Behavior of Piles Subjected to Uplift Loads In Sand

Aser Ibrahim[1], Mohamed Ashour[2], Ayman Altahrany[3]

[1]Graduate Student, Department of Structural Engineering, Mansoura University, Egypt and a Project Engineer at EMC Co. (Oil & Gas field), Egypt.
[2]Professor of Geotechnical Engineering, Department of Structural Engineering, Mansoura University, Egypt
[3]Asisstant Professor, Department of Structural Engineering, Mansoura University, Egypt
aser.ibr@live.com,ashouruah@gmail.com, atahrany@hotmail.com

Abstract: The paper presents a method that predicts the pile ultimate capacity and the mobilized side resistance in skin friction under uplift forces in sandy soils. The developing soil-pile skin resistance is assessed in a progressive/mobilized fashion up to failure using the soil and pile properties. A computer program is developed to employ the proposed method and to predict the pile-head load displacement curve up to failure. A parametric study is conducted to evaluate the effect of different soil parameters on the pile behavior under uplift forces. A finite element model is developed, validated and used to compare its predicted results with the proposed method results. The proposed method is validated based on comparisons between its predictions, full-scale load tests results using three piles subjected to axial tension loads in sandy soils and finite element predictions.

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1. Introduction

Piles are the common type of deep foundation used to transfer the loads from the superstructure to a deeper stratum when the soil immediately below the footing does not have an adequate bearing capacity. Piles are usually subjected to compressive loads. However, in many cases, they are required to resist tensile loads. Most of the available methods are only concerned with the ultimate tensile capacity. To determine the interaction between the foundation and the superstructure, it's essential to determine the pile's stiffness, which in general is represented by the load-displacement curve at the pile head. Methods that predict the pile behavior under axial loading, in general, can be divided into three broad categories according to Poulos and Davis (1980).

1. Load-transfer methods, which relate the pile displacement at several points along the pile length to the pile resistance.
2. Elasticity theory methods, which employ the equations described by Mindlin (1936) for surface loading within a semi-infinite mass.
3. Numerical methods, particularly the finite element based methods.

In the first category, the side resistance provided by the soil to the pile displacement is represented by a set of nonlinear springs along the pile shaft. The spring's characteristics are provided in the form of nonlinear resistance-displacement curves representing the skin friction effects. This relationship is expressed in terms of the shear stress developed along the interface (τ) versus the relative displacement between the pile shaft and the soil (z).

The methods that use the elasticity theory divide the pile into uniformly loaded elements. Compatibility between the displacements of the pile elements and the adjacent soil is imposed to obtain the solution. For the pile displacements, thecompressibility of the pile under axial load is considered. In most cases, Mindlin's equation (Mindlin, 1936) for a displacement due to a point load within a semi-infinite mass is used to obtain the soil displacements.

Currently, the finite element method is a powerful tool for analyzing various geotechnical problems (based on utilized models and reliability of input data) especially when it comes to inelastic behavior. Pile behavior under axial loading is one of many problems where the finite element could be a useful tool.

2. Methodology

The method developed by Ashour and Helal (2012a and 2012b) that determines the pile response under compression loads in sandy soils is modified to account for the change in the direction of loading. Two aspects of the method developed by Ashour and Helal (2012a and 2012b) were modified. First, the base resistance was omitted because any negative porewater pressure that may develop due to the voids created between the pile base and underlying soil (i.e. suction) would dissipate quickly. Second, the ratio of the tensile to compressive shaft capacity suggested by Nicola and Randolph (1993) is employed to assess the reduction in the shaft capacity due to tensile loading. It should be noted that Nicola and Randolph (1993) explored and quantified the Poisson's ratio effect and other potential mechanisms that explain the difference between the tensile and compressive shaft capacity. A FORTRAN computer program is implemented to conduct the parametric study and to assess the mobilized pile behavior under uplift forces in sandy soils.

Parametric Study

A parametric study is conducted to assess the effect of different soil parameters on the mobilized pile response under uplift forces. Figure 1 shows the pile and soil parameters adopted in the parametric study. The pile used is a 15-m long 0.5-m in diameter concrete pile.

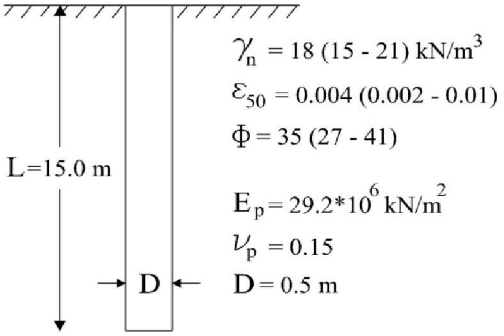


Fig. 1. Pile and soil parametes as adopted in the parametric study

Figures 2 through 7 show the effect of soil unit wheight(γ_n), strain at 50% stress level(ε_{50}) and the soil friction angle (Φ) on the pile response. To assess the effect of each parameter, the range of values between the parentheses in Fig. 1 is used while all other parameters remained constant.

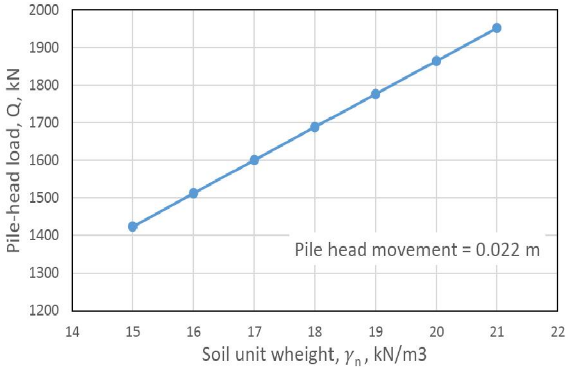


Fig. 2. Effect of γ_n on the pile-head load for a constant pile-head displacement value

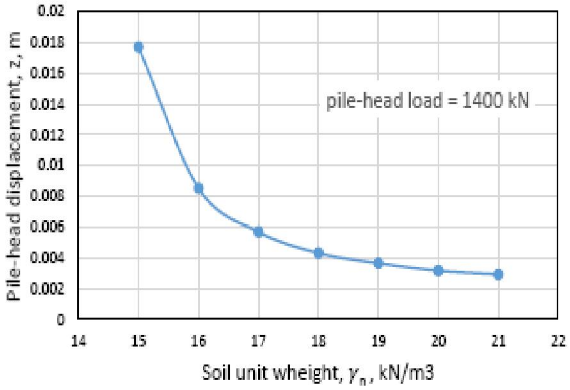


Fig. 3. Effect of γ_n on the pile-head displacement for a constant pile-head load value

The effect γ_n on the pile-head load and pile-head displacement is shown in Figs. 2 and 3 respectively. It can be noticed that for a given value of pile-head displacement, the pile-head load increases linearly with the increase in γ_n. On the other hand, the pile-head displacement decreases with the increase in γ_n or in other words the pile response becomes stiffer with the increase in γ_n.

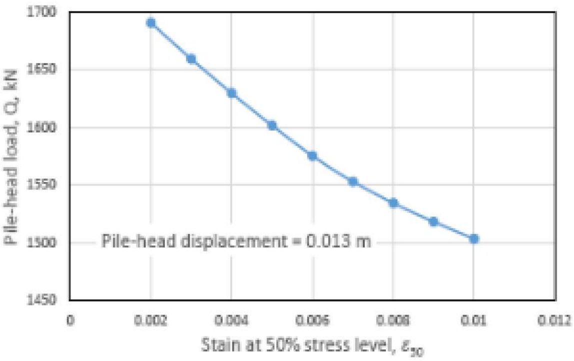


Fig. 4. Effect of ε_{50} on the pile-head load for a constant pile-head displacement value

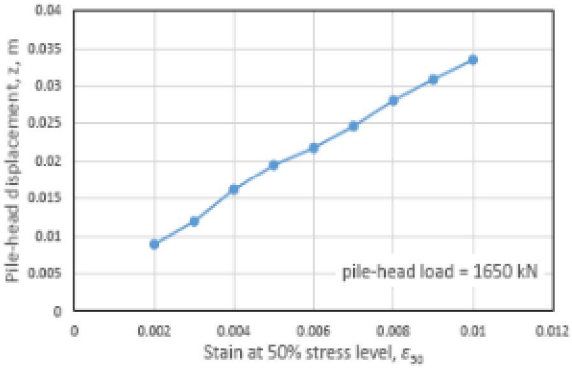


Fig. 5. Effect of ε_{50} on the pile-head displacement for a constant pile-head load value

Figures 4 and 5 show the effect of ε_{50} on the pile-head load and pile-head displacement respectively. It can be noticed that the pile gives a looser response with increasing values of ε_{50}.

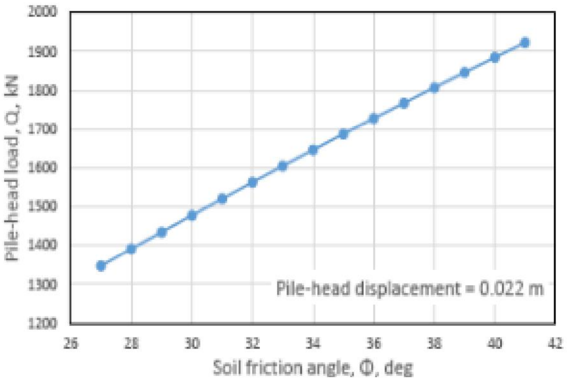


Fig. 6. Effect of Φ on the pile-head load for a constant pile-head displacement value

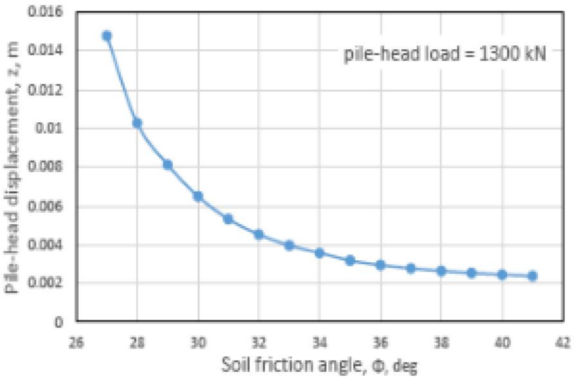


Fig. 7. Effect of Φ on the pile-head displacement for a constant pile-head load value

It can be noticed from Figs. 6 and 7 that the pile gives a stiffer response with increasing values of Φ.

Numerical analysis

The finite element method has become very popular in the field of geotechnical engineering. Therefore, a numerical model is developed using the finite element based program Plaxis to simulate the pile axial loading. After validation, the model is used to simulate full-scale load tests. A two-dimensional axisymmetric model is employed with the pile positioned along the axis of symmetry. A very fine mesh is used throughout the analysis. To avoid the direct influence of the boundary conditions, the distances from the pile base to the lower horizontal boundary and from the axis of symmetry to the outer vertical boundary of the models are kept large enough. A full fixity is used at the base of the geometry and a roller condition at the vertical sides. The two components of all the models are the pile and the soil. The piles discussed are made of concrete. They are modeled as a linear elastic nonporous material. The concrete elastic modulus in tension may be assumed the same as in compression up to the tensile strength (Park and Paulay 1974). Therefore, the value of the elastic modulus is taken equal to $29.2 * 10^{6}$ $\mathrm{KN/m^{2}}$ for concrete in tension and compression. Poisson's ratio is taken equal to 0.15 for concrete (Bowles 1996).

The soil is modeled as an elastoplastic material using the Mohr-Coulomb failure criteria. In the cases discussed in this study, the soil unsaturated unit weight (γ_{unsat}), Cohesion (C) and Friction angle (Φ) are reported. The soil saturated unit weight (γ_{sat}) is calculated or properly estimated. The values suggested by Bowles (1996) are used to estimate the soil elastic modulus (E) and Poisson's ratio (υ_{s}). The dilatancy angle (Ψ) is taken equal to Φ-30 when it's not reported as suggested in the Plaxis material models manual. The pile-soil interaction is simulated using interface elements placed around the pile. The interface reduction factor (R_{int}) is assessed using Eq. 1.

$$\tan\delta = R_{int} * \tan\emptyset \qquad (1)$$

Numerical model validation

The proposed finite element model is validated based on a comparison between its results and the results reported by Ribeiro (2013) of a full scale compression load test. The tested concrete pile was 40.6-m in length and 0.8-m in diameter. The pile cap was built 2.1 m below the ground level. The water was located 3.4-m below the ground surface. The soil layers properties are modeled as reported by Ribeiro (2013) and given in Table 1. It should be noted that when the friction angle Φ is equal to 0.0, the Mohr-Coulomb failure criteria is equivalent to the Tresca failure criteria. Figure 8 shows a comparison between the load-displacement curves reported by Ribeiro (2013) and the results predicted using the proposed finite element model for a pile tested in compression.

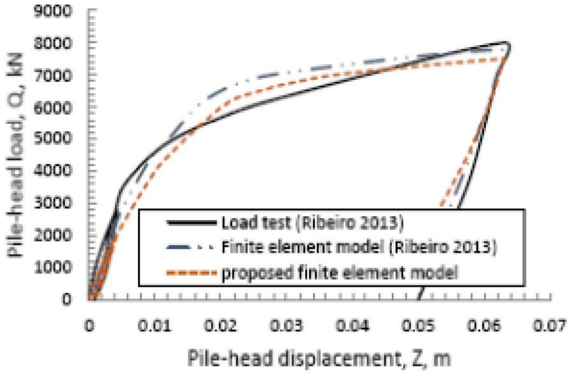


Fig. 8. A comparison between the published results and the proposed model for a compression load test

Table 1. Soil layers properties (Ribeiro, 2013)

layer	Length	Model	Material behavior	γ_{unsat} (KN/m^3)	E (MN/m^2)	υ	C (KN/m^2)	Φ (deg)	R_{int}
Superficial deposit	3 m	Mohr-Coulomb	Drained	18	25	0.3	-	30	0.63
Soft clay	12 m	Tresca	undrained	16	59	0.35	8	-	0.6
Medium clay	9 m	Tresca	undrained	18	77.7	0.35	26	-	0.6
Firm clay	4 m	Tresca	undrained	20	176.1	0.35	44	-	0.6
Gravel	2.5 m	Mohr-Coulomb	Drained	20.5	180	0.35	-	45	0.57
Very stiff clay	6 m	Tresca	undrained	21.5	200	0.25	200	-	0.5
Dense sand	4 m	Mohr-Coulomb	Drained	21.5	200	0.25	-	40	0.5
Hard clay	14.5 m	Tresca	undrained	21.5	200	0.25	600	-	0.5

An overall good agreement is noticed between the results obtained from the proposed finite element model and the published results. The results predicted using the proposed finite element model is almost parallel to the finite element results reported by Ribeiro (2013). In some areas, the load displacement curve predicted using the proposed finite element model is closer to the load test results than the model proposed by Ribeiro (2013). **Case studiy**

Comparison and Validation

The proposed method is validated based on a comparison between its predicted load-displacement curves and the reported curves from full-scale axial tension load tests in sandy soil. The curves from the numerical analysis are also presented for these tests.

Southern central region of Brazil

Carvalho and Albuquerque (2013) performed full-scale axial tension load tests on three bored concrete piles 0.35-m, 0.40-m and 0.50-m in diameter and 10-m long. The water table was below the base of the piles. The geotechnical parameters reported by Carvalho and Albuquerque (2013) and the interpreted parameters used in the numerical analysis and the proposed model are given in Table 2. The results and comparison are shown in Fig. 9.

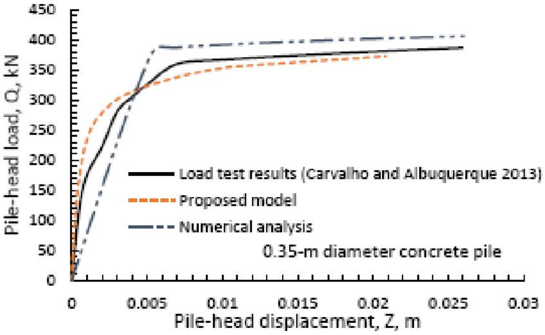
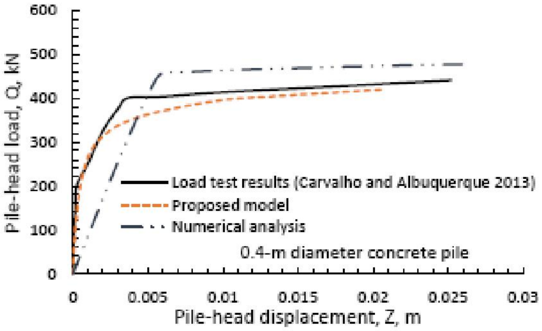


Table 2. Reported/interpreted input soil parameters used for tests in the Southern Central Region of Brazil

Reported (Carvalho and Albuquerque2013)							Interpreted				
Thickness (m)	γ_{unsat} (kN/m^3)	Φ (deg)	C (kN/m^2)	SPT-N_{72}	Specific gravity	e	γ_{sat} (kN/m^3)	E (kN/m^2)	υ	Ψ (deg)	ε_{50}
0 – 6	16.3	30	6	4	2.73	0.94	18.56	10000	0.3	0	0.007
6 – 12	18.9	23	20	7	2.76	0.71	19.91	22500			0.005



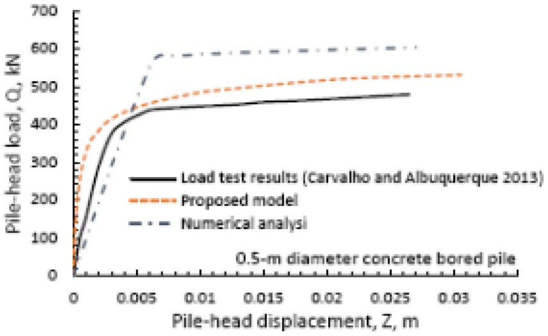


Fig. 9. Predicted pile-head response vs. field and numerical results of Brazil tests on piles with different diameters.

A good agreement is noticed between the predicted and published load displacement curves for the three piles. It can be noticed that the proposed model results are closer to the load test results than the results predicted using the numerical analysis.

Conclusions

1. The suggested technique can assessthe pile response under uplift forces based on pile and soil properties.
2. The effect of different soil parameters on the pile behavior under uplift loads is assessed based on a parametric study.
3. The good agreement between predicted and reported pile-head response obtained from field tests shows the capability of the suggested method.
4. The suggested technique can easily be used to assess the mobilized bile response, unlike the finite element programs that require a long modeling process and soil parameters that are not easily obtained.

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