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THE BEHAVIOR OF STEEL AND TIMBER SINGLE PILES UNDER AXIAL LOAD IN LOOSE SAND: EXPERIMENTAL STUDY AND NUMERICAL VALIDATION

EKSENEL YÜK ALTINDA ÇELIK VE AHŞAP TEKLI KAZIKLARIN GEVŞEK KUM İÇERİSİNDE DAVRANIŞLARI: DENEYSEL ÇALIŞMA VE SAYISAL DOĞRULAMA

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ABSTRACT

This paper presents the investigation of the behaviour of steel and timber model piles in loose sand under axial load, as well as validation of the experimental results with finite element method (FEM). Using a standard direct shear box test, the internal sand friction angle (ϕ) and the skin friction angle between the sand and the pile materials (δ) were determined. Model pile load tests were carried out in a calibration soil tank and the piles were installed as a non-displacement (pre-installed). The load was applied to the model pile by using a hydraulic jack and the settlement at the head of pile was measured by linear variable displacement transducer (LVDT), and the load-settlement curve of the single model piles was obtained. The finite element method (FEM)-based Plaxis 3D program was also used in this research to verify the experimental findings. Dependent on the results of the study, a reasonable agreement was found between the experimental results and the results of the (FEM) analysis.
Keywords: *Axial load, loose sand, steel and timber model piles, shear box test, FEM analysis*

ÖZET

Bu çalışmada, eksenel yük altında gevşek kumdaki çelik ve ahşap model kazıkların davranışının araştırılmasının yanı sıra sonlu elemanlar yöntemi (FEM) ile deneysel sonuçların doğrulanması sunulmuştur. Laboratuvarda, kesme kutusu deneyi kullanılarak, kumun içsel sürtünme açısı (ϕ) ve kum ile kazık malzemeleri arasındaki yüzey sürtünme açısı (δ) belirlenmiştir. Model kazık yükleme deneyleri bir kum tankında gerçekleştirilmiş ve kazıklar önceden kurulmuş olarak yerleştirilmiştir. Model kazığa hidrolik kriko kullanılarak yük uygulanmış ve kazık başındaki oturma, lineer değişken deplasman transdüseri (LVDT) ile ölçülmüştür ve tek model kazıkların yük-oturma eğrisi elde edilmiştir. Deneysel bulguları doğrulamak için bu araştırmada sonlu elemanlar yöntemi (FEM) tabanlı Plaxis 3D programı kullanılmıştır. Çalışmanın sonuçlarına bağlı olarak,

deneysel sonuçlar ile (FEM) analiz sonuçları arasında yeterli uyumun olduğu gözlemlenmiştir.
Anahtar Kelimeler: *Eksenel yük, gevşek kum, çelik ve ahşap model kazıklar, kesme kutusu deneyi, FEM analizi.*

1. INTRODUCTION

Piles are used to construct pile foundations, they are structural members fabricated from timber, concrete, steel and composite materials. Piles are considered deep foundation because the width or diameter of the pile is much smaller compared to their depth. Despite the high cost of pile foundations, it is often necessary to use them to guarantee the safety and protection of the structures. Unlike the shallow foundation, the mechanism of moving the load through the pile to the soil layers is complicated. In general, the axial loads applied to the piles are transferred into the ground by two mechanisms: the skin friction resistance and the end (point) bearing capacity. When the soil deposit is weak the end bearing capacity of the pile is almost negligible, therefore the most capacity of the pile is originated from skin friction resistance between the pile and adjacent soil. Steel and timber piles are considered to be one of the oldest types of pile foundations, they have been used for many years and remain an excellent choice for many applications (Coduto et al., 2001).

The determination of pile bearing capacity is not simple and it is quite complex, a lot of theories and empirical methods are available at present but they will not give the same value of bearing capacity, because there are many uncertainties in soil properties and soil-pile materials interface (Mijena, 2012). Due to the high expense of field pile load tests, researchers attempted to conduct small- and large-scale pile load tests to understand the response of non-displacement piles to axial load (Alawneh et al., 1999, Fioravante, 2002, Gavin and Gallagher, 2005, Goel and Patra, 2007, Loukidis and Salgado, 2008, Lashkari, 2013, Han et al., 2017). However, the small model pile load test does not exactly represent the full pile load test due to the scale effect (Tovar-Valencia et al., 2018). Recently, numerical modelling analysis based upon the FEM has become very popular in the analysis and design of geotechnical structures such as pile foundations, retaining walls, dams, etc. Therefore, many researchers studied the behaviour of a full-scale pile load test under axial load using FEM analysis (Basu et al., 2011, Salgado et al., 2017, Jazebi and Ahmadi, 2020). Before using FEM for the analysis of pile foundations, it must be validated by experimental results (Kampitsis et al., 2015). The interaction of the soil-pile is also an important factor which makes a significant contribution to determining the pile's bearing ability. In order to estimate the skin friction angle (δ) between the pile material and the soil, the interface shear test can be used (Potyondy, 1961, Yoshimi and Kishida, 1981, Reddy et al., 2000, Tiwari et al., 2010, Aksoy et al., 2016, Han et al., 2018). Furthermore, the impact of the skin friction angle on the pile shaft resistance was examined by a number of researchers, and they have stated that the high skin friction angle produces a greater bearing capacity of the pile (Tehrani et al., 2016, Tovar-Valencia et al., 2018).

The objective of this research is to study the behaviour of non-displacement (pre-installed) single model piles under the action of axial load in loose sand. Two model piles (closed-end steel pipe pile and timber pile) were used in the study. Using the shear box test, the internal friction angle of the sand (ϕ) and the skin friction angle between the sand and the pile material (δ) were determined. The model pile load tests were performed in a soil tank and the experimental results were obtained as load-settlement curves. The FEM analysis was employed using the Plaxis 3D software taking into account the soil-pile interaction and the FEM results were compared with the experimental results2. MaterIals and Method

2.1. Test Sand

The sand used in the experiments was river sand with uniform gradation taken from the Murat River in Elazığ, Turkey. The sand has been washed and oven-dried and sieved by passing sieve #18 (1 mm) opening sieve and retained on sieve #200 (0.075 mm). The gradation of sand had been obtained through a sieve analysis test that was executed according to ASTM D422-63 (Standard, 2007) as shown in Figure 1. The sand's specific gravity was determined based on ASTM D854-14 (ASTM). The maximum and the minimum dry densities for sand were measured by experiment in agreement with ASTM D4254 (ASTM, 2006). The index parameters of the sand are listed in Table 1. In consonance with the unified soil classification system (USCS), the sand was grouped as being poorly-graded sand (SP).

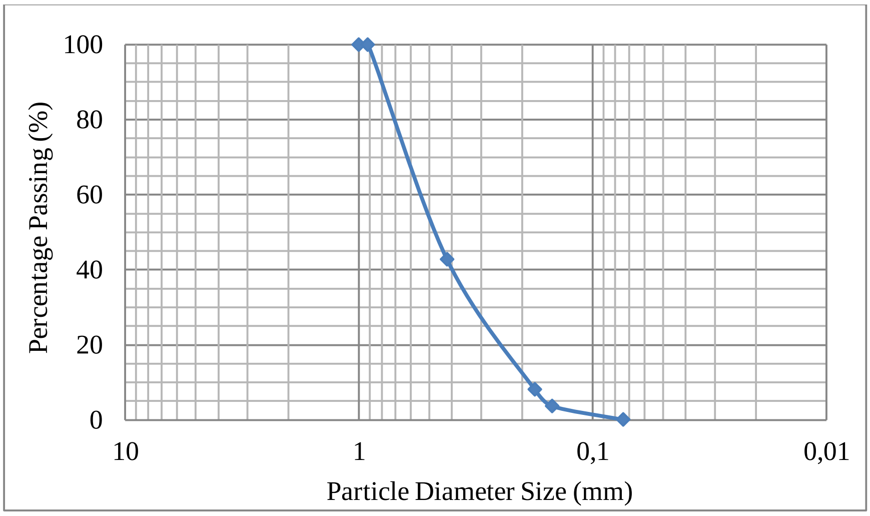

Figure 1. The sand grain size distribution curve.

Table 1. Index properties of the sand

Property	Value
Average diameter of the soil particle, D_{50}, (mm)	0.475
Uniformity coefficient, C_u	2.895
Curvature Coefficient, C_c	0.980
Soil Class (USCS)	SP
Specific gravity, G_s	2.77
Maximum dry unit weight, γ_{dmax} (kN/m$^{3)}$	17.66
Minimum dry unit weight, γ_{dmin} (kN/m^3)	14.32
Maximum void ratio, e_{max}	0.898
Minimum void ratio, e_{min}	0.539

2.2. Model Piles and Sand Tank

In this study, two model piles of different materials, including a closed-end steel pipe pile and a timber pile, were used. The diameter of the piles was 50 mm, the total length was 600 mm and the embedded length was 500 mm during the test. The steel pile was made of steel st-37 and the timber pile was made of the beech tree.

A specially designed steel tank made from steel with inside dimensions (75cm X 75cm X 100cm) was used in this study. To ensure that no interference occurs between the failure region around the model pile and the tank walls, the ratio of the diameter of the soil tank to the diameter of the model pile (D_{tank}/D_{pile}) must be greater than eight, as well as the diameter of the model pile has to be greater than the average diameter of the soil particles by twenty times ($20*D_{50}$) (Bolton et al., 1999, Salgado, 2012). In this study (D_{tank}/D_{pile}) = 15 which is greater than 8, and model pile diameter = 50 mm which is greater than ($20*D_{50}$ = 9.5 mm).

Loose sand was used for the test with relative density (Dr = 10 %) corresponding to a unit weight of 14.6 kN/m^3. A calibration was performed in the laboratory to obtain this relative density by pouring the test sand from a height of 10-15 cm into the soil tank by using a flexible plastic tube with a diameter of 5 cm.

2.3. Shear Interface Test

A shear box test with dimensions (6cm x 6cm x 2cm) was employed for determination of sand internal friction angle (φ) and the skin friction angle (δ) between sand and pile material. The shear box test was carried out in agreement with ASTM D-3080 (ASTM), and skin friction angle (δ) between sand and pile material was measured based on ASTM D5321/D5321M-14. Table 2 lists the internal friction angle of the sand and the skin friction angle between the sand and the two model piles.

Table 2. Internal friction angle of the sand and skin friction angles between sand and pile materials

Relative density of the sand (D_r, %)	Dry Unit Weight (γ_d), (kN/m^3)	Internal friction angle of the sand (φ), degree	Skin friction angle (δ) of sand-timber, degree	Skin friction angle (δ) of sand-steel, degree
10	14.6	41.0	35	29.5

2.4. Installation Model Piles and Test Procedure

Model pile load tests were executed in the soil model tank with sand relative density (Dr = 10%). For installing model piles, the pile was connected to a detachable shaft by special types of epoxy adhesive, and the detachable was threaded to load cell. In each test, the tank was filled with sand up to 40cm in depth, then the pile was lowered until the bottom of the pile lay on the sand, after that the pile verticality was checked by water bubble level and the filling tank was continued to a depth of 90 cm. The axial load was applied to the single model pile using a hydraulic jack, the model pile settlement rate was 1 mm/min, and the data were recorded in terms of axial load and settlement. Figure 2 displays the schematic diagram of the sand tank, test setup, and experimental apparatus.

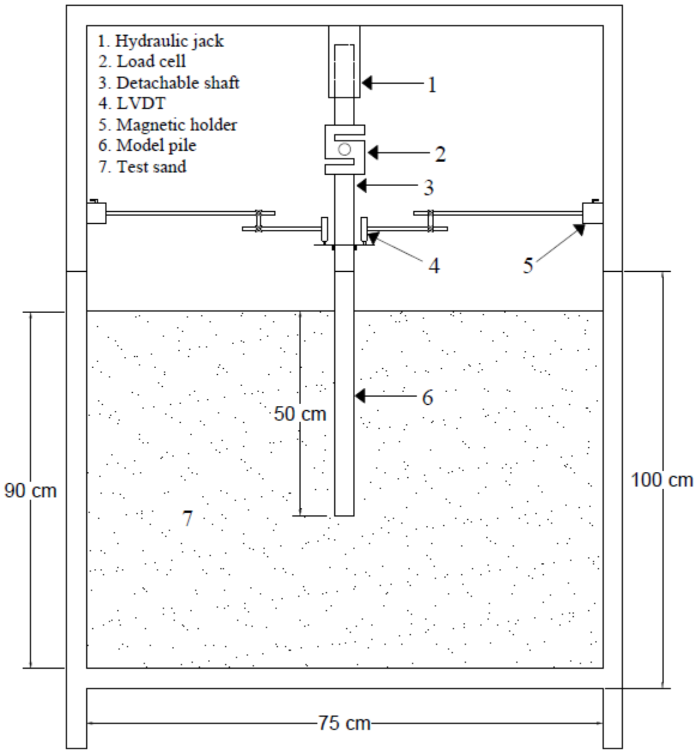

Figure 2. Schematic diagram of the soil model tank and experimental apparatus

2.5. Finite Element Method Analysis

In this study, the numerical finite element software Plaxis 3D has been used for the analysis of single model piles (steel and timber). The soil contour geometry and boundary conditions were established exactly like the sand tank. The advanced Hardening Soil model was used for modelling the test sand under drained condition. The model piles were modelled to obey linear elastic and non-porous materials. For appropriate modelling of soil-pile interaction, an interface element was defined between the sand and pile using the following equation offered by Plaxis 3D software.

$$\text{Tan}(\delta) = R_{int}\,\text{Tan}(\varphi) \quad (1)$$

Where δ is a skin friction angle between soil and pile, R_{int} is the strength reduction factor, and φ is the internal friction angle of the soil. The parameters of the interfaces are the same as the sand except for the interface reduction factor. The parameters of the sand, sand-pile interfaces, and model piles used in the FEM are listed in Table 3 and Table 4, respectively. After all the parameters were defined, a 10-node tetrahedral element was used to generate the 3D mesh for the entire model as shown in Figure 3. FEM analysis was performed and load-settlement curves for both model piles were obtained.

Table 3. Parameters of the test sand and interfaces used in FEM analysis

Parameters	Test sand	Sand-timber pile Interface	Sand-steel pile Interface	Unit
Dry Unit Weight (γ_d)	14.6	14.6	14.6	kN/m^3
E_{50}^{ref} (P_{ref} = 100 kPa)	2000	2000	2000	kN/m^2
E_{ur}^{ref} (P_{ref} = 100 kPa)	6000	6000	6000	kN/m^2
E_{oed}^{ref} (P_{ref} = 100 kPa)	2000	2000	2000	kN/m^2
C, Cohesion	0.0	0.0	0.0	kN/m^2
φ, Friction angle	41	41	41	degree
ψ, Dialatancy angle	0.0	0.0	0.0	degree
ν_{ur}, Poisson's ratio	0.3	0.3	0.3	-
m, Power	0.5	0.5	0.5	-
Tensile Strength	0.0	0.0	0.0	kN/m^2
R_{int}	1.0	0.80	0.65	-

Table 4. The parameters of the model piles used in the FEM analysis

Model Pile	Average Unit Weight (γ), (kN/m^3)	Elasticity Modulus (E) (kN/m^2)	Poisson's ratio
Timber	6.08	13.95 * 10^6	0.4
Steel	30.79	2.00 * 10^8	0.3

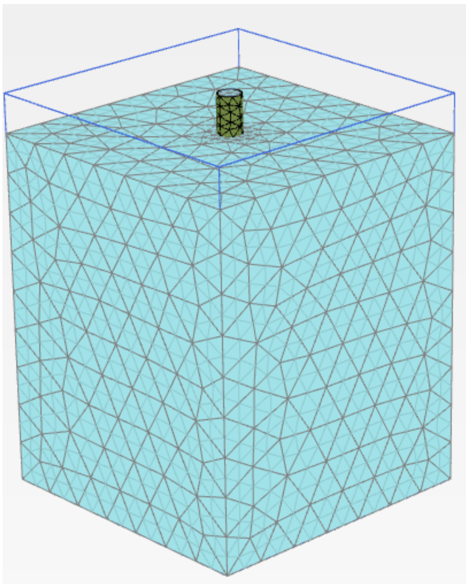

Figure 3. Three-dimensional mesh generated in Plaxis 3D program

3. RESULTS AND DISCUSSION

Two model pile load tests were performed in the laboratory under axial load for closed-end steel pipe pile and timber pile. FEM analysis was carried out under the same conditions. The results from the experimental and numerical were obtained and load-settlement curves of the model piles were drawn. The load-settlement curves for the timber and steel piles are shown in Figure 4 and Figure 5, respectively. From the load-settlement curves of model piles, it is clear that the timber model pile has a higher bearing capacity than steel, this is because the roughness of the timber is higher than steel and it produces more friction resistance. It can be seen that there is good compliance between experimental and numerical analysis results.

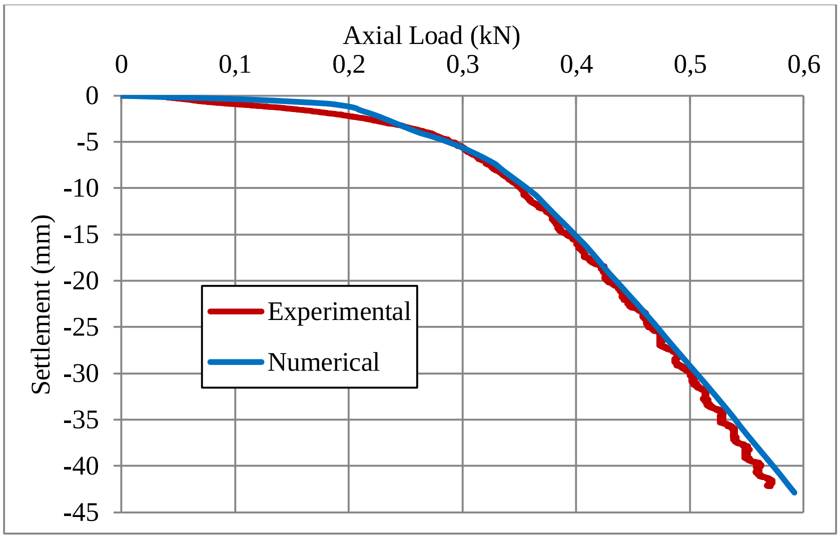

Figure 4. Load-Settlement curves of timber model pile

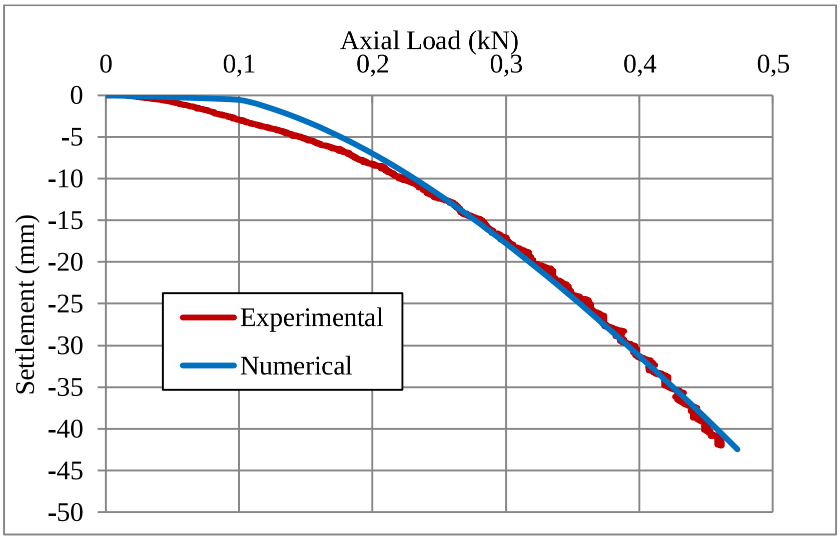

Figure 5. Load-Settlement curves of closed-end steel pipe model pile

4. CONCLUSION

The vertical model pile load tests were conducted experimentally for two different model pile materials (steel and timber) in loose sand. To validate the experimental results Plaxis 3D software based on FEM was used, based on the results of this study, it is possible to draw the following inference.

- From experimental and numerical results, the skin friction angle between soil and pile materials seems to play an important role in the bearing capacity of the pile, the higher skin friction angle produces a higher bearing capacity.
- It was found that there is a fairly good agreement between the load-displacement curves of model piles under axial load obtained by experimental and numerical methods.
- From this study, it can be concluded that the advanced hardening soil model with an appropriate interface element for soil-pile interaction can accurately simulate the behaviour of axially loaded model piles embedded in loose sand.

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SYMBOL LIST

Symbol	Explanation
FEM	Finite element method
ϕ	Internal friction angle of sand
δ	Interface friction angle between sand and pile materials
Gs	Specific gravity
Cu	Uniformity coefficient
Cc	Curvature Coefficient
e_{max}	Maximum void ratio
e_{min}	Minimum void ratio
LVDT	Linear variable displacement transducer
USCS	Unified soil classification system
SP	Poorly graded sand
D_{50}	Average diameter of the soil particle
γ_{dmax}	Maximum dry unit weight
γ_{dmin}	Minimum dry unit weight
R_{int}	Strength reduction factor