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Research Article

The Design of Piles under Combined Loading: Effect of Pile Length, Pile Spacing and Relative Density

*[1]Münire FINDIK, [2]İ. Devran ÇELİK, [3]Ercan Egemen BAŞAR, [4]S. Nilay KESKİN, [5]Soner UZUNDURKAN

[1]*Süleyman Demirel Üniversite, Fen Bilimleri Enstirüsü, İnşaat Mühendisliği Anabilim Dalı, Isparta, Türkiye,* mnr.dikmen@gmail.com, *ORCID ID:* http://orcid.org/0000-0001-7333-8713
[2]*Süleyman Demirel Üniversite, Mühendislik ve Doğa Bilimleri Fakültesi, İnşaat Mühendisliği Bölümü, Isparta, Türkiye,* devrancelik@sdu.edu.tr, *ORCID ID:* https://orcid.org/0000-0001-9011-4041
[3]*Süleyman Demirel Üniversite, Fen Bilimleri Enstirüsü, basarercan1@gmail.com, ORCID ID:* http://orcid.org/0000-0001-8175-6923
[4]*Süleyman Demirel Üniversite, Mühendislik ve Doğa Bilimleri Fakültesi, İnşaat Mühendisliği Bölümü, Isparta, Türkiye,* nilaykeskin@sdu.edu.tr, *ORCID ID:* https://orcid.org/0000-0002-0367-943X
[5]*Süleyman Demirel Üniversite, Mühendislik ve Doğa Bilimleri Fakültesi, İnşaat Mühendisliği Bölümü, Isparta, Türkiye,* soneruzundurukan@sdu.edu.tr, *ORCID ID:* https://orcid.org/0000-0003-4080-6642

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Abstract

In pile foundation systems, displacements in important structures affected by both axial and lateral loads must be limited within elastic limits. For elastic limits; effects of the important parameters such as; pile diameter, pile spacing, pile length /pile diameter ratio and relative density were examined. For this purpose, loadings were carried out in medium-dense and extreme dense sand conditions with the following parameter considerations: pile length/pile diameter ratios of 10, 15 and 30, pile spacings of 3D and 6D and for relative density of the soil 50% and 85%. By determining the vertical and lateral displacements of the pile foundation system formed under axial and lateral load effects and loading related ground stresses, the relationship between the foundation system and the ground was expressed. Experimental data were analyzed in Plaxis 3D. From the results of the performed model tests and Plaxis 3D optimum design parameters have been determined for soil-structure interaction in lateral loaded pile foundation systems.

Keywords: Pile Foundations, Lateral Loaded Pile, Cohesionless Soils, Plaxis 3D

*[3]Corresponding author

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Kombine Yükleme Altında Kazıkların Tasarımında; Kazık Uzunluğunun, Kazık Aralığının ve Rölatif Sıkılığın Etkisi

Öz

Kazıklı temel sistemlerinde hem eksenel hem de yanal yükler altındaki önemli yapılarda yer değiştirmelerin elastik sınırlar içerisinde sınırlandırılması gerekmektedir. Elastik sınırlar içinde kalarak izin verilen deplasman yükleme koşulları için; kazık çapı, kazık aralığı, kazık uzunluğu/kazık çapı oranı ve relative sıkılığının etkisi dikkate alınmalıdır. Bu amaçla deneyler orta ve çok sıkı kum koşullarında kazık boyu/kazı çapı oranları 10,15 ve 30, kazık aralıkları 3D ve 6D ve zeminin rölatif sıkılığı %50 ve %85 olarak dikkate alınarak gerçekleştirilmiştir. Eksenel ve yanal yük etkileri altındaki yüklemeye bağlı olarak kazıklı temel sisteminin düşey ve yanal yer değiştirmeleri ve zemin gerilmeleri belirlenerek temel sistemi ile zemin arasındaki ilişki ifade edilmiştir. Deneysel veriler Plaxis 3D programında da analiz edilmiştir. Yapılan model testleri ve Plaxis 3D sonuçlarından, yatay yüklü kazıklı temel sistemlerinde zemin-yapı etkileşimi için optimum tasarım parametreleri belirlenmiştir.

Anahtar kelimeler: *Kazıklı Temel, Yanal Yüklü Kazık, Kohezyonsuz Zemin, Plaxis 3D*

1. Introduction

Pile foundations are commonly preferred in the conditions of; insufficient carrying capacity under superstructure loads, occurrence of different or exceeding settlement and shallow foundations not being sufficient. These foundations are serviceable to vertical, lateral or combined loads. Lateral load analysis is required for pile foundations in; (a) earthquake and wind loads for high-rise buildings, (b) horizontal loads caused by wave and ship loads for harbour and shore structures, (c) wind and wave loads for off-shore structures. Horizontal loaded piles are forced to lateral deformation and bending. If the pile carrying capacity is exceeded, plastic hinges are formed on the pile and the pile load carrying length is limited by the depth of plastic hinge occurrence. In the condition that a foundation member is loaded in the horizontal direction until the failure, which is the ultimate loading condition. At the ultimate condition, related to soil-structure interaction; active, passive and state of rest conditions occur around the pile. For piles under vertical loads, calculations with empirical approaches can be done, however, calculation and design stages of lateral loaded piles are much more complicated. In addition, cohesive and cohesionless ground settings, soil stratification, existence of ground water, load types, rigid or flexible pile, bearing condition of the pile edge, single or group pile design are among the parameters that affect the horizontal loaded pile behaviour.

In literature from past to present, there are many analytical and experimental studies conducted on the design and investigation of the behaviour of piles. Behaviour of piles and pile groups under lateral loading condition can be categorised as; limit condition (Broms, 1964); Ground reaction method (Matlock & Reese, 1960); Elastic continuity approach (Poulos, 1971; Banerjee & Davis 1978); Compression – Displacement (p - y) approach is commonly used for the design of piles exposed to lateral loading. This method, which is based on the Winkler theory, describes the interaction between empirically derived non-linear spring and structure, with laterally loaded ground model (Reese et al., 1974); With the progression of the technology, this problem can be investigated more sensitively and faster by using Finite Element Models (FEM) (Maqtadir & Desai, 1986; Brown & Shie, 1991; Trochanis et al., 1991; Kimura et al., 1995; Yang & Jeremic, 2005; Rajagopal & Karthigeyan, 2008).

Expected performance level from the piles is to not cause failure risk by not exceeding the allowed displacement limit during the service life, as a design principle. In order to meet the earthquake effects with minimum damage, true behaviour of the structure under horizontal loads and the parameters affecting the behaviour must be determined. Engineering parameters that are important for the design of piled foundations, such as; pile diameter, distance between the piles, pile dimeter/pile length ratio, material which the pile is used in, ground properties, relative density etc. should be knowledgeable about. This is because the pile behaviour under lateral load and the ultimate lateral load carrying capacity are determined by pile length and diameter, pile frictional angle, pile hardness, ground type and density. The more preferred empirical p-y curves accept more rigidity and underestimate the ultimate resistance at a depth of 4 times the pile diameter. Therefore, these curves need to be updated (Adeel et al., 2022).

In literature, experimental and numerical studies are carried out for single pile, pile group, horizontal ground and slope. Salini et al. (2009), have investigated the effects of pile diameter, pile length, pile material and density, soil density and pile roughness on the pile lateral load carrying capacity with experiments using soft steel pile model. It has been detected that as length, diameter, weight and roughness of the pile and the soil density increased the lateral load carrying capacity of piles increased aswell. The lateral load capacity of the pile increased with increasing diameter for the same length due to pile stiffness. Pile group has more lateral load carrying capacity compared to single piles, this increase has been determined as %100 in the conducted study. Phanikanth et al., (2010a), lateral load behaviour of fixed head single pile in cohesionless soil for different degrees of relative densities under dry and submerged conditions. In the conducted parametric study, displacement values of short rigid piles with fixed cap in loose sand has increased approximately %49 when the soil condition has been changed from dry to submerged. For medium and high density of soil, displacement increases for wet soil condition compared to dry condition are %30 and %33, respectively. For loose, medium and high density of soil, displacement increases for submerged soil condition compared to dry condition are %37, %25 and %29, respectively displacement values for flexible piles. Phanikanth et al. (2010b), have investigated the effects of soils with different degrees of relative densities and changes in water content on the lateral loaded piles. For short piles in loose sand that are not socketed and with free cap, approximately %58 increase has been observed in the displacements in submerged condition compared to dry condition. For medium-dense and high-dense sand, displacement increases are approximately %30 and %27, respectively. Uncuoğlu and Laman (2013) lateral load capacity of rigid short piles in sand soil; pile length, pile diameter, pile section geometry and pile material variables were investigated. For this purpose, piles with different materials, 3 different diameters, and L/D ratios of 3,4,5 are utilised. Increasing the pile diameter has positively affected the stability of the short rigid piles that are under overturning moment, lateral load carrying capacity has increased distinctively especially in the loose sand condition. Increasing the pile length has contributed to the system in both loose and high-dense conditions. As a result, the increase in the L/D ratio due to pile length increase, diameter increase and the change in soil relative density have increased the lateral load carrying capacity. Uray et al. (2019) investigated the horizontal bearing capacity of a horizontally loaded single pile for 25 mm horizontal displacement in the Plaxis 3D program. Parameters such as different corrected SPT, pile diameter and pile length have been selected as variable. It has been observed that the variation of pile length (L) and pile diameter (D) shows linear behaviour after a certain L value in the design graphs, in which the variation of the lateral load (Q) of the individual pile is given.

Piles are generally built in groups to support the structures and pile group behaviour is distinctively different from single piles. Pile-ground-pile interactions cause more deviation in the pile group compared to single pile for the same average load. Bending moment of the pile group is significantly higher than of the single pile due to ground resistance getting weaker (Brown et al., 1987). Chandrasekaran et al. (2010), carried out static lateral load experiments on soft model pile groups buried in clay soil. In the experiments, 3 pile groups featuring piles with L/D ratios of 15,30 and 40, placed in 3-9D settings, are used. Lateral load carrying capacity of the piles from 3x3 grid and 3D spacing group is approximately %40 lower than of the single pile. In the 7D spacing, the maximum bending moments were similar to those of a single pile. Chore et al. (2012), investigated lateral load applied two groups of piles including non-linear behaviour of cohesive soil with finite element model method. Serial and parallel pile combinations are considered. Pile diameter of 30-40-50-60 cm and pile length of 3 m are considered. Pile placement is done using spacings between 2D-5D. It has been observed that the lateral resistance of the pile group increases with the increase in the diameter of the pile. Increase in the lateral load carrying capacity is higher in the serial placement condition of the piles compared to the parallel placement condition of the piles. With the increase in the pile diameter and placement, positive bending moment has decreased and negative bending moment has increased.

Load transfer mechanism of the laterally loaded piles in sloping ground is complex. When the force applied to the laterally loaded piles is in the slope direction, lateral load carrying capacity of the pile decreases significantly. This condition is also dependant on the pile location in regard to slope. Studies conducted on this subject experimentally and numerically regarding the pile behaviour were investigated Sivapriya and Gandhi (2011); in order to investigate the pile behaviour in slope ground, conducted experiments with changing pile locations and slope. It is detected that as the slope increases, the load carrying capacity decreases and as the pile gets further away from the slope, capacity increases. As the soil resistance increase and pile gets further away from the slope and the applied load increased, bending moment has also increased. Sivapriya and Gandhi (2013), in clay soil, placed with different distance than the slope, single pile behaviour under lateral load is investigated using 1 g model tests and

Plaxis 3D analysis. Pile load carrying capacity has seen to decrease approximately %10-50, affiliated to the soil strength (cohesion) and the slope of the ground.

Finite element model has predicted the bending moment higher compared to the experimental tests. Deendayal et al (2017) repeated experiments for L/D ratios 20, 25 and 30 in a single pile embedded in soft clay at a slope of 1V: 1H, 1V: 1.5H, 1V: 2H, 1V: 3H. The pile bearing capacity decreases when the ground surface changes from horizontal to 1V: 5H slope. Test results were compared with finite element model PLAXIS 3D results. It has been observed that increasing the slope decreases the lateral load capacity both in the test and in the finite element analysis. As the passive resistance in front of the pile decreases on the sloped surfaces, the pile carrying capacity is reduced. The same results were obtained for the L/D ratio 20, 25 and 30. In the experiments conducted for aluminum piles, the bending moment increased as the slope increased. As the L/D ratio increased, the distance at which the maximum bending moment occurred decreased. Rathod et al. (2018), Sawant et al. (2012a-b) investigated the behaviour of a laterally loaded pile on sloping ground using the three-dimensional finite element method. As the slope and edge distance of the soil increased at any depth, the displacement and bending moment decreased. Effect of slope ground on the pile has seen to decrease for S=5D offset distance. Sawant and Shukla (2012b) as expected, the bearing capacity of the foundations decreases significantly as the distance between the foundations and the slope edge decreases (Moem et al., 2022).

For design engineers, pile behaviour under axial load combined with lateral load is in a complex condition. In recent years, experimental and numerical studies are carried out to investigate the combined load effect. Lee et al. (2011), showed that the presence of axial load on a driven pile damages its lateral capacity, as the lateral displacement of the model pile head increases as the axial load increases in sandy soil. Bending moments in the pile cap under axial load compared to condition without axial load, have increased %10, %36 and %39 for loose, medium-dense and high-dense sands, respectively. Zadeh and Kalantari (2011) indicate that the combined loads in the lateral behaviour of the piles significantly increase the lateral capacity in sand and greatly reduce the capacity in clayey soils. In sandy soils, based on the level of the vertical loads, lateral load carrying capacity of the piles increases up to %40 percent along with the piles. As the lateral response L/B ratio of piles under combined vertical and lateral loading increases, the combined loading on the lateral capacity decreases. Zhang et al. (2020), have investigated pile behaviour in horizontal ground and slope ground with test and finite element method. 3D simulation of single pile in different shapes was made using ABAQUS program. Horizontal and vertical load combinations were applied. Tests and analyses carried out in order to examine the load carrying capacity of the ground has shown that the asymmetric ground load around the pile causes lateral displacement to the pile, increase in the slope angle decreases single pile carrying capacity, vertical load causes more horizontal displacement as the slope angle increases.

With the literature considered, pile foundation systems under combined loading should be investigated furthermore. In this experimental study, parameters like lateral displacement under axial and lateral load, ground stresses caused by loading were investigated and relation between the ground and the pile foundation is tried to be presented. In the pile foundation design, knowledge about important parameters such as pile diameter, spacing between the piles, pile length/pile diameter ratio, soil relative density is necessary. Therefore, as a result of the performed model tests, a suitable approach for ground-structure interaction in lateral loaded pile foundation systems is chosen and optimum design parameters are tried to be identified.

2. Experimental studies

In this study, design parameters such as settlement under axial and lateral load, deformation, displacement and maximum moment were examined with pile foundation system and relation between the foundation system, the structure and the ground was investigated. The occurrence of displacements is expected, especially in the structures serving under dynamic loads such as wave load and earthquake load, however, it is also expected for these displacements to remain in elastic boundaries. With this condition considered, investigation of elastic and post-elastic behaviour of structures and obtainment of optimum design parameters are aimed. For model tests to be carried out, different combinations are made by changing engineering parameters such as pile diameters, pile spacing, pile length/pile diameter ratio, relative density of the soil which pile foundation is placed. Namings of the combinations used in the study can be seen in Table 1 In the definition of the combinations, pile length, soil relative density and pile placement spacing are used. For 8 mm pile diameter, Length/Diameter (L/D) ratio has been selected 10,15 and 30 while pile lengths are selected 80 mm, 120 mm and 240 mm. Spacing/Diameter (S/D) ratio is selected 3 and 6 and raft slab size has been selected 80*128 mm and 128*224 mm, accordingly. In sandy soil, selected two conditions of relative relative density are 50 (medium-dense) and 85 (high-dense). Effect of the soil relative density has been investigated in the tests. For the nomenclature in the Table, L/D pile length to diameter ratios of 10,15 and 30, and medium-dense soil relative density (M) and very high-dense soil relative density (V) are specified. Pile spacing conditions are specified 3/6 based on their properties.

In the tests, sand soil with the grain diameter of 0,5-1,0 mm was used. In the model tests, in order to determine the properties of the used soil; sieve analysis, pyknometer (ASTM D854-14), maximum and minimum void ratios (ASTM D4253-16), direct shear box (Astm D3080) tests for %50 and %85 relative densities were performed. Granulometry curve of the soil is presented in Figure 1.

Sieve analysis results of poorly graded sand (SP) are presented in Table 2. (ASTM 6913). Relative density properties are presented in Table 3 and Table 4. For %50 and %85 relative density values, necessary engineerin paramaters are determined for the placement of the model in the test tank.

Table 1. Namings for tests and graphs.

Test box 500*750*500 mm								
Pile	L/D			Dr		S/D		Test Name
Diameter	10	15	30	50	85	3	6	
Diameter 8 mm	*			*		*		E10M3D8
	*				*	*		E10V3D8
	*			*			*	E10M6D8
	*				*		*	E10V6D8
		*		*		*		E15M3D8
		*			*	*		E15V3D8
		*		*			*	E15M6D8
		*			*		*	E15V6D8
			*	*		*		E30M3D8
			*		*	*		E30V3D8
			*	*			*	E30M6D8
			*		*		*	E30V6D8

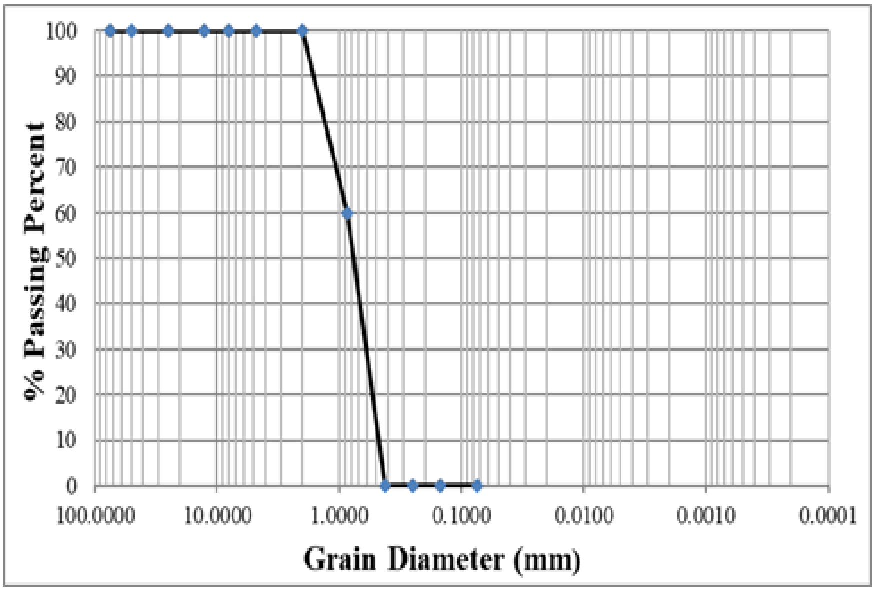


Figure 1. Grain diameter distribution of sand soil.

Table 2. Physical properties of the sand.

Granulometer parameters	Unit	Value
Coarse Sand Percentage	%	0
Medium Sand Percentage	%	100
Fine Sand Percentage	%	0
D10	mm	0.48
D30	mm	0.65
D60	mm	0.85
D50	-	0.75
Uniformity Coefficient Cu	-	1.77
Gradation Coefficient Cc	-	1.03
Soil Class	-	SP

Table 4. Material properties of sand soil for high-dense and medium-dense conditions.

	%85	%50	Stell
γ_{dry}	1.70E-04	1.58E-04	77.8E-04
E(kN/cm²)	3.9	2.5	21000
v	0.3	0.3	0.3
G(kN/cm²)	1.385	0.81	
Φ(°)	42	39	-
c(kN/cm²)	0	0	-

In model tests, test tank and raft sizes should be determined to keep the impact of boundary effects on test results minimal. In literature it is mentioned that the boundary effects do not change the test results and many studies are conducted about what are the raft and test tank sizes should be for the occurrence of semi-infinite setting. As a result of these studies, it has been determined that boundary conditions will not affect the experiment and thus provide semi-infinite environmental conditions if there is no spacing when between the edge points of the foundation and the tank edges is 2B and there is 2L length of soil after L pile length is placed (Gandhi & Selvam, 1997; Yetimoğlu, 1998; Terzi et al., 2009; Sadrekerimi, 2010; Sawwaf, 2010; Yılmaz, 2010; Bağrıaçık & Laman, 2011). In conclusion, sizes of the sand tank used in the tests are 500*750*500 mm.

In all the tests, in order to standardise the relative density of the soil layer, pluviation method is used. Therefore, sand grain placement is performed from same height with same density. Sand from the pluviation gains speed in the pipe and is dropped from a fixed height into the tank. This natural flow ensures the occurrence of soil layer with %50 relative density. Tank depth is 500 mm, for every 50 mm a mark has been placed, according to this: using oven cases with 30 mm diameter and 20 mm depth, relative density is checked by taking samples from top and bottom parts of the tank, twice for each filling.

Soil is placed in layers of 50 mm height into the tank. For very high-dense soil placement, sandy soil is placed into the tank in 50 mm layers of which are compacted using electrical vibration device until the desired layer thickness obtained. During the compaction, in order to obtain uniform relative density and to prevent the sand grains from breaking, a steel plate with the dimensions of 120*120*2 was affixed.

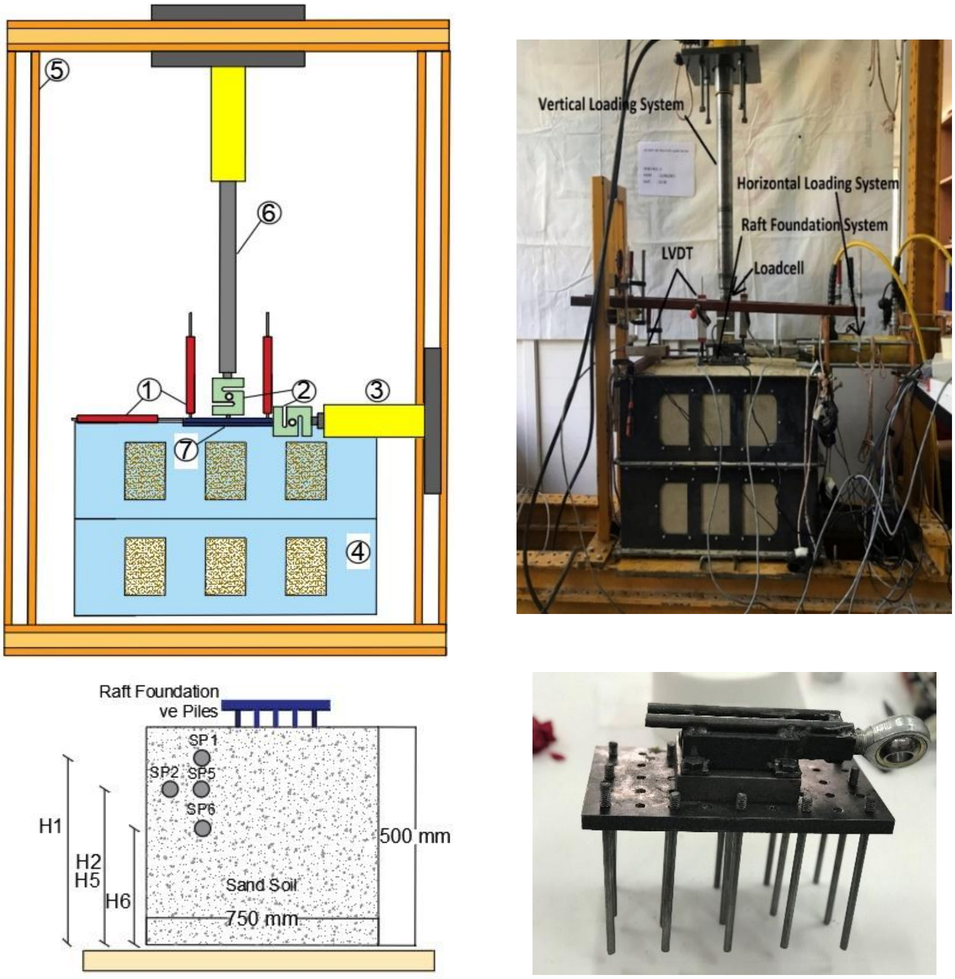
In the test setup of which the schematic view is presented in Figure 2.a; loading beam, loading piston, loading arm, load cell, displacement meter, piled raft foundation, pressure gauges are present. Loading piston capacity is 20 tonne and has a loading speed of 0.5 mm/min. Load cell inside the loading arm is for 5 tonne and has a sensitivity of 0.01 kN. Displacement meters are capable of measuring to 50 mm with 0.01 mm sensitivity. As can be seen in Figrue 2b, piled raft foundation is placed in the sand tank with a speed of 0.5 mm/min and later load–settlement curves can be obtained with the help of these systems. With the pressure gauges, which are presented in Figure 2c, pressure values occurring at the bottom part of the raft foundation can be measured.

In order to get readings of the vertical and horizontal loads affecting the piled raft foundations, two electronical S type load cells with 5 tonne capacity are used during the tests. In the foundation groups with raft slab size of 80*128 mm, 200 kg (0,2 kN) vertical load is applied before applying the horizontal load. For the foundation groups with raft slab size of 128*224 mm, 500 kg (0,5 kN) vertical load is applied before applying the horizontal load. For the vertical loading, 0,6 times the ultimate vertical load is determined and applied (Zadeh & Kalantiri, 2011). Displacement of the pile group has been determined with the displacement meters placed on the raft slab in vertical and horizontal directions. During the tests, all the measurements are transferred to computer using datalogger. For displacements, mm unit is used, kN unit is used for loads and kPa unit is used for pressures.

3. Numerical Study

In the study, data from the tests are verified with numerical analyses using Plaxis 3D CE V20 programs (Plaxis 3D, 2013). The ground is modelled 3D as 50*75 cm in width and 50 cm in depth, with the consideration of case dimensions. In order to reflect the ground behaviour more realistic, parameters defined in the models were selected carefully, which are presented in Table 4. Angle of dilatancy has been defined using $\psi=\theta-30°$ formula in Plaxis 3D Foundation program.

Due to the non-linear stress deformation behaviour of the ground in Plaxis 3D v-2013 Reference Manual, this behaviour



1. Dısplacement Meter
2-3. Loadcell
4. Sand Tank
5. Load Frame
6. Loading Arm
7. Piled Raft Foundations

Figure 2. Experiment equipment and schematic illustration.

has been defined "Mohr-Coulomb (MC)". Pile and raft foundation have been defined with Linear Elastic model and selected material properties are presented in Table 5.

Numerical analyses are carried out in four stages. These stages are as following; definition of initial stress condition, forming of the piled raft foundation, applying the vertical and horizontal load.

Vertical load has been applied distributed load on the foundation in one stage. Horizontal load has been applied incrementally with 0,2 kN each

Table 5. Steel material properties.

	Pile (8 mm)	Foundation (3D)	Foundation (6D)
γk (N/cm3)	0.077	0.077	0.077
E(N/cm²)	2.1x107	2.1x107	2.1x107
D(cm)	0.8	2	2
A(cm²)	0.5027	102.4	286.72
I2-I3(cm4)	0.0201		

interval until the failure of the ground as point load. After the acquisition of the initial stresses, the displacement values occurred in the initial phase have been resetted to zero for the next stages of the calculations.

Model tests subjected to static loading are carried out in order to investigate the effect of the boundary conditions on the test results using two sand tanks with the dimensions of 50*75*50 cm and 75*150*100 cm. Numerical models are created in Plaxis 3D program for different foundation dimensions using stiffness parameters presented in Table 3 and Table 4. Numerical analyses are performed for 50*75*50 cm (Figure 3b), 75*150*100 cm (Figure 3c) and field conditions (Figure 3d). As mentioned in the literatüre (Ateş et al, 2021) results obtained from the reference tests are compared to Plaxis 3D finite element model program results. In all three conditions, lateral displacement and carrying capacity results were similar. Therefore, the tanks used in the study were acceptable for the test results.

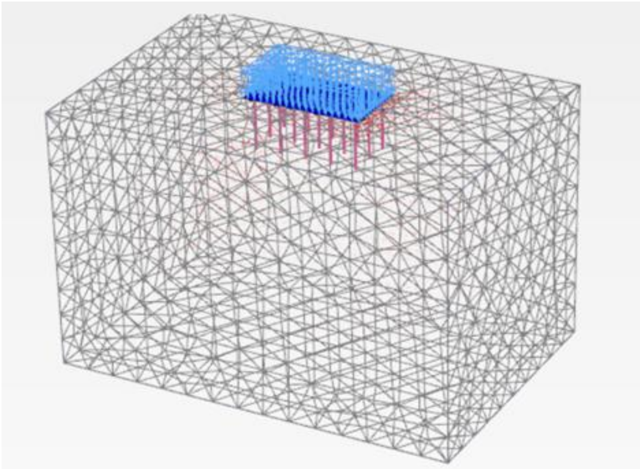
Load-displacement graphs obtained from the analyses for the evaluation of the boundary condition, maximum pile length used in the study are given comparatively for two different (relative density) conditions. From the graphs, results for the sample with L/D ratio of 30 for sand tank boundary conditions can be seen matching. Therefore, the sand tank with 50x75x50cm dimensions used in the study is sufficient.

4. Research findings

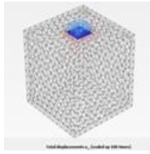
In this study, piled foundation system under vertical load has been analysed under static incremental horizontal load. Horizontal load initial condition has been created for the changing vertical load condition regarding the piled foundation system geometry. In this section, applied vertical load values for two different slab size and settlement conditions are presented comparatively.

Vertical Force- Vertical Displacement

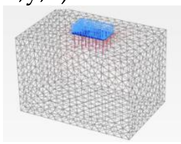
In foundation groups with raft slab size of 80*128 mm vertical load is applied before applying the horizontal load. Displacement of the pile group is measured with two different measurings using displacement meters placed on the raft slab in the vertical direction. For medium-dense sand comparison with L/D: 10,15 and 30, E10M3D8, E15M3D8, E30M3D8 tests are compared.



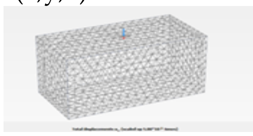
a. Piled Raft Foundation 3D Plaxis Model



b.(x,y,z)50*75*50 cm.

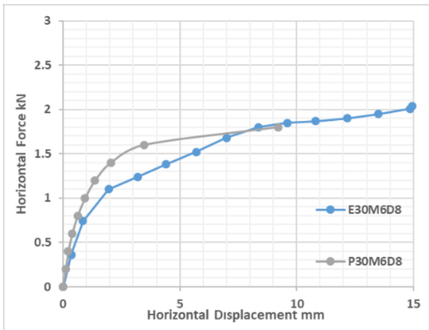


c. (x,y,z) 150*75*100 cm.

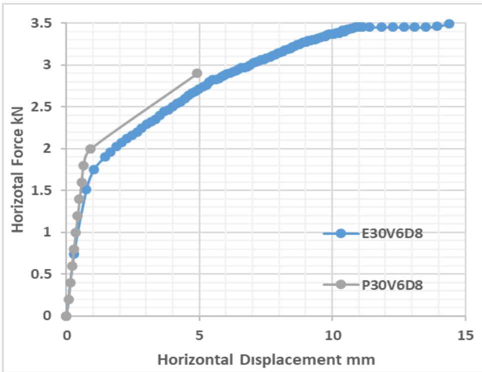


d. (x,y,z)10*20*10 m.

Figure 3. Plaxis 3D numerical models overall view and tank dimensions.



a) Medium dense soil



b) Very dense soil

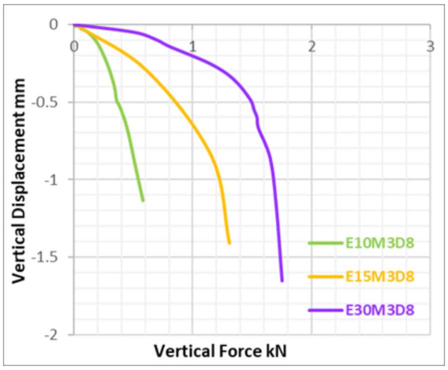
Figure 4. Verification of the finite element analysis and test results for L/D ratio of 30.

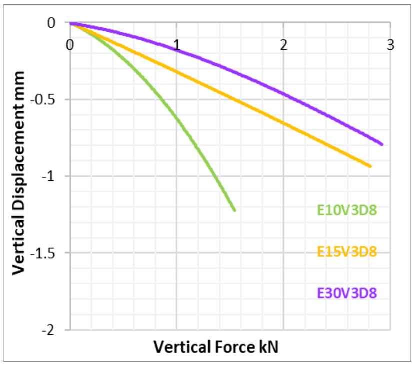
For very high-dense sand comparison with L/D: 10,15 and 30, E10V3D8, E15V3D8, E30V3D8 tests are compared

For the foundation groups with raft slab size of 128*224 mm, 500 kg (0,5 kN) vertical load is applied before applying the horizontal load. Displacement of the pile group is measured with two different measurings using displacement meters placed on the raft slab in the vertical direction.

For medium-dense sand comparison with L/D: 10,15 and 30, E10M6D8, E15M6D8,E30M6D8 tests are compared. For very high-dense sand comparison with L/D: 10,15 and 30, E10V6D8, E15V6D8, E30V6D8 tests are compared.

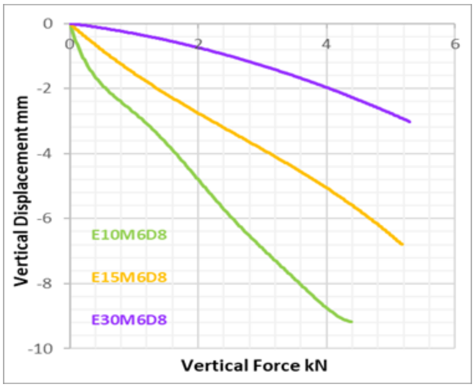
Based on the superstructure load, settlement occurs in the raft and pile systems. When this settlement is calculated: raft width, ground elasticity

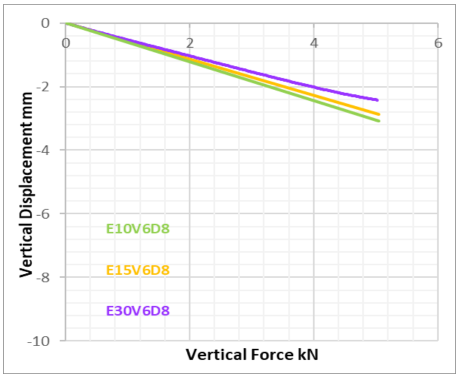




a) Medium dense soil   b)Very dense soil

Figure 5. L/D ratio comparison under vertical force for medium-dense and very high-dense soil.





a) Medium dense soil   b)Very dense soil

Figure 6. L/D ratio comparison under vertical force for medium-dense and very high-dense soil.

module, ground poisson ratio should be considered. From the test results, it was seen that as the raft size increased, the settlement decreased. In addition, as the soil relative density increase, the ground elasticity module will increase aswell and as the elasticity module increases, settlement of the piled raft foundation decreases.

Short piled raft foundation was exposed to more settlement compared to long piled raft foundation. Because the settlement has decreased due to the increase in the lateral friction. For medium-dense soils and 6D placement, maximum capacity for short piles has been achieved at a greater displacement while for the long piles maximum capacity was reached at a smaller displacement. For medium-dense soil, 3D pile placement was seen to be ideal while for the high-dense soil, 6D was a more optimum placement. For same values of settlement, long piles have more carrying capacity compared to short piles.

Horizontal Force – Horizontal Displacement

All samples brought to the final vertical limit in the study were analysed under static incremental lateral load. The results obtained in this context are presented in the section.

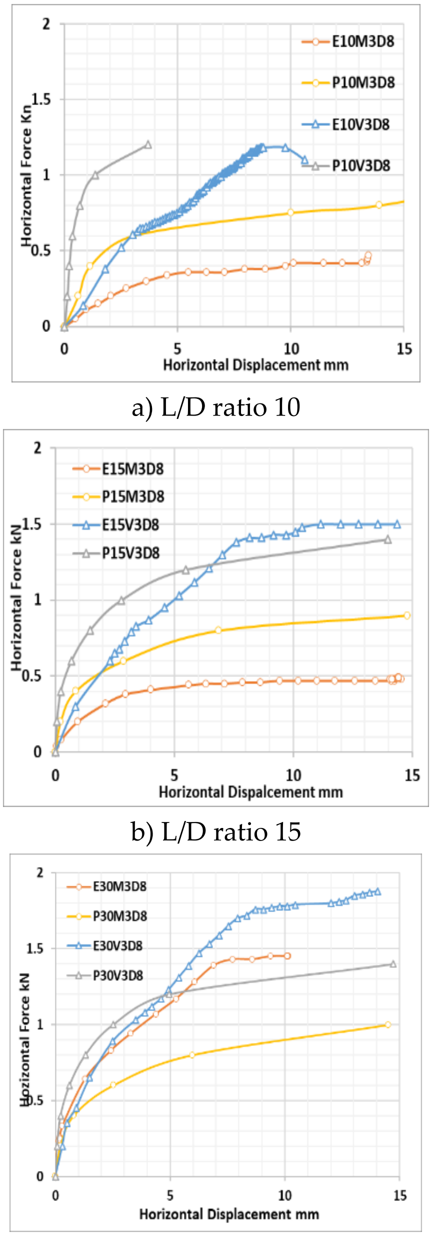
- Effect of Soil Relative Density Ratio

In order to investigate the effect of soil placement on the carrying capacity of pile groups, tests are carried out for two different relative density values. In the model with raft slab of 80*128 mm; piles with 8 mm diameter, L/D ratios of 10,15 and 30, and relative densities of 50 and 85 are utilised. Test names for these models are determined; E10M3D8, E10V3D8, E15M3D8, E15V3D8, E30M3D8 and E30V3D8. Tests are repeated for these correlations. In 3D placement condition, for all pile lengths, horizontal load-vertical displacement graphs are presented comparatively for medium and high-dense soil conditions with equal axis scaling. In graphs, numerical analysis results created for all model tests with the use of Plaxis 3D finite element model program are also presented.

Increase in the soil relative density affecting the horizontal carrying capacity positively can be seen in all the graphs. For the condition of pile length/diameter ratio being 10, very high-dense soil compared to medium-dense, 2,72 times higher capacity was obtained. For 15 length/diameter ratio, this increase is 3 times and for 30, 1,8 times. Lateral displacement response of L/D 30 condition compared to L/D 10 and 15 conditions was a more rigid slope in the graphs. In performed model tests, lateral soil resistance is exceeded at 8 mm position for L/D ratios of 10 and 15 in medium-dense soil condition. However, a resistance occurrence was observed at 8 mm in long pile but then gained rigidity and went into collapse mode at 15 mm position. As the vertical stresses throughout the pile increase, lateral stresses increase aswell. The increase of the lateral stresses results with higher passive forces being active (Chatterjee, 2022). This condition reflects that with the increase in the passive soil pressure support, pile shows resistance again.

This obtained result is in agreement with Broms (1964b) study. According to Broms (1964b); horizontally loaded pile is forced to deform and bend in horizontal direction. In cohesionless soils, reaching the ultimate load and plastic hinge occurrence on the pile conditions are expressed related to passive stresses. If the pile carrying capacity is exceeded, plastic hinge occurs on the pile and load carrying length of the pile cannot increase any further and is limited at the depth of the plastic hinge. A ground element loaded in the horizontal direction will be loaded until the failure occurs. When the limit condition, the failure condition, is reached, passive stresses are formed in the ground.

From the results, first displacement resistances of the high-dense placement were seen notably higher compared to the medium-dense placement, for all the pile lengths. From the comparison of the graphs, lateral displacement resistance for L/D ratio 10 and 15 occurred at 3 mm and foundation system regained resistance at 5 mm.



a) L/D ratio 10

b) L/D ratio 15

c) L/D ratio 30

Figure 7. Graphs for L/D ratio of 10,15,30.

For L/D ratio of 30, obtained results show that lateral displacement resistance compared to the other lengths has proceeded without a notable loss until 8 mm. For the following displacements, it was seen that rigidity did not lose value and this condition went on until 15 mm with positive contributions to the capacity.

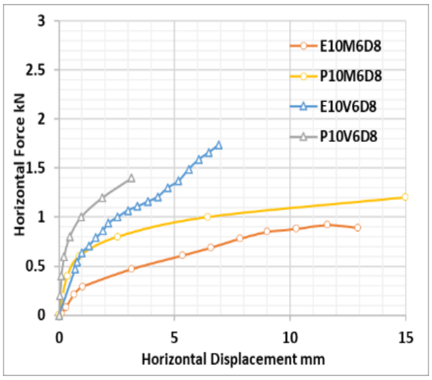
Numerical analysis results of 8 mm pile for medium and very dense soil conditions for different pile lengths have shown that for the L/D ratio of 10 condition, while high dense soil condition ultimate value is matching, settlement stiffness is seperated with the test results.

For medium dense condition, ultimate value has been found approximately 1,5 times of the test results. Displacement stifness was also higher for the numerical model in this condition. As the pile length increased, the numerical analysis and test results became more consistent with each other. The most ideal of the results has been obtained from L/D ratio of 30, high dense soil condition. The L/D ratio of 30, high dense soil condition numerical analysis result was matching with the test result until the horizontal displacement value of 5 mm. Following that point, separations was observed in pile behaviour due to space between the grains in the pile-soil interaction zone. The analyses has shown that the block/bulk behaviour occurring in the pile-soil interaction zone with the increase in the pile length and the soil relative density is positively affecting the alignment between the numerical analysis and test results. Therefore, it can be concluded that the effects of void/space between the grains and deformation occurrence on the piles should be taken into consideration for numerical analysis.

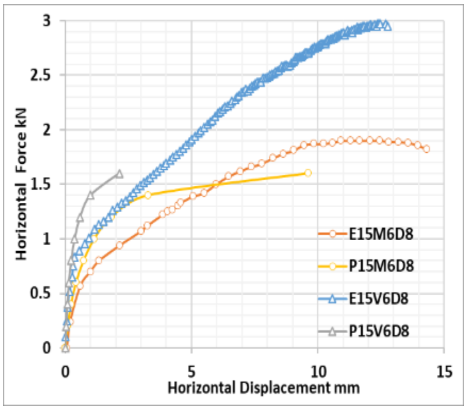
In the model with raft slab of 128*224 mm; piles with 8 mm diameter, L/D ratios of 10,15 and 30, and relative densities of 50 and 85 are utilised. Test names for these models are determined; E10M6D8, E10V6D8, E15M6D8, E15V6D8, E30M6D8 and E30V6D8.

In 6D placement compared to 3D placement, obtained horizontal force values are average of 2 times high. In the condition of pile length/diameter ratio being 10, very high-dense soil compared to medium-dense soil has resulted with 2,2 times higher horizontal carrying capacity. For L/D ratio of 15 condition, this increase is 1,5 times and for L/D ratio of 30, it is 1,8 times as much.

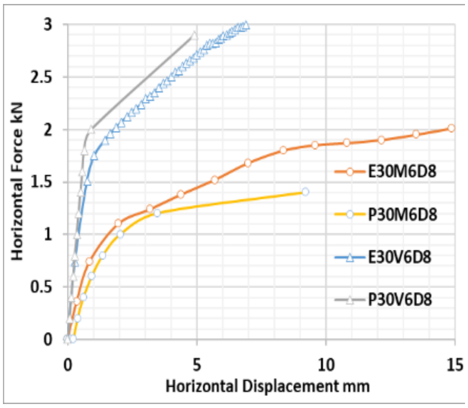
Model test results of 6D pile setting show that obtained capacity curve behaviour in medium-dense and high-dense conditions for L/D ratio of 10 is similar to 3D setting. In design of the laterally loaded piles, ultimate lateral resistance of the soil affecting the pile is the most important aspect (Zhang et al., 2005). However, for L/D ratio of 15 and 30 conditions, the increase in the soil density around the pile surroundings has affected the behaviour distinctively. For L/D ratio of 15 condition, first displacement rigidity loss values are matching. For L/D ratio of 30 condition, displacement stiffness is exceeded for the same lateral displacement again, however, obtained capacity increase for this condition is twice as much.



a) L/D ratio 10



b) L/D ratio 15



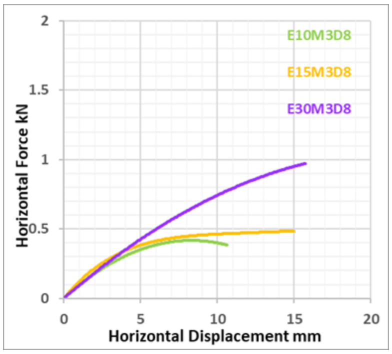
c) L/D ratio 30

Figure 8. Graphs for L/D ratio of 10,15,30.

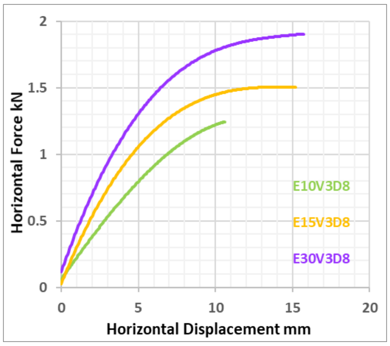
Comparison of the numerical analysis results of 8 mm pile diameter for 6D placement and the model test results have shown that the consistency between models has increased. This condition can be explained with the activity of the soil between the piles in pile-soil interaction zone under horizontal load. In 3D placement, while the side surfaces of the most outer piles and pile toe provide resistance for lateral load, in 6D placement, soil layer between the piles is added to this resistance as friction. Therefore, the zone under the slab is contributive to the block/bulk behaviour. Thus, the gap between the numerical analysis and the model test gets narrowed.

- Effect of L/D Ratio

In the model with raft slab of 80*128 mm; piles with 8 mm diameter, L/D ratios of 10,15 and 30, E10M3D8, E15M3D8, E30M3D8 tests are compared. For very high-dense sand comparison with L/D ratios of 10,15 and 30, E10V3D8, E15V3D8, E30V3D8 tests are compared.



a) Medium dense soil

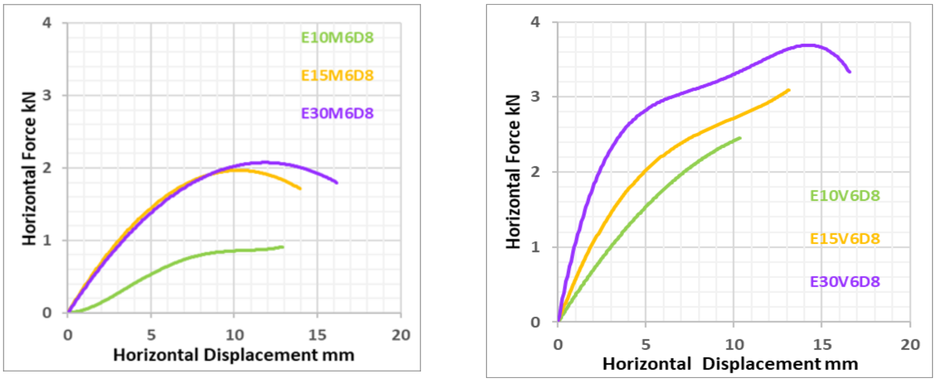


b)Very dense soil

Figure 9. L/D ratio comparison in medium-dense and high-dense soils.

In figure 9, effect of change in the pile length on the lateral carrying capacity in medium and high-dense setting can be seen. For medium-dense condition, behaviour for lateral displacement is similar for all pile lengths. Behaviours for L/D ratios of 10 and 15 are very similar. For L/D ratio of 30, the passive stresses caused by soil loading after 10 mm lateral displacement, has reflected to results and increased the ultimate carrying capacity twice as much. Graphs of very high-dense setting shows that the increase in the pile length has increased lateral carrying capacity notably. Most distinctive difference in the graphs is that collapse occurred soon after the ultimate load is reached in L/D ratio of 10 condition, however, ultimate loads are in a stoop rather than a focused point for other pile length conditions.

In the model with raft slab of 128*224 mm; piles with 8 mm diameter, L/D ratios of 10,15 and 30, E10M6D8, E15M6D8, E30M6D8 tests are compared. For very high-dense sand comparison with L/D ratios of 10,15 and 30, E10V6D8, E15V6D8, E30V6D8 tests are compared.



a) Medium dense soil b)Very dense soil

Figure 10. L/D ratio comparison in medium-dense and high-dense soils.

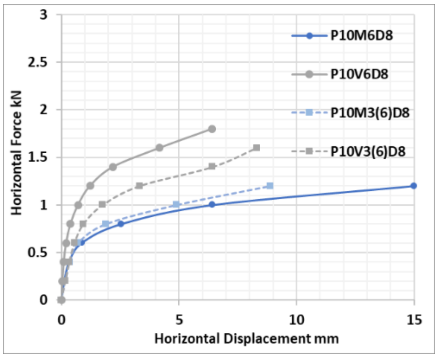
In 6D setting, the increase in the pile length, due to soil condition being medium-dense, couldn't provide much contribution to L/D ratio of 30 condition unlike to L/D ratios of 10 and 15 conditions. In medium-dense soil setting, no further contributions to the foundation system were detected from pile length L/D ratio being higher than 15. However, increasing pile length contributes to the lateral carrying capacity at the same rate in the very high-dense soil setting.

From investigating the L/D ratio and the lateral load carrying capacity relations, it was detected that L/D ratio increasing by the increase of pile length, which increases the pile friction area, has a positive impactful effect on the lateral load carrying capacity of the pile (Ersoy & Yıldırım, 2014). Pile length increase has provided more contribution to lateral load carrying capacity in high-dense sand setting compared to loose sand setting (Uncuoğlu & Laman, 2013).

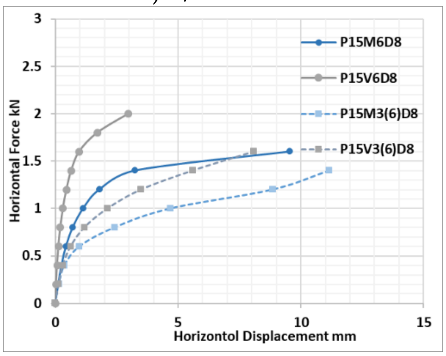
In the conducted experimental studies in the literature, it was observed that lateral support of the piles and lateral carrying capacity of the foundation system is higher in dense soil compared to loose soil. Long piles due to having more surface area contacting the surrounding soil, can dissipate mroe energy (Nguyen et al., 2017). It was observed that due to increase in the L/D ratio also increasing the carrying support provided by the pile lateral friction, the lateral load carrying capacity of the foundation system has increased %70-200, which is in agreement with the studies in the literature.

In the study, 3D placement for 8 mm pile diameter and 12.8*22.4 cm slab dimensions is modelled using Plaxis 3D and the results from the model is presented comparatively with 6D placement results for the same size of slab in Figure 11.

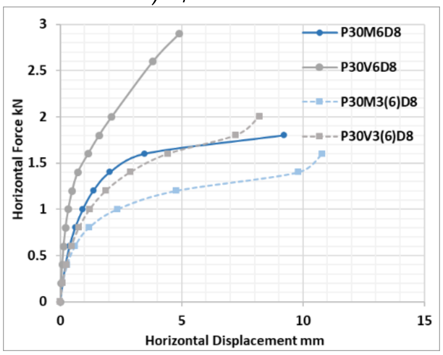
For the determination of the lateral displacement stiffness of the piled foundation systems working under horizontal loads, test and numerical.



a) L/D 10 ratio



b) L/D 15 ratio



c) L/D30 ratio

Figure 11. 3D and 6D Plaxis 3D analysis results.

analysis results have shown that pile-soil interaction zone is substantial. Biggest slab used in this study with 6D placement has been analysed also for the 3D placement in numerical analysis. For the two different placements, by means of lateral resistance, the change in the interaction performance of the soil between the piles can be seen. 6D placement compared to 3D placement, for L/D ratio of 30 condition, has resulted with 70% higher capacity for high dense condition and 28% for medium dense condition. For L/D ratio of 15, this increase between the placements were 10% for high dense and 14% for medium dense. For L/D ratio of 10, 12% for high dense condition and 13% for (8 mm displacement) medium dense condition. Analyses show that the pile-soil interaction between the piles positively and significantly affects the lateral displacement stiffness. This effect, the gain, can be seen more clearly as the pile length increases.

- Ground Pressure Comparison

For the structure and soil interaction, in order to make an economical design in such a way that the deformation remains elastic and within acceptable limits, it is important to determine the stresses and displacements caused by the deformation in the soil environment caused by the loads acting on the foundation soils.

Due to soils having a complex structure, in order to obtain realistic stress-deformation analysis, model tests were prepared and soil pressures caused by the loadings and other changing parameters were measured using the soil pressure gauges placed at certain elevations.

Force-soil pressure graphs are presented using the data obtained from the pressure gauges placed at different elevations for each test. For L/D ratio of

10; E10M3D8 and E10V3D8 tests in medium and high-dense conditions for 80*128 mm foundation, E10M6D8 and E10V6D8 tests in medium and high-dense conditions for 128*224 mm foundation are utilised in comparison.

In the tests for this category, soil pressure gauges SP1, SP5 and SP6 has been placed 25 cm into the tank at -10 cm, -15 cm and -20 cm elevations. In order to observe the changes in the lateral soil pressure, SP2 was placed 15 cm into the tank at -15 cm elevation.

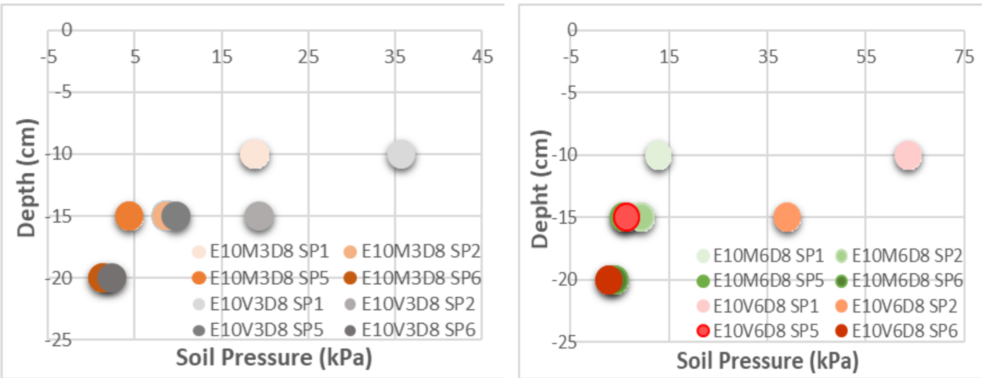


Figure 12. Soil pressures for L/D ratio of 10 in medium-dense and very high-dense soil.

For L/D ratio of 15; E15M3D8 and E15V3D8 tests in medium and high-dense conditions for 80*128 mm foundation, E15M6D8 and E15V6D8 tests in medium and high-dense conditions for 128*224 mm foundation are utilised in comparison.

For the tests in this category, soil pressure gauges SP1, SP5 and SP6 has been placed 25 cm into the tank at -15 cm, -20 cm and -25 cm elevations. In order to observe the changes in the lateral soil pressure, SP2 was placed 15 cm into the tank at -20 cm elevation.

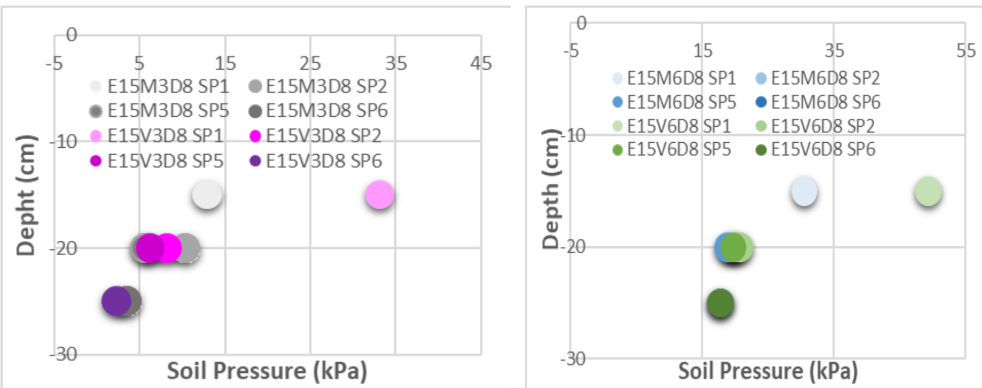


Figure 13. Soil pressures for L/D ratio of 15 in medium-dense and very high-dense soil.

For L/D ratio of 30; E30M3D8 and E30V3D8 tests in medium and high-dense conditions for 80*128 mm foundation, E30M6D8 and E30V6D8 tests in medium and high-dense conditions for 128*224 mm foundation are utilised in comparison.

For the tests in this category, soil pressure gauges SP1, SP5 and SP6 has been placed 25 cm into the tank at -25 cm, -30 cm and -35 cm elevations. In order to observe the changes in the lateral soil pressure, SP2 was placed 15 cm into the tank at -30 cm elevation.

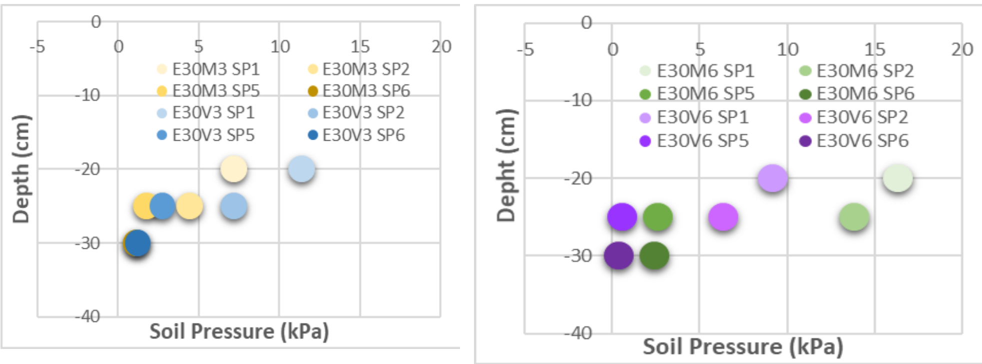


Figure 14. Soil pressures for L/D ratio of 30 in medium-dense and very high-dense soil.

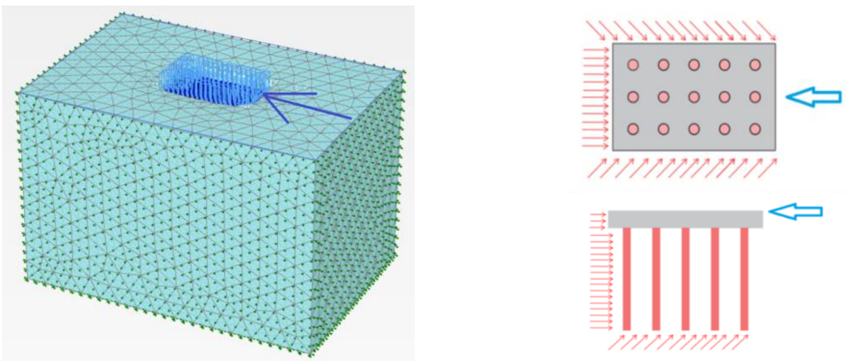
Laterally loaded piles usually are designed according to bending moment and displacement criterions, in many conditions. Because the ultimate carrying capacity of the soil surrounding the pile can only be reached at very high displacement values. The soil response is nonlinear, although the ultimate carrying capacity of the soil surrounding the pile is in many cases not fully activated. As a result of this; relation between load, moment and displacement in laterally loaded piles are nonlinear, even at safe load values (Duncan et al., 1994).

There are two factors causing the nonlinear behaviour for laterally loaded piles. First, load-displacement behaviour of the soil surrounding the pile is nonlinear. As the load is transmitted from the pile to the ground at an increasing rate, the displacement increases with a greater rate. The second is when the strength of the soil at the top of the pile reaches it's ultimate value, additional loads are transmitted to deeper soils as they do not reach the ultimate value of strength to the same degree. To transfer loads to deeper soils, the pile displaces more along the depth and the soil resistance increases along the depth. Therefore, the moments increase much faster than the load acting on the pile head. The analyses show that for the larger value of the lateral load, the maximum moment and soil resistance occur at deeper depths, not at the pile head (Duncan et al., 1994).

In the case of lateral loads, the piles act as a transversely loaded carrier element. Lateral load is transferred to the surrounding soil by means of the soil's lateral resistance. When a pile is loaded laterally, some or all parts of the pile tries to slide horizontally in the direction of the applied load. This behaviour causes the pile to bend, rotate or shift (Salgado, 2007). As the pile applies pressure on the ground in front of it, compressive stresses and deformations develop in the soil that provides resistance to the pile movement.

Accordingly; as the number of piles increased, as the raft head grew and as the carrying capacity increased due to the increase in the soil relative density, the stress values formed in the soil has increased aswell. For the L/D ratio of 10, the ground pressures increased by %100 when switched from medium-dense to very high-dense setting, this increase is %60 when switched from 3D to 6D setting. For the L/D ratio of 15, the ground pressures increased by %120 when switched from medium-dense to very high-dense setting, this increase is %50 when switched from 3D to 6D setting. For the L/D ratio of 30, the ground pressures increased by %100 when switched from medium-dense to very high-dense setting, this increase is %50 when switched from 3D to 6D setting. Because the load transferred to the pile base is related to the stiffness of the pile. The L/D ratio, which is the slenderness (pile length / pile diameter), is defined as a parameter of pile stiffness. As the stiffness of the piles decreases, the load transferred to the pile point decreases (Birand, 2001).

In addition, the stress change depending on the L/D ratio was also examined. Ground loading conditions and loading direction of the conducted experimental study have been presented in Figure 15a. Depending on the static incremental load, stresses occurring in the ground forms around the load resisting pile-soil interaction surfaces (Figure 15.b). With the increase of the L/D ratio depending on the pile length, stresses are concentrating on the pile ends and load resisting surfaces. Visuals for the ground stresses are presented in Figure 16.



a) 3D visual b) Plan and section visuals

Figure 15. Loading direction and resistance surfaces.

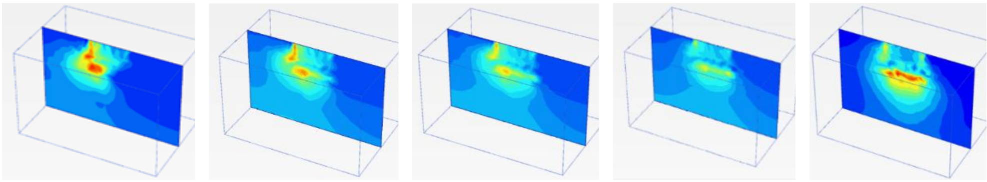


Figure 16. Stress change with the increasing load.

Lateral load analysis procedures differ for short, medium and long shafts. Short, medium and long shaft classifications are based on shaft characteristics (ie length, diameter and bending stiffness) and ground conditions described below. A pile with an L/T < 2 based on stiffness is considered "short" as long as it maintains a lateral deflection pattern close to a straight line.

The pile is defined as "long" when L/T = 4. L is the length of the pile below the ground surface and T is relative hardness defined $T = (EI/f)^{0.2}$; where f is the subsoil reaction coefficient (F/L^3). The relative hardness value changes with T, EI and f. For a short pile, the bending stiffness (EI) in the analysis can have a constant value (linear elastic). The subfloor reaction coefficient f changes with the deflection level and decreases with increasing lateral load.

When (4 > (L/T) > 2) the shaft acts as a "middle" pile. When a middle pile is analysed as a long pile, it results in an overestimated lateral response. It should be noted that the classification of pile type in this study (ie, assessment of its relative stiffness, T) is based on the initial bending stiffness of the shaft and the average of the subsoil reaction coefficient (f), including free-field liquefaction effect (Report CA04-0252, 2008).

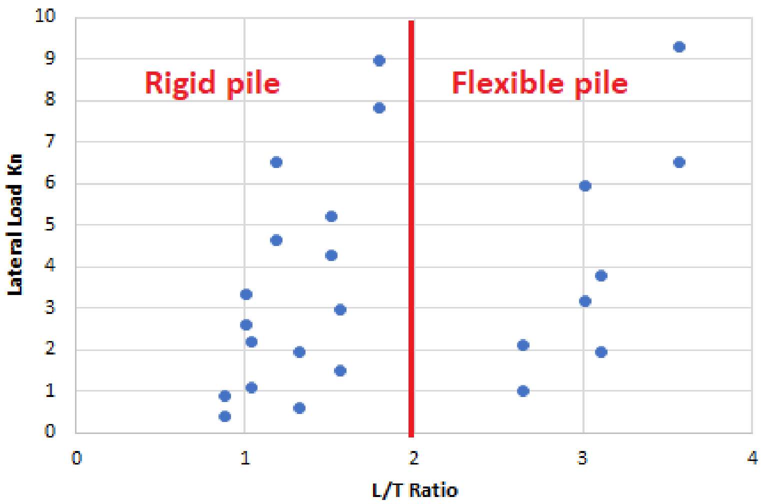


Figure 17. Horizontal load capacities based on L/T ratio.

L/T ratios were calculated for two different diameters (8 and 16 mm) and three different L/D ratios 10, 15 and 30 depending on the pile diameter and presented in a table. It is presented in Figure 12 that the test results of the piles classified as short and medium piles depending on the L/T ratio show behavioural differences depending on the slenderness. For the short piles failure condition, failure occurs as a result of the soil reaching the limit state before the piles reach the limit state, while for the long piles failure condition, failure occurs when the piles reach the limit state.

5. Conclusions

In this study, model experiments were carried out to examine the pile foundations under vertical and horizontal loads in cohesionless soils for their behaviour regarding the lateral load carrying capacity and the variables. The effects of relative compactness, pile spacing and L/D ratio were investigated in the experiments. Load-displacement graphs and soil pressure values for different depths are presented.

As seen in the soil resistance-compactness relationship, with the increase in the relative compactness of the soil, the lateral carrying capacity of the soil increased 1.5-1.7 times for 80*128 mm piled foundation and 1.5-2.2 times for 128*224 mm foundation. For this reason, the overall lateral support of the pile has increased and the results have increased accordingly.

The increase in soil resistance increased the displacement stiffness applied by the soil to the pile. When the raft foundation condition of 80*128 mm, where the pile spacing is placed in 3D, is changed to the 6D setting 128*224 mm raft foundation, the contact area of the raft and the ground has increased, thus increasing the friction area and making a positive contribution to the lateral load carrying capacity.

The optimum pile spacing is specified as 1.5D-12D in the literature. When the pile spacing increased from 3D to 6D, the lateral load carrying capacity increased by 50-70% in medium dense soil and 100% in very high dense soil. While the optimum pile spacing is 3D in medium dense soil setting, it is determined as 6D in very high dense soil setting.

Lateral load carrying capacity increased with the increase of L/D ratio from 10 to 30 based on the pile length. For the 80*128 mm foundation with L/D ratio of 10 in medium dense soil setting, with the increase in the L/D ratio, an increase of 20 percent was achieved for L/D ratio of 15 , and %90 increase for the L/D ratio of 30. These increases for L/D ratios when compared for the very high dense soil condition, it was detected %25 for L/D ratio of 15 and %110 for L/D ratio of 30. In the 128*224 m raft foundation, this increase is 100%-165% in medium dense sand, and 25%-75% in very high dense sand.

Lateral bearing capacity has increased at all pile lengths up to lateral displacement of 10% of the pile diameter. After this level, the lateral bearing capacity for L/D ratio 10 started to decrease, but the lateral displacement resistance continued to increase up to a certain value at L/D 15 and L/D 30 ratios where the pile length increased.

Soil pressures in horizontal loading condition, in cases where the L/D ratio is 10 and 15, were formed at the pile point the most and increased with depth, as seen in the short pile behaviour. In the L/D ratio of 30 condition, the maximum soil resistance was formed at the higher levels of the pile, and the stresses measured from the pressure gauges at the pile point decreased compared to other lengths. Because as the slenderness of the piles increases, the load transferred to the pile point decreases.

From the finite element analysis carried out using Plaxis 3D, for medium dense soil, as the pile length increased, the lateral carrying capacity has increased linearly. From the tests, for 3D placement, as the L/D ratio raised from 10 to 15 and for 6D placement as the L/D ratio raised from 15 to 30, effect of the pile increase has not been observed. Field conditions were considered for the tests. Ground behaviour has been observed to change as extra space/void is formed between the grounds due to loading. This behaviour could not be addressed in the finite element models and due to this, the ground has acted more rigid and resulted with higher capacity.

6D placement models compared to 3D placement models have resulted with higher lateral resistance capability. In 3D placement even with the pile increase, the results were lower than of the 6D placement. The reason for this condition is the lateral surfaces of the outer piles and soil-pile end point interactions. In 6D placement, soil-pile interactions between the piles is also added to this condition and therefore 6D placements has higher lateral displacement resistance. This result has been obtained in both test and the numerical models.

In the finite element analysis carried out in Plaxis 3D program, as the pile length increased in high dense soil a lineer increase has been observed in lateral carrying capacity. The high dense soil condition results are matching for finite element model analysis and test.

Declaration of Ethical Standards

The authors declare that they comply with all ethical standards.

Credit Authorship Contribution Statement

Author 1: Sources, Research, Methodology Essay, Writing – original draft, Visualization, Analysis and interpretation, Editing
Author 2: Experiment, Methodology, Analysis and Interpretation, Project management, Financing Visualization, Editing
Author 3: Research, Experiment,
Author 4: Analysis and interpretation Visualization, Editing,
Author 5: Analysis and interpretation Visualization, Editing,

Declaration of Competitive Interests

The authors have no conflict of interest to declare regarding the content of this article.

Data Availability

All data generated or analyzed during this study are included in this published article. Data will be made available if deemed necessary.

Acknowledgement

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6. References

Ashour M., Norris G., & Elfass S. (2008). Analysis of Laterally Loaded Long or Intermediate Drilled Shafts of Small or Large Diameter in Layered Soil, *Report CA04-0252, Department of civil and environmental engineering university of nevada*, Reno.

Ateş, B., & Şadoglu, E. (2021). Experimental Investigation of Optimum Pile Spacing of Pile Raft Foundations on Sand Soils, *Technical journal*, 32(1), 10477 - 10494. https://doi.org/10.18400/tekderg.644885

Brown, D. A., Reese, L. C., & O'Neill, M. W. (1987). Cyclic Lateral Loading of a Large-Scale Pile Group *Journal of geotechnical engineering*, 120 (6), 1018-1033. , 113(11), 1326– 1343. https://doi.org/10.1061/(ASCE)0733-9410(1987)113:11(1326)

Chandrasekaran, S. S. Boominathan, A. & Dodagoudar, G. R. (2010). Group Interaction Effects on Laterally Loaded Piles İn Clay, *Journal of geotechnıcal and geoenvıronmental engıneerıng*, 136(4). https://doi.org/10.1061/(ASCE)GT.1943-5606.0000245

Duncan, M. J., & Ooi, P. S. K. (1994). Lateral Load Analysis of Groups of Piles and Drilled Shafts, *Journal of geotecnical engineering*, ASCE, 120(6), 1034. https://doi.org/10.1061/(ASCE)0733-9410(1994)120:6(1034)

Duncan, M., Evans, L. T. & Ooi, P. S. K. (1994). Lateral Load Analysis of Single Piles and Drilled Shafts, *Journal of geotechnical engineering*, 120 (6), 1018-1033. https://doi.org/10.1061/(ASCE)0733-9410(1994)120:6(1018)

Kımura, M., Adachı, T., Kameı, H., & Zhang, F. (1995). 3-D Finite Element Analyses of The Ultimate Behaviour of Laterally Loaded Cast-In- Place Concrete Piles, Proc., *5th Int. Symp. On Numerical Models İn Geomechanics*, G. N. Pande and S. Pietruszczak, Eds., Numog V.A.A. Balkema, Rotterdam.

Lee, J., Prezzi, M., & Salgado, R. (2011). Experimental İnvestigation of the Combined Load Response of Model Piles Driven İn Sand. *Geotech Test J* 34(6),1–15. https://doi.org/10.1520/GTJ103269

Matlock, H., & Reese, L. C. (1960). Generalized Solutions for Laterally Loaded Piles, *Transactions of the american society of civil engineers*, 127(1), 1220–1247. https://doi.org/10.1061/JSFEAQ.0000303

Nguyen, Q. Van, Fatahi, B. & Hokmabadi, A. S. (2017). Influence of Size and Load Bearing Mechanism of Piles on Seismic Performance of Buildings Considering Soil-Pilestructure Interaction, *International journal of geomechanics*, 17(7), 1–22. https://doi.org/10.1061/(ASCE)GM.1943-5622.0000869

Phanikanth, V. S., Choudhury Deepankar, & Reddy G. R. (2010). Behaviour of Fixed Head Single Pile İn Cohesionless Soil Under Lateral Loads, *EDJE*, 15(M),1243-1262.

Phanikanth, V.S., Choudhury, D. & Reddy G. R. (2010). Response of Single Pile Under Lateral Loads in Cohesionless Soils. *Electronic journal of geotechnical engineering*, 15(10)-H, 813-830.

Plaxıs 3D. (2013). Manuals. Plaxis Finite Element Code for Soil and Rock Analysis 3D Version 2013, (Edited by Brınkgreeve, R.J.B.), Delft University of Technology & PLAXIS The Netherlands.

Poulos, H. G. & Davis, E. H. (1980). Pile Foundation Analysis and Design, Rainbow- Bridge Book Co., England.

Poulos, H. G. (1971a). Behavior of Laterally Loaded Piles I. Single Piles, *Journal of soil mechanics & foundations div*, 97(5), 711–731. https://doi.org/10.1061/JSFEAQ.0001592

Poulos, H. G. (1971b). Behavior Of Laterally Loaded Piles II. Pile Groups, *Journal of soil mechanics & foundations div*, 97(5), 733–751. https://doi.org/10.1061/JSFEAQ.0001593.

Reese, Cox, W. R. & Koop, F. D. (1974). Analysis of Laterally Loaded Piles İn Sand, Offshore *Technology conference*, Texas, May. https://doi.org/10.4043/2080-MS.

Sadrekerimi, J., & Asem, A. (2010). The Effect of Pile Spacing on Bearing Capacity of Pile Groups, From Research to Design in European Practice, Bratislava, Slovak Republic.

Salgado, R. (2007). The Engineering of Foundations. The Mcgraw-Hill Companies, Inc., UK.

Salini U. & Girish M. S. (2009). Lateral Load Capacity of Model Piles on Cohesionless Soil, *EDJE*, 14, 1-11.

Sawant, V.A., & Shukla, S.K. (2012). Finite Element Analysis for Laterally Loaded Piles İn Sloping Ground, *Coupled systems mechanics*, 1(1): 59-78. https://doi.org/10.12989/csm.2012.1.1.059

Sawwaf, M. (2010). Experimental Study of Eccentrically Loaded Raft with Connected and Unconnected Short Piles, *Journal geotecnical. geoenviron. engineering., ASCE*, 136(10), 1394-1402. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000341

Terzaghi, K. (1955). Evaluation of Coefficients of Subgrade Reaction, *Géotechnique*, (4), 297-326.

Terzi, N.U., Kılıç, H., & Gültekin, S., (2009). Experimental and Numerical Investigation of Behavior of a Laterally Loaded Model Pile in Sand Environment, *Journal of engineering sciences*, 15(1), 119-127.

Uncuoğlu E., & Laman M., (2013). Experimental Investigation of the Behavior of Laterally Loaded Short Piles, *Technical journal*, 24(116) ,6257-6278, 394

Uray E., Zarzour M., & Tan Ö. (2019). Investigation of Preliminary Design Guidelines for Horizontal Loaded Pile in Sandy Soils, 8th International *Geotechnical symposium*, Istanbul, November.

Zadeh, N. G., & Kalantari, B. (2011). Performance of single pile under vertical and lateral load in sand, clay and layered soil. *EJGE, 16*, 1131-1146.

Zhang J., Wang X., Wang H., & Qin H. (2020). Model Test and Numerical Simulation of Single Pile Response Under Combined Loading İn Slope, *Appl. Sci.* 10(17), 6140. https://doi.org/10.3390/app10176140

Zhang, L., Silva, F. & Grismala, R. (2005). Ultimate Lateral Resistance to Piles İn Cohesionless Soils. *Journal of geotechnical and geoenvironmental engineering*, 131(1), 78-83. https://doi.org/10.1061/(ASCE)1090-0241(2005)131:1(78)