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ORIGINAL PAPER

3D Numerical Modeling of a Single Pipe Pile Under Axial Compression Embedded in Organic Soil

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Abstract The objective of this paper is to numerically study the behavior pipe pile under axial compression embedded in organic soil has been numerically predicted. The pipe pile used in the study has been produced by steel and it has outer and inner diameters of 20 mm and 15 mm, respectively. The pile embedded in organic soil, which has the pile length ratios of 10, 20 and 30 (L/D), has been exposed to the axial load for different diameter ratios (d/D = 0, 0.25, 0.50 and 0.75). Numerical analyses have been performed by using Plaxis 3D computer program which is based on finite element method. The capability of the numerical analysis in the prediction of the load capacity of pipe pile has been studied. It has been understood that the results obtained from numerical analysis and experiment are in a good agreement, and then it has been observed in the parametric study that the load capacity of single pipe pile increases with the increase of the pile length and the wall thickness.

Keywords Foundation · Numerical analyses · Pile · Soil modeling · Soil–structure interaction

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1 Introduction

The physical properties of organic soils are very effected by the existence of even a small quantity of organic substances. The organic soils grain size consists of silt or clay particles; so that, they are frequently defined as organic clayey soil or organic silty soil (Khadka 2011). An organic soil is one which has an adequate content of organic matters that affects shear strength and compressibility of the soil. Organic soil containing fibrous particles has more frictional resistance than soft silt and clay deposits (Mesri and Ajlouni 2007). In order to mobilize the maximum frictional resistance in these types of soils, high deformation rates are required when compared to soft clay soils (Hardy and Thomson 1956; Tressider 1958; MacFarlane 1969). Organic soils have also very high secondary consolidation value, higher water content and liquid limit compared to inorganic silt and clay. When the organic soil is in the limits of proposed project area, it is frequently viewed as problematic field for making of dikes, roads, storage facilities, housing developments and industrial parks. It requires continued maintenance processes or high initial costs (Colley 1950; Thomson 1957; Hanrahan and Rogers 1981). In order to maintain long term performance of the structures, the organic soils are improved by different soil modification methods including excavating and replacing, displacing, or precompression. Pile foundation is also used to overcome low strength and high settlement problems of the organic soil (Brawner 1958; Lea and Brawber 1963; Keene and Zawodniak 1968; Samson and La Rochelle 1972; Hansbo 1982; Jones et al. 1986; Jorgenson 1987; Magnan 1994).

Always piles are exposed to axial loads due to their own weights apart from the additional load which is structure load. So that, it is quite important to investigate the pile behavior under the axial loading. Pile foundations which are the part of the structure are generally used to carry the load of the superstructure. Piles are members with long and slender characteristics, which transference the load to deeper soil or rock of less compressibility and high load capacity escaping shallow soil layers of low bearing capacity (Adeb and Smith 2005). Full-scale field tests are highly desirable, but they are expensive, difficult to perform and time-consuming. For these reasons, laboratory experiments are generally carried out with small scale piles in the test tanks. Moreover, the laboratory experiments are widespread because of they are cheap, easy to arrange and weather independent. Hence, the experimental studies about the performance of a single pile under the axial loading have received extensive attention from the previous researchers. Kérisel and Adam (1962) studied the performance of a single pile in-situ tests and determined the factors that affect the bearing capacity of a single pile. These factors consisted of the relative density, the depth, the diameter of the pile and the loading rate. Many researchers such as Horvath (1995) and Al-Mhaidib (2001) investigated the effect of the loading rate on the axial pile capacity. Paik et al. (2011) studied the axial behavior of the tapered piles in sandy soil. They showed that the shaft load of tapered piles continuously increased with the pile settlement. Lee et al. (2011) researched the axial loads effects on the lateral performance of the piles driven into the sand. The study revealed that the presence of an axial load on a pile driven into the sand is detrimental to its lateral capacity because the lateral displacement of the model pile head increased with the increase of the axial load. Akguner and Kirkit (2012) studied the effect of the axial load on the bearing capacity of the cast-in-place pile to compare with the empirical methods. They reported that the bearing capacity obtained from the empirical methods agree reasonably well with those of calculated from pile load tests. Stringer and Madabhushi (2013) investigated the transfer of the axial load during a liquefaction. They found that the pile shaft friction continued during an earthquake in both dense and loose sand soil. The influence of axially loaded piles on the ultimate shaft friction and load–displacement behavior in clay soil was also studied by Karlsrud (2014). Barari et al. (2015) studied the interaction of fluid-structures-seabed of a monopile foundation of the wind turbine in liquefiable soil. They used the finite difference program to investigate the mechanisms of the monopiles in saturated granular soil. The axial load capacity of piles has been investigated from the toe and unit shaft resistance which increase linearly with depth but reaching a limit value or critical depth after a certain depth (Leland and Kraft 1991). Fattah and Al-Soudani 2016) studied the behavior of the plug on the pile bearing capacity and the plug removal effects. Several parameters were conducted like the percentage of diameter to length of pile, type of installation in loose sand, removal of the plug with respect to the length of the plug in three stages. It was observed that the percentage of decreasing in pile bearing capacity for the open-ended pile increased with the increase of removal of the plug length. Canakci and Hamed (2017) investigated the axial behavior of the piles install into the organic soil made at two different densities. It was used four types of pile materials such as steel, wood, rough concrete and smooth concrete, and with many lengths to the diameter ratios. The ultimate resistance of unit shaft for the rough concrete pile was more than those of other piles at the same soil condition and the pile length. It has been understood from the past studies reviews that there is a miss information's on the performance of the pile in organic soil. Hence, furthermost of the reported field and laboratory researches have been obtained to emphasis on exploration the pile performance in clay and sand soil. Otherwise, there have been no literature on the pile behavior under the axial compression in this type of soil. So that, for a more comprehensive considerate the interaction of the pile-soil, it is essential to study the behavior of a pile exposed to an axial load installed

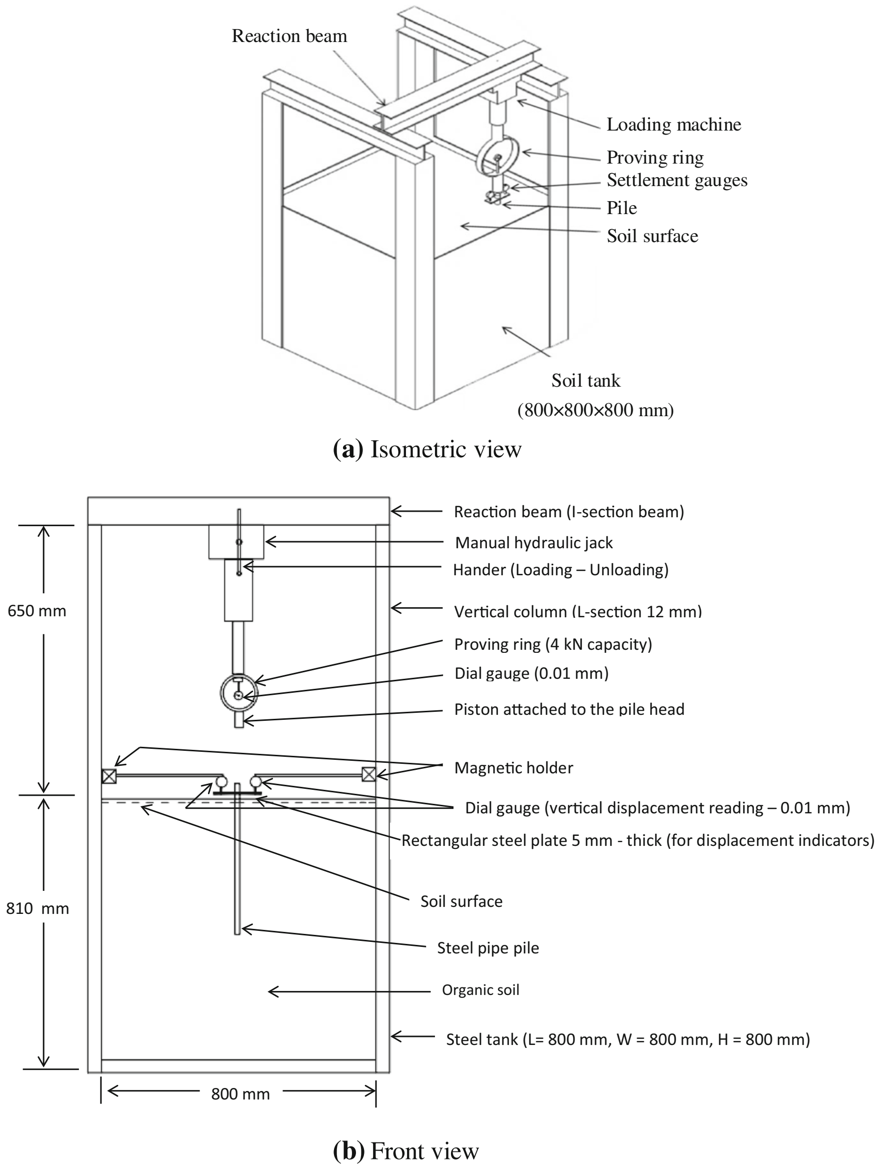


Fig. 1 Details of the test tank in case of axial compression (Canakci and Hamed 2017)

in organic soil. In this paper, numerical investigations have been conducted on vertical piles under axial compression driven in organic soil.

In this study, a single pipe pile behavior under axial compression embedded in organic soil has been numerically predicted. The pipe pile used in the study has been produced by steel and it has outside and inside diameters of 20 mm and 15 mm, respectively. The pile embedded in organic soil, which has the pile length ratios of 10, 20 and 30 (L/D), has been exposed to the axial load for different diameter ratios (d/D = 0, 0.25, 0.50 and 0.75). Numerical analyses have been performed by using Plaxis 3D computer program which is depend on the method of finite element. The Mohr–Coulomb (MC) model has been chosen to simulate the organic soil behavior because it is focused on the short-term stability in the numerical analysis. The result obtained from the numerical analysis related to the pipe pile under the axial compression has been compared with the experiments performed by Canakci and Hamed (2017). Thus, the success of the numerical analysis in the prediction of the load

Table 1 Properties of the organic soil used in this study

Item	Quantity
Organic content (%)	23
pH	6.7
Maximum dry density[a] (kN/m^3)	10.3
Optimum water content[a] (%)	39
Liquid limit (%)	75
Plastic limit (%)	45
Natural water content (%)	97
Fine sand (%)	23.4
Clay and silt (%)	76.6
Specific gravity	2.24

[a]Maximum dry density and optimum water content have been determined according to standard compaction test (ASTM D698 2012)

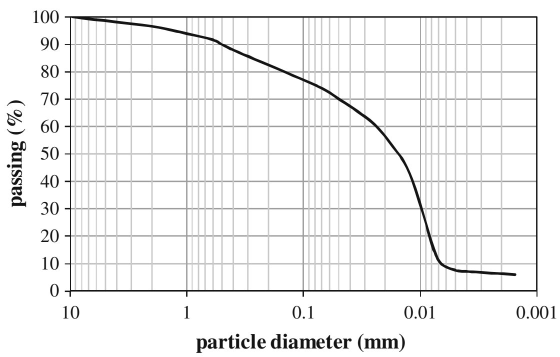


Fig. 2 Particle size distribution curve of the organic soil

capacity of pipe pile has been studied. It has been understood that the results obtained from numerical analysis and experiments are in a good agreement, and then it has been observed in the parametric study that the load capacity of single pipe pile increases with the increase of the pile length and the wall thickness.

2 Experimental Studies

The original tests had been carried out by Canakci and Hamed (2017) in the laboratory. Pile tests were carried out in a test tank. The details of test program dimensions of the tank, material properties of test piles, sample preparation, and loading setup can be found from the study of Canakci and Hamed (2017). Nevertheless, test tank and loading set up is shown in Fig. 1. The soil adopted in this research was obtained from a city of Sakarya in Turkey. The organic content (OC) of the selected soil was obtained by using ignition in an oven at 440 °C for 4 h. Some standards have been used such as ASTM D2974, ASTM D854 (2014) and ASTM D422 (2002) so as to determine organic content, gradation and specific gravity, respectively. The characteristics of these parameters are presented in Table 1. The distribution of soil particles is also presented in Fig. 2. As shown in Table 2, presented organic soils are classified based on ASTM with many classification systems and the organic soil conducted in this research is classified as Sapric (H_7–H_{10}), high ash, and slightly acidic. Organic soils are characteristically variable materials,

Table 2 Classification of organic soil based on ASTM

ASTM Standard	Criteria	Designation	Present study
Fiber content (ASTM D1997 2008)	Fibric (H_1–H_3)	67% < fiber	22.3% Sapric
	Hemic (H_4–H_6)	33% < fiber < 67% fiber	
	Sapric (H_7–H_{10})	33% > fiber	
Ash content (ASTM D2974 2013)	Low ash	5% > ash	77% High ash
	Medium ash	5% < ash < 15%	
	High ash	15% < ash	
Acidity (ASTM D2976 2004)	Highly acidic	pH < 4.5	6.7 Slightly acidic
	Moderately acidic	4.5 < pH < 5.5	
	Slightly acidic	5.5 < pH < 7.0	
	Basic	pH ≥ 7.0	

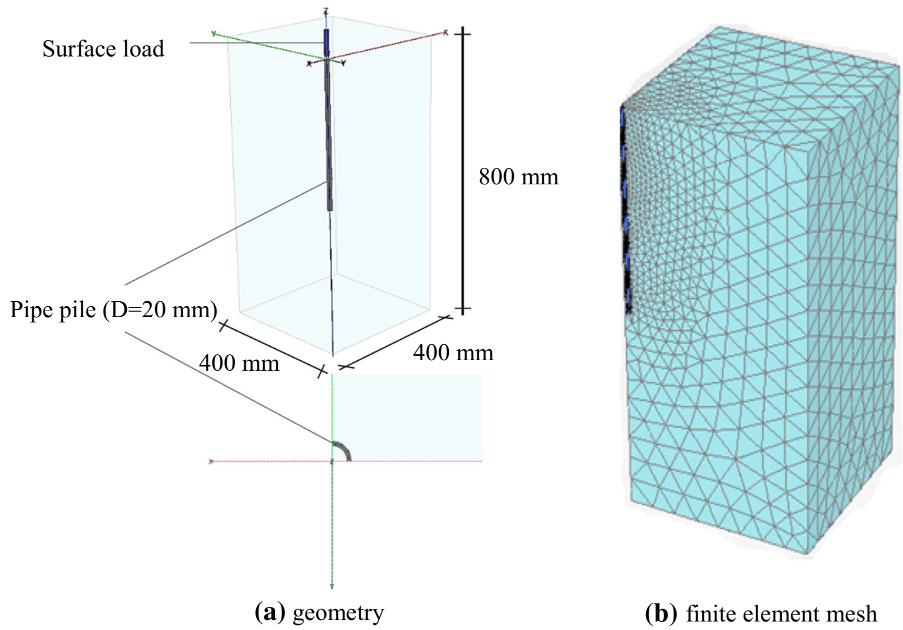


Fig. 3 The pipe pile under the axial load

Table 3 Material model parameters for the organic soil and the pipe pile

Item	Soil	Pile
Material model	MC	LE
Drainage type	Undrained	Non-porous
Unit weight, γ (kN/m^3)	7.7	77.0
Elastic modulus, E (kN/m^2)	4000	2×10^8
Cohesion, c (kN/m^2)	3	–
Internal friction angle, ϕ (°)	36	–
Dilation angle, ψ (°)	6	–
Poisson's ratio, *v*	0.25	0.30

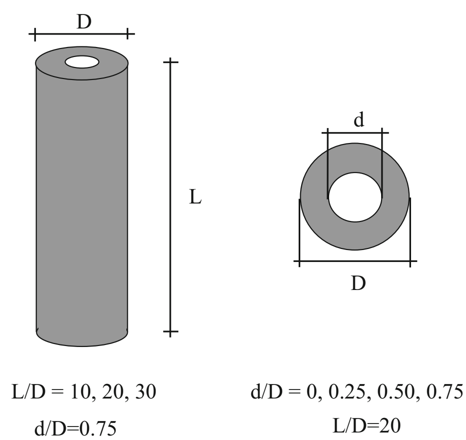


Fig. 4 Geometric parameters of the pipe pile

the limited laboratory exploration concerning pile behavior in organic soil, that help to define the behavior of these difficult soil interact with piles with excessive precision. However, Authors expected that the new conclusions of this study may contribute to the thoughtful of pile response in organic soils, and its output results could be appropriate to organic soils at sites.

3 Numerical Studies

The load–settlement performance of a single pipe pile was simulated, numerical analyses using Plaxis 3D were executed to simulate the vertical pile under axial loading case, which is depend on the method of finite element (Plaxis 3D 2015). The soil and pipe pile clusters were made with 10 nodes. Model in three-dimension is appropriate to apply the loading system for the condition of pipe pile and surface area. To simulate the pipe pile using Plaxis 3D, a working area of 400 mm width, 400 mm length and 800 mm height was adopted, and the geometry was simulated by means of a model in which the pipe pile was positioned along the axis of symmetry (Fig. 3). During analyzing the results, the pipe piles have been analyzed as the

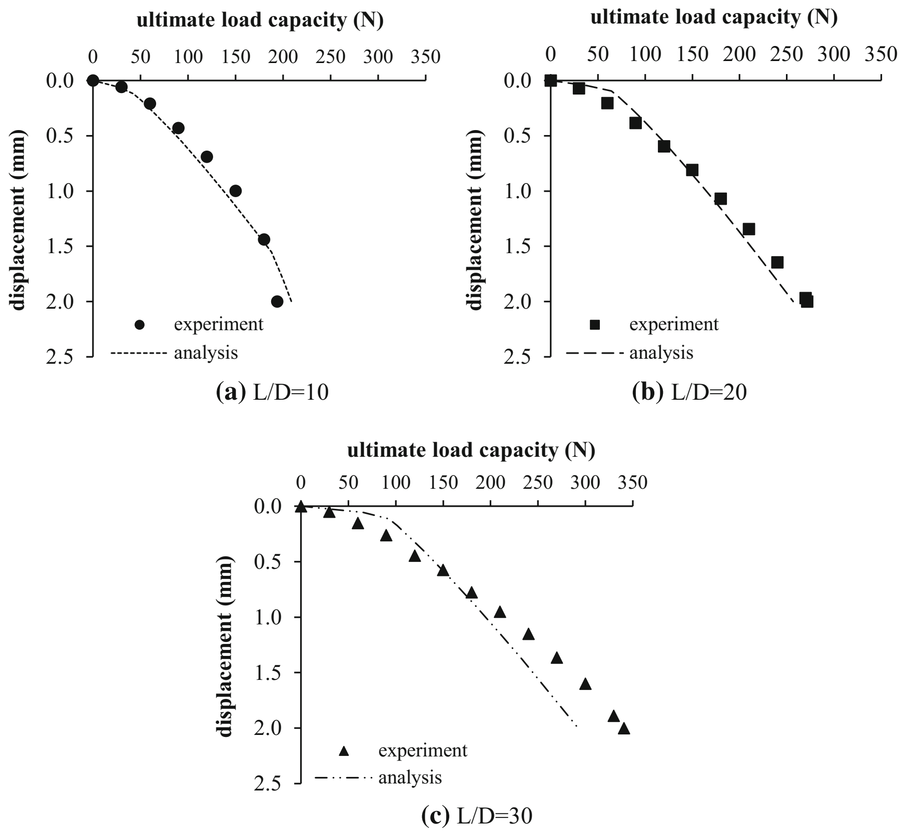


Fig. 5 Comparison between the experiment and the numerical analysis

volume pile model. The volume model has been conducted for different types of pile and it has been reflected as a nonporous material with circular shape. Parameters with different limitation of pile used in the study are given in Table 3. Before starting 3D analyses, the entire problem and quarter of that were modeled, separately. The results obtained from these analyses were found to be quite compatible with each other. Hence, the analyses were carried out by modeling a quarter of geometry instead of the entire of it to save time. Besides, the mesh using finite element for the problem was selected as the medium density and it was created mesh densification in the location of the structural element. In this study, the analyses of the bearing capacity of the pipe pile was calculated by the method of staged construction and the method of plastic analysis determination. Numerical analyses have been performed in dry soil conditions. Hence, pore water pressure is not considered in this study.

A different lengths and wall thicknesses of pipe piles were modeled. Analyzing of results were carried out for pile length ratios (L/D) of 10, 20 and 30 while the diameter ratio (d/D) of 0.75 was constant. Furthermore, while the pile length ratio of 20 was constant, the analyses were made for four different diameter ratios of 0, 0.25, 0.50 and 0.75 (Fig. 4). They had an outer diameter of 20 mm and they were defined as a quarter circle. The Mohr–Coulomb model of was conducted as the constitutive model for the soil. Several researchers have attempted to model the behavior of organic soil using normal soil constitutive models, mostly the conventional Mohr–Coulomb model (Long 2005). Brinkgreve et al. (1993) obtained reasonable results with Plaxis over organic soil using either the Mohr–Coulomb or Modified Cam-Clay constitutive models. However careful choice of input parameters was required. The behavior of soils in the analysis of geotechnical engineering problems is frequently investigated with the Mohr–Coulomb material model because of some reason given herein. For instance; it is needed a limited number of model parameters, the failure criteria can be defined by using simple physical properties like cohesion and internal

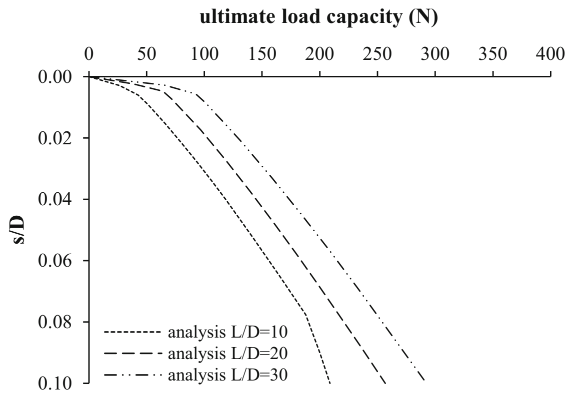


Fig. 6 Ultimate load capacity versus s/D for L/D = 10, 20 and 30

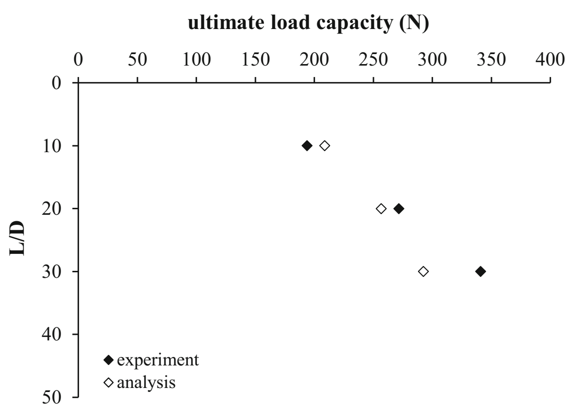


Fig. 7 Comparison between the experiment and the numerical analysis for L/D = 10, 20 and 30

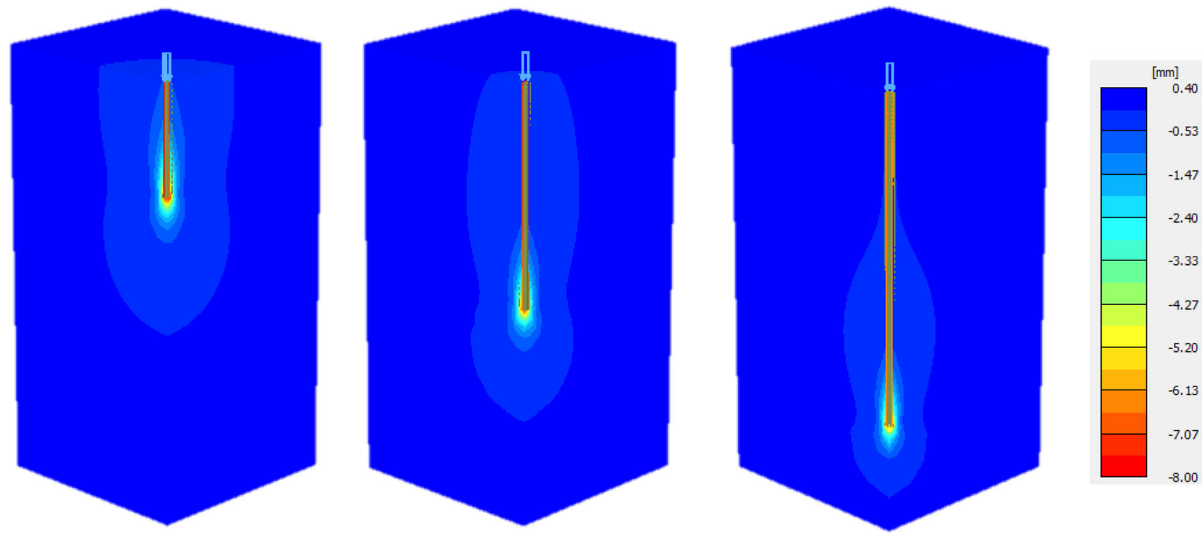
friction angle, geotechnical engineers are familiar with the required model parameters, and these parameters (i.e. c, ϕ, ψ, ν and E) can be easily obtained by fundamental soil mechanics laboratory experiments to be performed on soil samples. Since the soil was the organic soil, undrained behavior of soil was considered.

Linear elastic model was used for all types of pile and it was decided as non-porous material. The material model with many parameters used in the pile analyses were given in Table 3. Applying load was done through surface load for the axial compression. The result of the analysis was presented in terms of load–settlement and the bearing capacity ratio. In this study, the load value at the settlement corresponding to a value of 10% of the pile outer diameter was considered as the failure load (De Nicola and Randolph 1999).

4 Results and Discussion

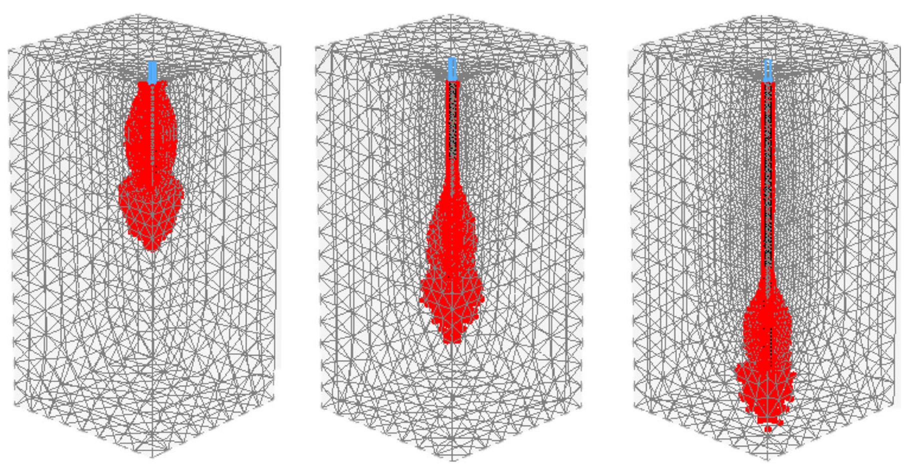
It has been clearly observed from experimental results that when the ratio of L/D increases, the bearing capacity significantly increases. The reason why can be shown as the embedded length of the pile. Because, the shorter pile has less interface contact surface with soil. Therefore, frictional resistance of the pile due to vertical movement under the axial load is less. Hereafter, it is apparent that when the length of the pile embedded in the soil was increased leads to further resistance due to large contact surface with soil. Also, the friction generated between the soil and the pile skin increases when the pile length increases. The similar observations have been reported in the results of the previous experimental studies performed by Rao and Nasr (2010) and Gaaver (2013). In the experiments, the ultimate pile bearing capacity has been defined as the load which leads to the pile head displacement corresponding to 10% of the pile outer diameter for the axial load (De Nicola and Randolph 1999).

Numerical analyses were performed by using three-dimensional model with Plaxis 3D for the axial load. The results obtained from the finite element analysis for the single pipe pile were compared with the results obtained from the experiments. Some results of the behavior of the pipe piles under the axial load obtained from the finite element method have been presented in this section. Figure 5 has showed the load capacity-displacement behavior of the pipe pile installed in the organic soil for the different pile length ratios (L/D) as a comparison between the data of the experiment and the analysis. The figure has indicated that the results give the good estimations in general for all pile length ratios, but the coherence decreases with the increase of the pile length ratio. This can be attributed to the fact that the organic soil has larger grains which may crush under the effect of the stress (Gui and Bolton 1998; Bolton et al. 1999). When the process of loading has finished, the final distribution of the soil particles could be different from its initial case. Consequently, the predictable opposition against the pile penetration would be different. The numerical study provides the reasonable calculations for the measured ultimate load



(a) L/D=10 **(b)** L/D=20 **(c)** L/D=30

Fig. 8 Vertical displacement distributions with d/D = 0.75



(a) L/D=10 **(b)** L/D=20 **(c)** L/D=30

Fig. 9 Stress distributions with d/D = 0.75

of the pipe piles in the organic soil. In other words, it is reasonable to predict the performance of the single piles in the organic soils by using the Mohr–Coulomb model with a specified number of the input parameters such as cohesion (c), dilation angle (ψ), internal friction angle (ϕ), elastic modulus (E) and Poisson's ratio (v). During the analyses, the load at the settlement value corresponding to 10% of the pile outer diameter has been measured as the ultimate load capacity (De Nicola and Randolph 1999).

4.1 The Effect of the Pile Length

Effect of pile length on the pile load capacity was examined. The pipe pile diameter ratio (d/D) was fixed at 0.75. The analyses were calculated for 3 different ratios where the pile length ratio (L/D) was 10, 20 and 30. The data has given in the form of the load–settlement (where, s/D refers to a dimensionless expression which is obtained by dividing the settlement by the outer diameter of the pile). The output

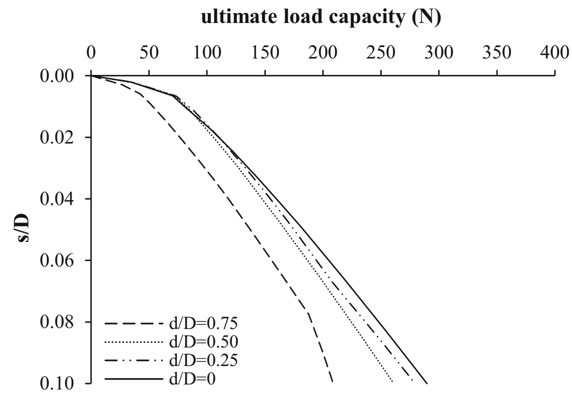


Fig. 10 Ultimate load capacity versus s/D with L/D = 20

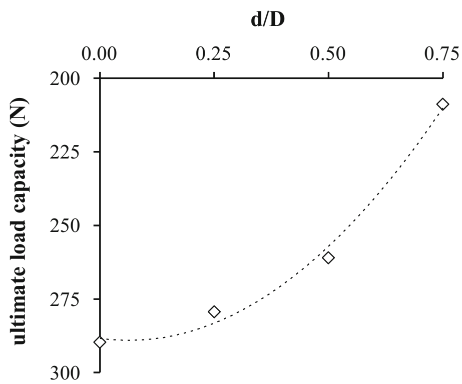


Fig. 11 Ultimate load capacity versus d/D with L/D = 20

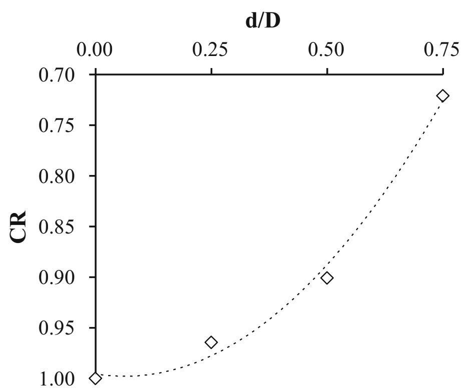


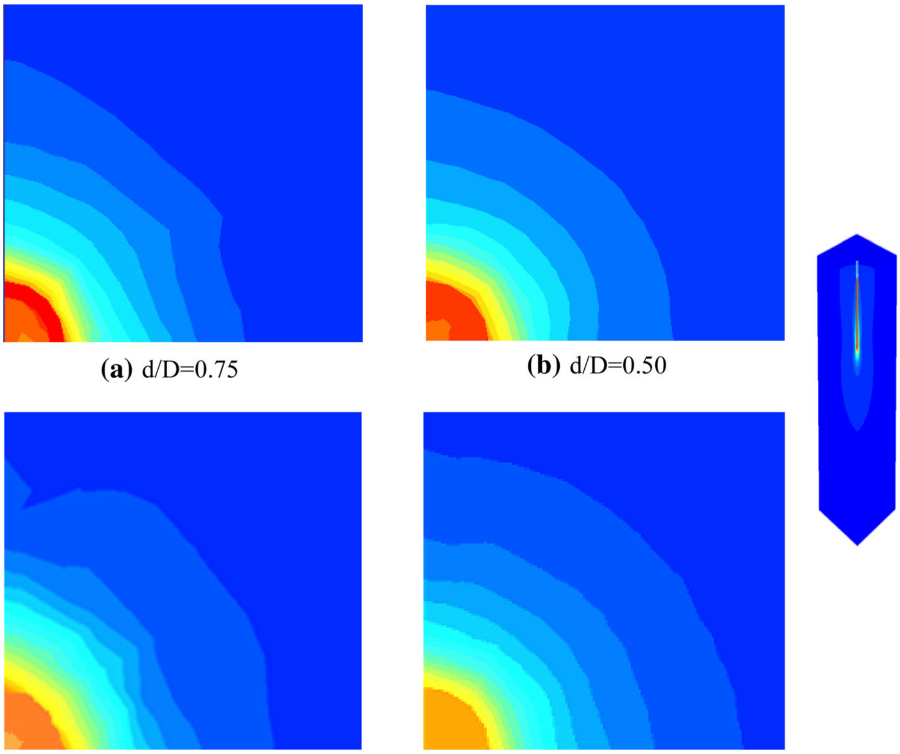
Fig. 12 CR versus d/D with L/D = 20

results obtained from the analysis detected that the pile ultimate load resistance increased when the length of pile was increased. Ultimate load of the pile length ratio of 30 was approximately 1.5 times greater than the load capacity of pile length ratio of 10 (Fig. 6).

Figure 7 shows the load capacity-L/D performance of the pipe pile in the organic soil for different pile length ratios (L/D). The results obtained showed significant effect of the pile length ratio on the ultimate load capacity. The figure has also revealed that the results give the reasonable estimations in general for all pile length ratios, but the coherence decreases with the increase of the pile length ratio. This can be attributed to the fact that organic soil has larger grains that may crush under stress level (Gui and Bolton 1998; Bolton et al. 1999). At the end of load application process in the experiments, the final grain size distribution could be different from its initial condition. Consequently, the expected resistance against pile penetration would be different. The effect of the pile length on settlement distribution was predicted. It has been found that the settlement intensity has occurred through the pile at L/D = 10. Although the displacement distribution seems to be concentrated at the end of the pile, the low length ratio causes the displacements to reach the surface. The displacements are concentrated around the pile head at L/D = 20 and 30 and the intensity of the displacements does not reach the surface because of high pile length (Fig. 8). This situation can be explained that by the fact that most of the load is covered by the tip region of the pile. The influence of the pile length on the stress distribution was also studied. The change of plastic points with the pile length increase was given in Fig. 9. The stresses at L/D = 10 have intensified throughout the pile and this intensity has continued up to the soil surface. While the stresses at L/D = 20 have occurred throughout the pile, but their effect has decreased, the stresses intensities haven't gone on throughout the pile and they haven't reached up to the soil surface at L/D = 30. The stress intensity at the head of the pile has decreased for L/D = 30. When the pile length increase, the stresses at the end of the pile have reduced and the stress distribution has intensified in that region.

4.2 The Effect of the Wall Thickness of Pile

The effect of the pipe pile wall thickness on the ultimate load pile capacity was predicted. The pipe pile diameter ratio was expressed in d/D, and the analyses were performed for 4 different values (0, 0.25, 0.50 and 0.75) and L/D is fixed at 20. The analysis results are presented as the load–settlement.



(a) d/D=0.75 **(b)** d/D=0.50 **(c)** d/D=0.25 **(d)** d/D=0

Fig. 13 Displacement distributions with L/D = 20

The capacity decreases by around 40% with the increase of d/D (i.e. from 0 to 0.75). With this result, it has been understood that the length is thought to be effective more than wall thickness for a pipe pile. The ultimate load pile capacity decreases with the increase of the diameter ratio (Fig. 10). After a certain wall thickness (i.e. d/D = 0.50), this decrease happens more quantity. While the capacity at d/D = 0 is reduced by about 3% compared to the capacity at d/D = 0.25. The capacity at d/D = 0.50 is decreased by approximately 25% compared to that of at d/D = 0.75 (Fig. 11). This situation can be explained that by the fact that the area at the end of the pipe pile is too little when d/D is increased. Therefore, when the pipe pile diameter ratio is increased, it is more quickly reached to the desired displacements value at a constant load value. In other words, for a constant displacement value, the load capacity value is greater when the d/D is decreased. The variation of the pile capacity with the diameter ratio is expressed by the capacity ratio (CR), which is a dimensionless parameter. CR is defined as the ratio of the pipe pile (d/D ≠ 0) to the circular pile (d/D = 0). CR was decreased with the increase of d/D. The capacity ratio is 1 when d/D is 0, and the capacity ratio is about 0.72 when d/D is 0.75 (Fig. 12). In the analyses, the influence of the wall thickness of the pipe pile on displacement distribution was predicted. The displacement intensity decreases significantly with the increase of wall thickness. In the case of d/D = 0.75, the displacement density at the end of the pile is large, whereas at d/D = 0.50, the displacements in and around the pile are somewhat reduced. In the case of d/D = 0.25, the wall thickness increases a little more and there is a decrease again in displacement at the end of the pile. In the case of full pile (d/D = 0), the displacement intensity decreases significantly and the intensity affecting the pile circumference is reduced (Fig. 13).

5 Conclusions

The present study was designed to predict the effect of the axial behavior of different pile lengths and wall thicknesses in the organic soil numerically. This study has shown that:

- The ultimate load pile increases with the increase of L/D.
- The displacement contours exhibited expected behavior and the settlement didn't reach the soil surface by focused at the end of the pile with the increase of pipe pile length.
- The stresses at the end of the pile have reduced and the stress contours has intensified in that region with the increase of the pipe pile length.
- The numerical model is capable of the calculating the pile capacity. Since, numerical study provides reasonable predictions for the measured ultimate load of the piles in organic soil. The ultimate load capacity decreases with the increase of d/D.
- The displacement contours reflected estimates and the displacements in and around the pile decreased with the increase of pipe pile wall thickness.
- The severity of the stress occurred the end of the pile increased with the increase of the wall thickness, the small stresses occurred during the pile and the soil surface in wide area.
- A good compatibility between the predicted and modeled load–displacement performance has been obtained using the proposed reliable and simple finite element analysis procedure.

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