Submitted for the Degree of Master of Philosophy in Civil Engineering, Tanta University, **Pullout Capacity of Screw Piles in Sand,** (2014).

6 Al-Mhaidib, A.I., Eng. J., University of Qatar, **Influence of shearing rate on interfacial friction between sand and steel**, (2006b), 19, 1-16.

7 Brinkgreve, et al., Delft University of Technology & PLAXIS by The Netherlands, **Plaxis 3D Foundation manual, Version 1.5**, (2006).

8 Dickin, E. A., and Leung, C. F., **Performance of piles with enlarged bases subject to uplift forces**. Can. (1990), Geotech. J., 27(5), 546–556.

9 El Naggar, M. H., and Abdelghany, Y., Proc., 4th Int. Conf. on Geotechnical Earthquake Engineering, International Society for Soil Mechanics and Geotechnical Engineering, London, Paper 1567, Helical **screw piles (HSP) capacity for axial cyclic loadings in cohesive soils**, (2007).

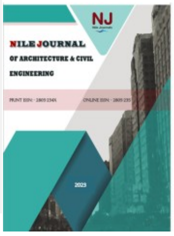
10 El Sharnouby, M. M., and El Naggar, M. H., Can. Geotech. J., **Field investigation of axial monotonic and cyclic performance of reinforced helical pull-down micropiles**, (2012), 49(5), 560–573.

11 F. Xu et al., Soil Mechanics and Foundation Engineering, Springer Science+Business Media New York, **Response of a Single Pile Subjected to Tension Load by Using Softening Models,** Vol. 54, No. 1, March 2017 (Russian Original No. 1, January-February 2017), DOI 10.1007/s11204-017-9428-6.

12 Fatahi, et al., Geomechanics and Engineering, **Performance of laterally loaded piles considering soil and interface parameters**. (2014).

13 Fioravante, et al., Proc.,6thInt. Conf. on Physical Modelling in Geotechnics, Taylor & Francis, Leiden, the Netherlands, **On the effects of Residual Tangent Stresses in Centrifuge Pile Tests**, (2006), 827–833.

14 Franke, E., and Muth, G., Proc., 11th Int. Conf. on Soil Mechanics and Foundations, **Scale effect in 1g model tests on horizontally loaded piles**, (1985), Vol.2, Balkema, Rotterdam, theNetherlands,1011–1014.



15 Ghaly A. et al, Canadian Geotechnical Journal, Model **Investigation of the Performance of Single Anchors and Groups of Anchors,** (1994), Vol. 31, No. 2, pp. 273-284.

16 Ghaly, A. M., and Clemence, S. P., **Pullout performance of inclined helical screw anchors in sand**, (1998), J. Geotech. Eng., 10.1061/(ASCE)1090 -0241(1998)124:7(617), 617–627.

17 H. Alielahi et al. Electronic Journal of Geotechnical Engineering (EJGE), **Influence of Under-Reamed Pile Groups Arrangement on Tensile Bearing Capacity using FE Method**, Vol. 19, Bund. L, (2014), (PP. 1395-1410).

18 Han et al. J. Geomech., Modeling **behavior of friction pile in compacted glacial till** Int. (2016), 10.1061/(ASCE)GM .1943-5622.0000659, D4016009.

19 J.P. Turner, F.H. Kulhawy, Electric Power Research Institute, Palo Alto, Calif. CA, USA, **Experimental Analysis of Drilled Foundations Subjected to Repeated Axial Loads Under Drained Conditions**, (1987), Report EL-5325.

20 K. Gaaver, Alexandria Engineering Journal, **Uplift Capacity of Single Piles and Pile Groups Embedded in Cohesionless soil**, (2013), Volume 52, Issue 3, Pages 365-372.

21 Kotal A. and khan A., **(**IJRET) International Journal of Research in Engineering and Technology, **Model Test on Uplift Capacity of Pile Anchors in Cohesionless Soil,** (2015), eISSN: 2319-1163 | pISSN: 2321-7308, Volume: 04 Special Issue: 01, (PP. 7-11).

22 M. Abu El-Khair, A THESIS Submitted for the Degree of Master of Science in Engineering (Structural Engineering), Faculty of Engineering, Tanta University, **Behavior of Laterally Loaded Finned Piles in Clay Soil**, (2019).

23 M. Sakr, Nazir, Azzam, W. and Sallam, A., Applied Ocean Research, Model **study of single pile with wings under uplift loads**, 100 (2020) 102187, 0141-1187/ © 2020 Elsevier Ltd.

24 M. Sakr, Geotech. J., **Performance of helical piles in oil sand**, Can. (2009), 46(9), 1046–1061.

25 Muir Wood, D. SponPress, London, **Geotechnical Modelling,** (2004).

26 Nazir, A. K. and Nasr, A., journal of advanced research, **Pullout capacity of batter pile in Sand**, (2012), Vol.4, Issue 2, pp. 147-154.

27 Permanent Committee for the Code of Practice for soil mechanics, design and implementation of foundations, (ECP 202-2001), Ministry of Housing, Utilities and Urban Development Housing and Building National Research Center, ARAB REPUBLIC OF EGYPT, **Egyptian code for soil mechanics, design and implementation of foundations,** (2007).

28 Prakoso, W. A., and Kulhawy, F. H. J. Geotech. Geoenviron. Eng., **Contribution to piled raft foundation design** (2001), 10.1061/ (ASCE)1090-0241(2001)127:1(17), 17–24.

29 Robinsky E.I. and Morrison C.F. Can. Geotech. J., **Sand Displacement and Compaction Around Model Friction Piles**, (1964), 1(2), pp. 81-93

30 Vesic, A. S., National Cooperative Highway Research Program. Synthesis of Highway Practice No. 42, Transportation Research Board, Washington, DC, **Design of piles foundation**, (1977).

31 Vesic, A.S., Journal of Soil Mechanics and Foundations Div., **Breakout resistance of objects embedded in ocean bottom**, (1971), ASCE, Vol. 97, No. 9, pp. 1183-1205.

32 W. Azzam and A. Elwakil, paper is part of the International Journal of Geomechanics, **Model Study on the Performance of Single-Finned Pile in Sand under Tension Loads, (**2016), ©ASCE, ISSN1532-3641.

33 Arqub, O.A., Al-Smadi, M. **Fuzzy conformable fractional differential equations: novel extended approach and new numerical solutions,** (2020) Soft Comput 24, 12501–12522. https://doi.org/10.1007/s00500-020-04687-0.

34 Graßhoff, H. **Systemsteifigkeit und Flٹchengründung**, Ber. Nr. 6, Lehrgebiet Grundbau, Bodenmechanik und Unterird. Bauen, (1987), Berg. Universitٹt GH Wuppertal.

35 Sakr, M. A., Nazier, A., Azzam, W. R. and Sallam, A. **Behavior of Grouted Single Screw Piles under Inclined Tensile Loads in Sand**, Electronic journal of Geotechnical Engineering EJGE. Vol. 21, (2016), Bund. 2 Volume19F, pp. 571-591.

36 Sakr, M. A., Nazer, A. K., Azzam, W. R. and Sallam. A. A., **Uplift Capacity of Single Pile with Wing in Sand-Numerical Study**, International Conference on Advances in Structural and Geotechnical Engineering ICASGE'19- 25-28 March
37 (2019), Hurghada, Egypt

Pei, Te, and Tong Qiu. "**A Numerical Investigation of Laterally Loaded Steel Fin**

**Pile Foundation in Sand**." *International Journal of Geomechanics* 22.7 (2022): 04022102.

38 Bariker, Pankaj, Sreevalsa Kolathayar, and Sembulichampalayam Sennimalai Chandrasekaran. "**Lateral Resistance of Finned-Piles in c–Φ Soils: Experimental Investigations and Numerical Studies.**" *Indian Geotechnical Journal* (2023): 1-18.