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Investigation of Structural Behavior of Piles in Liquefiable Cohesionless Soils

Ercan Egemen BAŞAR[1], İlyas Devran ÇELİK[1], Soner UZUNDURUKAN[1], Münire FINDIK[1]

ABSTRACT: Piled foundation design and behaviour under static and dynamic loading (wave motion, earthquake, wind, vibration loadings of machinery) conditions are study subjects that are focus of interest recently in the geotechnical engineering applications. Liquefaction can be described as strength and stiffness loss of a loose, saturated non-cohesive soil under undrained cyclic loading as a result of increasing pore water pressures which reduce effective stress. Large deformations and lateral flow occurring in the layers of liquefied soil during earthquake could lead to strength and stiffness lose which may result with pile buckling and considerably increased earthquake damage on the superstructure. Predicting the bearing capacity and the deformation shape of the piled foundations during the earthquake is essential for the economy and the structural safety of the design. In this study model pile tests are conducted in uniform sandy soil and pile structural capacity is investigated under the effects of relative density and degree of saturation of surrounding soil, and pile embedment depth. Steel rods were used to represent the piles in the model tests. Sand soil was placed in a cylindirical tank at different thicknesses to provide for different pile embedment depths. Soils were compacted at four different compaction level to provide relative densities in the range of 45-80%. Static incremental load has been applied on the upper plate of the pile system in the tests. While the increase in the relative density affects the structural capacity of the piles positively, surrounding soil being saturated has resulted with capacity losses. Experimental results show that there is a consistency between our experimental findings and literature about deformation shape and buckling length of piles in liquified soils.

Keywords: Pile foundation, liquefaction, cohesionless soils

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INTRODUCTION

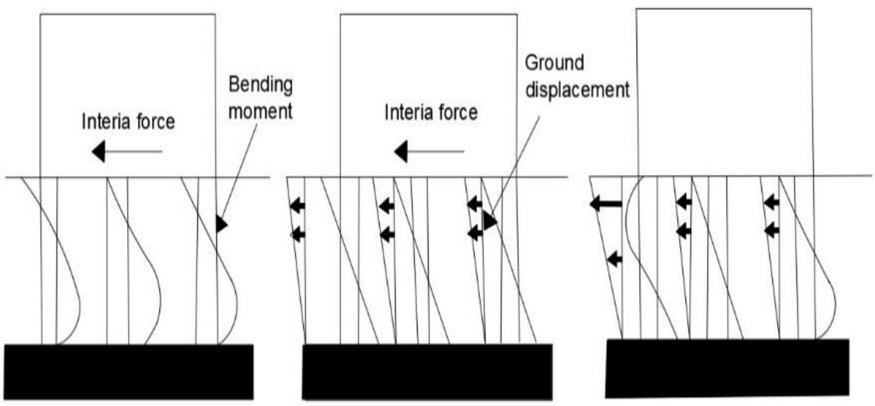
Model tests have been carried out for a long time in order to determine the optimum design parameters for pile foundations. Main purpose of these tests is to investigate the pile and foundation behavior in the ground for static and dynamic conditions and contribute to the literature. For the pile foundation systems, piles are subjected to various loading conditions in the tests. In model tests, behavior of lateral, vertical and eccentric loaded have been investigated. In addition, ratios of superstructure load shared between the pile and the raft foundation can be studied aswell. In such studies, loading is limited by certain deformation and stress criteria. Therefore, structural behavior cannot be studied thoroughly due to The soil reaching its ultimate capacity soil reaches its ultimate capacity before. However for piles that are socketed into very stiff soil or bedrock, certain conditions may lead to structural failure of piles before soil reaches it's limit shear strength. Soil liquefaction can lead to a decrease in lateral confinement effect and soil stiffness in the soil surrounding the pile, which might lead to structural damage occurrences in piles. In this study, in order to investigate the behavior of rock socketed pile foundation system, model tests are carried out with piles socketed into tank floor, confined with soils with different relative densities and saturation degrees. From the tests; buckling shape and length of piles, effect of lateral soil confinement and of soil liquefaction on the piles are examined.

It is known that shear forces affecting cohesionless soil can lead to shear deformation and rearrangement of soil particles. For loose and fully saturated cohesionless soils under drained loading conditions, there is enough time for water to leave the environment and soils are able to preserve their strength due to compaction. However, since pore water can not discharge from the environment fast enough under undrained loading conditions such as earthquake, excess pore water pressures are build up and may not be dissipated quickly. Such conditions causes effective stresses to decrease and soil to lose its rigidness, which eventually leads to soil liquefaction. Liquefied soil condition and consequent lateral spreading causes notable damage on the piles. Lateral spreading induces very high Stresses on the piles and therefore it increases the amount of damage on the affected piles. Forces induced upon the piles by the lateral spreading causes displacement values to exceed the allowable maximum limit and plastic deformation occurs (Tokimatsu 1997; Bhattacharya 2003).

Pile foundations in liquefiable soils subjected to seismic shock may fail due to excessive settlement, shear or bending loads. In addition to these mechanisms, buckling caused by the lateral spreading of the soil due to liquefaction is accepted as the main cause of various pile foundation failures during earthquakes (Hamada, 1992; Ishihara,1997; Tokimatsu et al,1998; Goh and Q'Rourke, 1999; Abdoun and Dobry, 2002; Finn and Fujita; 2002; Bhattacharya, 2005). Buckling represents the sudden instability of the pile when the axial load reaches the critical value. Interaction of axial loading and lateral loading condition should be taken into account for the design. (Dash et al, 2010) For bending-buckling alone, the pile can be considered safe, however, the bending-buckling condition during the liquefaction may result in pile failure. (Bhattacharya and God, 2013). Dash et al. (2010), have indicated an unpredictable condition in the design parameters for the piles. They have stated that the case of bending and buckling moment combination affecting the system should be simultaneously considered in the design. When these two parameters are considered seperately, the necessary safety criteria is not met. It is also mentioned that this design consideration should be correlated to the Length/Diameter (L/D) that is the slenderness ratio of the piles aswell. Shanker et al. (2007), have investigated the buckling condition of the piles in the liquefied soil and emphasized that fundamental paremeters for this condition are soil degradation, pile slenderness ratio, pile rigidness factor and the socketing of the pile edge. Kimura and Takimatsu (2005), have investigated the buckling behaviour of the piles in the liquefied soil. They concluded that under liquefied soil condition, the piles with high slenderness ratios may be affected by additional vertical loads as the amount of p-y curves. Liquefaction condition added to the present p-y loads may result with unwanted situations. In case the effectiveness of the soil surrounding the piles disappear, these vertical loads could cause buckling failure for the piles.

When a comprehensive literature review is made, different approaches to the design of piles can be seen. Some of these approaches are; an approach based on experimental equation (Vesic 1977; Coyle and Castello 1981), an analytical approach based on variational principles (Seo et al. 2009; Basu et al. 2009), a finite element (FE) based numerical approach (Basu et al. others 2010, 2014) and the buckling instability approach (Bhattacharya 2003; Bhattacharya et al. 2005). Tomlinson and Woodward (2007) and Salgado (2008), investigated the failure of a pile under axial loading. In this experimental study, in order to examine the behaviour of the pile foundation system inserted into the bedrock, model experiments were carried out on piles socketed into the bottom of the tank surrounded by soils of different densities and saturaion degrees, and buckling type of the pile, buckling length, lateral limitation order of the soil piles and the behavior of the pile in liquefaction were examined.

Tokimatsu et al. (1997), has defined soil-pile interaction in liquefiable soils in three stages and expressed the pile failure schematic for the liquefied soils, as presented in Figure 1. Superstructure related inertia force remains effective until the pore water pressure increases. The pore water pressure increases due to kinematic forces occurring in the liquefied soil. As a result of dynamic effects, kinematic forces become effective in soils with lateral spreading, thus displacement values increase and pile performance decreases.



I)During Shaking before lıquefaction II)During Shaking After lıquefaction III) Lateral movement after eartquake

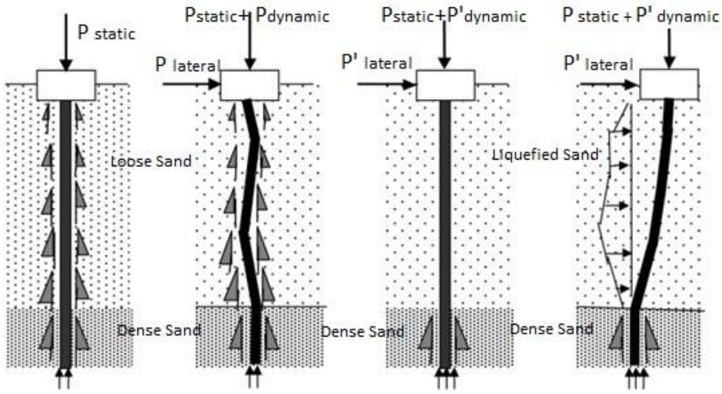
Figure 1. Schematic diagram for pile failure (Tokimatsu et al., 1998)

Bhattacharya (2003), has investigated the state of stresses of end-bearing piles under seismic liquefaction.

1. Before the seismic liquefaction occurs; in the loose soil surrounding the pile, significant rigidness losses may not occur and loose soil, by means of strength, will support the pile and the pile will keep behaving like a beam settled on elastic soil.

2. For a layer of soil that is prone to liquefaction; during the earthquake, liquefied layer starts losing its rigidness as the pore water pressure increases, piles with high slenderness ratio will lose their stability and as the lateral forces increase, the buckling failure will occur in the piles.

3. In slope soils; due to lateral spreading of the soil, additional loads may be experienced in the piles which will behave as a beam-column and failures as shown in Figure 2 may occur in the piles.



Before earthquake in level ground | Shaking starts, soil yet to liquefy. Pile acting as a beam | Soil has liquefied. Internia forces may act. Pile acts as a column, and may buckle. | In sloping ground, lateral spreading may start

Figure 2. Schematic Diagram for Pile Failure (Bhattacharya, 2003)

Bhattacharya et al. (2004), investigated the behavior of 14 pile foundation system in liquefiable soils with 1/50 g centrifuge tests. In tests, tank with dimensions of 560 mm x 235 mm x 220 mm and aluminium piles with outer diameter of 9,3 mm and inner diameter of 8,5 mm are used. Slenderness ratio has been investigated. Soil displacement caused by the lateral spreading and the bending of the piles are correlated with pile slenderness ratio. Soil remains liquefied even after the seismic activity stops and plastic deformation may occur in the piles.

Bhattarcharya et al. (2009), expressed the buckling problems of pile systems caused by their combination with liquefaction with theoretical formulas by utilising Euler – Bernoulli beam theory. In their study, under axial load, buckling conditions of piles with socketed edges placed in soils with different density and saturation degrees are investigated. How the soil surrounding the piles and the forces in the piles was affected by axial loads is investigated through the model test systems. It was stated in the study that natural frequency of the pile system immensely drops during the liquefaction. Also during the liquefaction, axial load capacity of the pile decreases and buckling failure may occur. In other words, strength of the soil surrounding the pile decreases immensely. Therefore, the buckling failure which is emphasized to be associated to the pile slenderness ratio may occur in the piles.

Bhattacharya (2003) has indicated that the condition of buckling load being %50 percent or more of the axial load has resulted with significant foundation damage. Dash (2010) has determined the safety factor for the buckling load to the axial load ratio as 1.33. The bending moment amplification coefficient increases as the axial load comes close to buckling load. Forementioned condition causes the pile bending moment to reach plastic moment capacity at a lower value of lateral load. This failure indicates the cause of failure as the lateral load increase during seismic activity combined with high axial load.

Bending resistance is decisive on the bending failure (Dash et al, 2010). Bending stiffnes is a key parameter to the piled foundation design. Increasing the pile bending stiffness would result with an increase in the pile bending capacity and the axial load capacity (Zhang et al, 2020). Bending stiffness also can be increased by means of higher material strength (Bhattacharya and Goda, 2013).

Basar et al. (2019), by applying rubber cushioning to lateral loaded pile, have found that moment and shear force values somewhat decrease. Accordingly, it is mentioned that the material of the cushioning surrounding the buried part of the pile may affect the pile section internal forces.

For buckling mechanism of piles, pile slenderness, the relative density of the foundation soil they are in, as well as pile buried depth are effective parameters. In other study, piles in sandy soils that are exposed to axial load with 1/3 and 2/3 buried depth / total length ratios was examined (Jesmani et al, 2012). The study has shown that the piles with higher buried depth / total length ratios resulted with higher buckling load. As the pile length of the fully buried piles increased, an increase in the buckling load is observed. In layered soils, the pile should be sufficiently buried in the non-liquefied ground, otherwise the pile deflections increase and the piles bend at smaller moments.

Lateral loading caused by slope movement and earthquake load increases the lateral deflections of the pile, which can cause the pile to buckle even at lower axial loads. Partially buried piles in sloping lands are used mostly in bridge piers foundations, sea and harbor structures. Fındık et al. (2019), evaluated seismic performance of piled offshore structures under lateral load. Damping of the moment values and the shear force on the piles was concluded to be highly correlated with the pile buried depth (the part of the pile that is sunk into the soil). In addition, it is also mentioned that pile buried depth. Should be at least % 40-45 of the pile total length.

Initially bent in the pile may be caused by the pile driving technique used during pile installation or the presence of rocks under the pile. This pile condition increases the lateral deflection of the pile and the pile buckling probability. The quarter-sine bending amplitude and half-sine bending amplitude in the manufacture of the piles, reduce the buckling load carrying capacity of the piles depending on the increasing initial bending ratio (Nadeem et al, 2015).

MATERIALS AND METHODS

There are programs in the scope of foundation design literature that can analyse raft and pile systems coupled together. Behavior and load carrying capacity of the systems investigated using softwares utilising numerical analysis methods, should also be validated with model tests due to inconsistencies in the soil profile. Such validations are important for the safety of the system. In order to examine the behavior of piled raft foundation, scaled field tests can be performed. Although not performed in all projects due to its costs, scaled loading tests are carried out in qualified projects. Parametric studies for the behavior of piled raft foundation can be performed in laboratories with small scaled model tests and more economic solution approaches can be acquired. In this study, pile buckling length and pile load carrying capacity is tried to be determined using uniform soil with diameter of 0.5-1.2 mm under dry, saturated and liquefied conditions. For this purpose, piled foundation model is prepared using 4 solid steel rods with diameter of 4 mm. Upper and lower boundary conditions of steel rods representing steel piles are fixated to rigid steel plates. Upper plate represent a rigid raft and the lower plate ensures rigid socket conditions for the qualified pile edge behavior. General views of the piled foundation system and the loading mechanism used in the tests are presented in Figure 3.

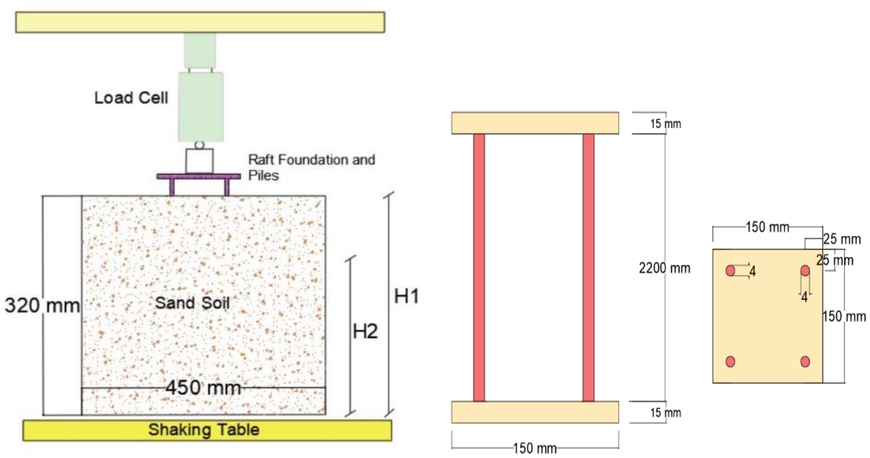


Figure 3. Test setup section and configuration

In model tests, the dimensions of the test tank and the raft should be determined in such a way that the boundary effect has the least effect on the test results. In the literature, many studies have been carried out on what the dimensions of the raft and test tank should be in order to create semi-infinite ambient conditions where boundary effects do not change the test results. As a result of these studies, it has been determined that if there is a gap between the edge points of the foundation and the sides of the tank when a 2L-length soil is placed under the 2B and L piles, the boundary conditions will not affect the test and thus semi-infinite ambient conditions will be provided (Sawwaf, 2010; Sadrekerimi, 2010; Yetimoğlu, 1998). ; Yilmaz, 2010). It is widely used in model tests in sand tanks with dimensions ranging from 4D to 15D, and centrifuge tests (Liu et al. 2010a, b; Tamura et al. 2009)

In the tests, sandy soil is placed in a cylindrical tank that is 450 mm in diameter and 320 mm high. Since the end pile was worked, the height of the tank was chosen as the length of the pile. The sandy soil has been placed in the tank with different saturation, relative densities and tank fill height parameters. Loading is applied static incrementally onto the upper plate of the pile system. Load value is detected using a load cell placed between the hydraulic piston and the plate. Displacements on the upper plate of the system under loading has been measured using a displacement sensor.

Sieve analysis has been performed in order to define the grain size of the soil sample used in the tests and pycnometer method is used to obtain specific gravitiy of soil particles. Maximum and minimum void ratio are determined respectively according to the ASTM D 4253 and ASTM D4254 standards in order to calculate the soil relative densities. Calculated values for the soil sample are presented in the Table 1. Properties of the S235 structural steel that is the pile material are presented in Table 2.

Table 1. Soil sample properties

Sample	D10	D30	D60	Cu	Cc	e_{max}	e_{min}	γ_s(Kn/m^3)
Sand	0.25	0.38	0.8	3.2	0.72	1.00	0.53	26.72

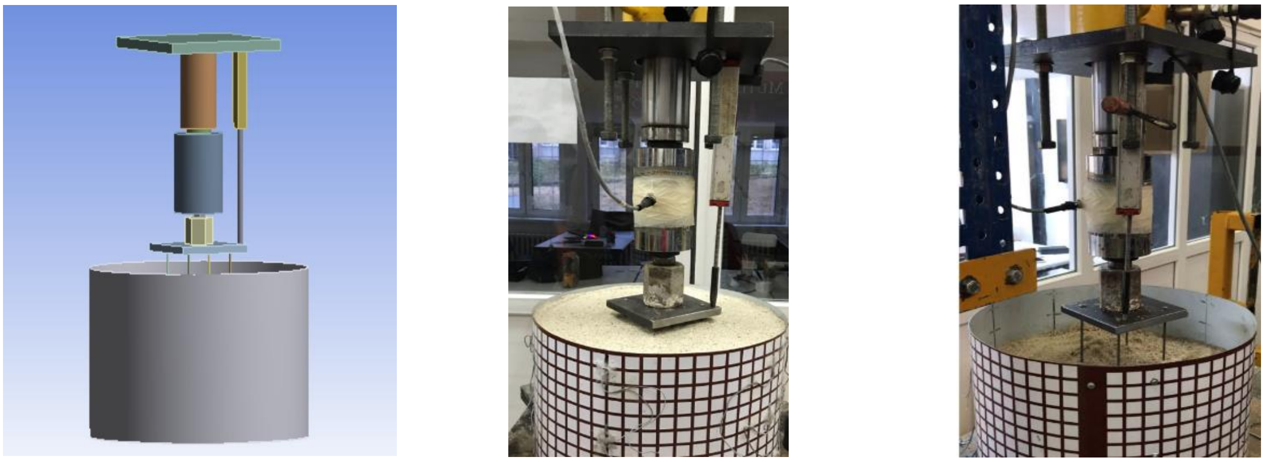
Table 2. Steel sample properties

Sample	Tensile Strength MPa	Yield Strength MPa	Elasticity MPa	Poisson's ratio
S235	360-510	235	200000	0.3

Firstly, without providing any soil condition, incremental load has been applied onto model pile system until the buckling failure occurred. Therefore, critical buckling load that can constitute reference for different soil conditions is obtained. In order to investigate how the critical buckling load and the buckling lentgh is affected by the relationship between the soil and the pile system, tests with pile depth of 200 mm and 300 mm are performed. In order to investigate the effect of the different soil relative densities on the pile behavior, soil relative denstiy ratios are varied in the range of 45/80. All combinations are repeated for dry soil, saturated soil and the liquefaction conditions. In order to meet the liquefaction condition for the soil, vibrations are applied to the sand tank by using the shaking table (1m*1m dimensions, 1-10 hz frequency range, 500 mm/sec speed and 10 cm displacement).
Combinations used in the model tests are presented in the Table 3. To reflect the behavior rock socketed pile, pile edge on the bottom side is fixated to a rigid plate that is placed on the tank floor. To prevent the soil deformations to affect the measured displacement values during the loading, sufficient space has been allowed between the pile upper plate and the soil. LVDT placed on the upper plate is used to measure the displacement values.

Table 3. Test Combinations

	Load (kN)	Sand Height (mm)	Compaction (Dr %)	Saturation	Loading
M1	407	-	-	Dry	Static
M2	1118	300	80	Dry	Static
M3	873	300	60	Dry	Static
M4	632	300	50	Dry	Static
M5	551	300	45	Dry	Static
M6	523	200	60	Dry	Static
M7	444	200	45	Dry	Static
M8	446	200	60	100	Static
M9	445	200	50	100	Static
M10	377	200	45	100	Static
M11	376	200	45	100	Dynamic



(a) (b) (c)

Figure 4. Views from the test (a) 3D visual, (b) Bruied depth:300 mm, (c) Buried depth:200 mm

RESULTS AND DISCUSSION

In this study, foundation system modelled as end bearing pile is analysed experimentally under static incremental load for different soil conditions. Analysis results are evaluated for different combinations that are formed of relative density, pile buried depth, dry and saturated soil conditions. In this context, pile critical buckling load, buckling length and foundation system load-displacement graphs are acquired. The effects of different soil conditions on pile system behavior is investigated according to the obtained results. Ultimate carrying capacity and the conditions of all the specimens are presented in Figure 5.

In order to determine the buckling load for the pile component section properties and support conditions alone, no-soil condition is chosen as the reference specimen. Reference specimen is named as M1 and the other results are evaluated accordingly. Soil fill is defined from pile buried depth in the tests. In the tests for the 300 mm of pile buried depth condition, soil relative density values are used in the range of %45-80. For the 200 mm pile buried depth condition, relative density values are used in the range of %45-60 and behaviors of the saturated and the liquefied conditions are specifically investigated for this buried depth.

Pile elastic critical buckling load is calculated using Euler critical load formula in order to obtain a reference value for the tests. The mentioned formula is presented below. Pile allowable load that is the pile elastic buckling load is indicated by Pcr. Leffective indicates pile effective length in the liquefied zone that varies by equivalent euler buckling which depends on the pile boundary conditions and liquefied soil depth. E indicates the modulus of elasticity and the I indicates the moment of inertia.

$$P_{cr} = \frac{\pi^2}{L_{effective}{}^2}\ EI \tag{1}$$

$$P_{cr} = \frac{\pi^2}{154^2}\ 200 * 10^3 * 12.56 = 426\ kg = 4.26kN$$

E= 200*10^3 MPa

I= 12.56 mm^4

$L_{effective}$ = 220*0.7 = 154 mm

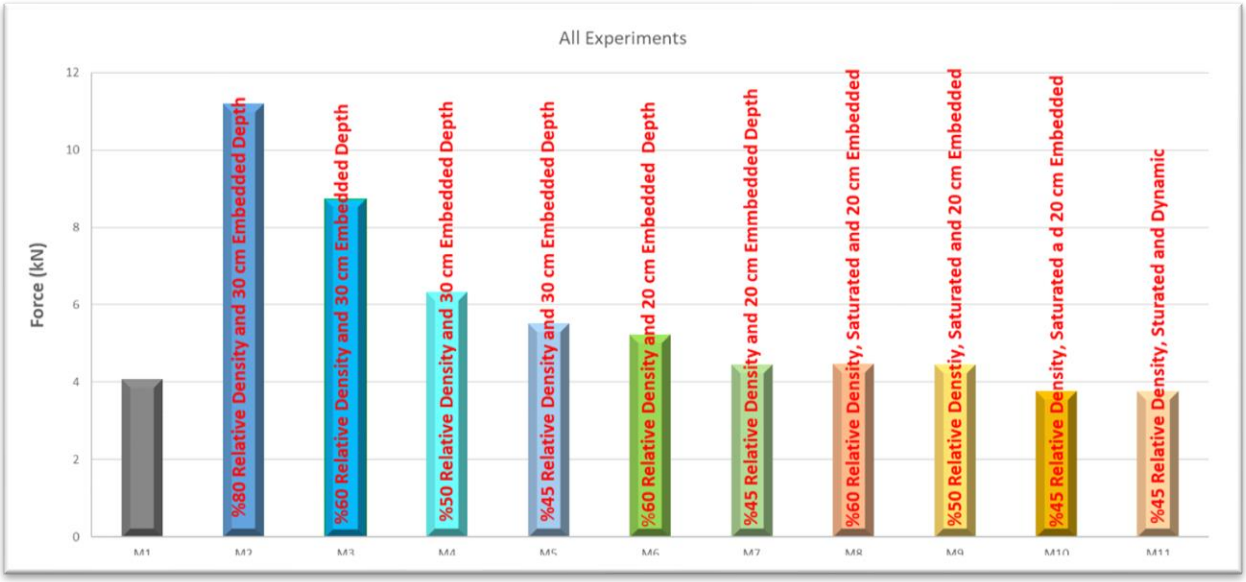


Figure 5. Maximum Load Carrying Capacity of the Models

Maximum load carrying capacity diagram of the pile systems for different soil conditions are presented in the Figure 5 Dynamic condition not being quite effective can be seen in the mentioned graphs. From the graphs, it can be seen that the M1 reference specimen has the lowest capacity among all models as expected. This condition puts forward the effect of buried depth on the pile support conditions independently of the soil fill and saturation. Increase in the soil relative density and pile buried depth affecting the critical buckling load directly, supports the approach of soil-pile interaction. Highest carrying capacity obtained among the tests is from the M2 model that is 300 mm pile buried depth and %80 relative density ratio conditions. M2 model capacity value has resulted with approximately three times of the reference specimen. When the relation between the soil relative density and capacity is evaluated, the change in the capacity based on the relative density is seen to be similar for both 300 mm and 200 mm buried depth conditions. Therefore, it can be stated that soil relative density directly affects the pile buckling length and the support conditions thus making it decisive on the capacity

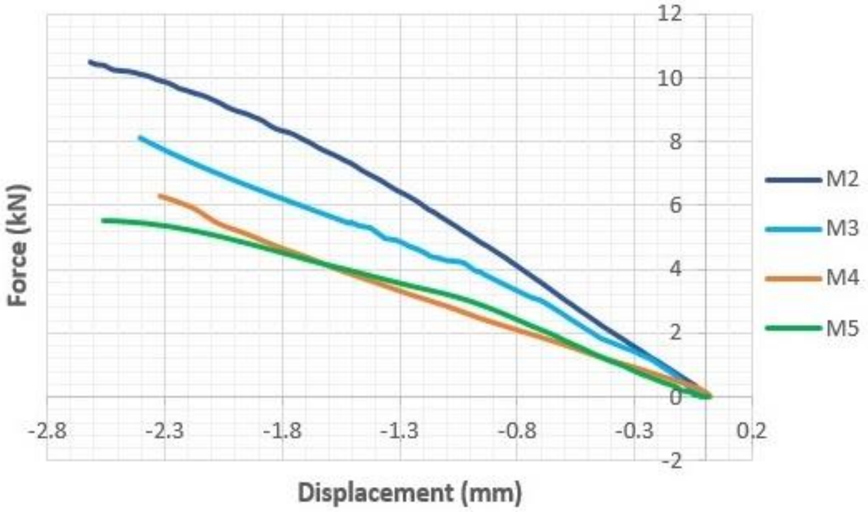


Figure 6. Load-Displacement Graphs of the pile systems for dry soil condition

In order to determine the interaction between the pile system and the soil layer, load - foundation upper grade vertical displacements are obtained. In this context, obtained capacity curves of the pile system are presented comparatively. Tests are repeated for dry sandy soil specimen with soil relative density values of %80-60-50-45. Tests has shown that increase in the soil relative density due to lateral confinement effect of the soil surrounding the piles has increased the carrying capacity of the vertically loaded pile. It can be seen in Figure 6. that as the soil density increase, the buckling resistance of the pile also increases. This increase affects not just the capacity but also the system rigidness aswell. Similarity between rigidness distribution and the soil relative density can be seen in the graphs. Rigidness values decrease as the soil compactness decreases. Load-vertical displacement values in the graphs show that ductile behavior seems to improve as the soil relative density increases.

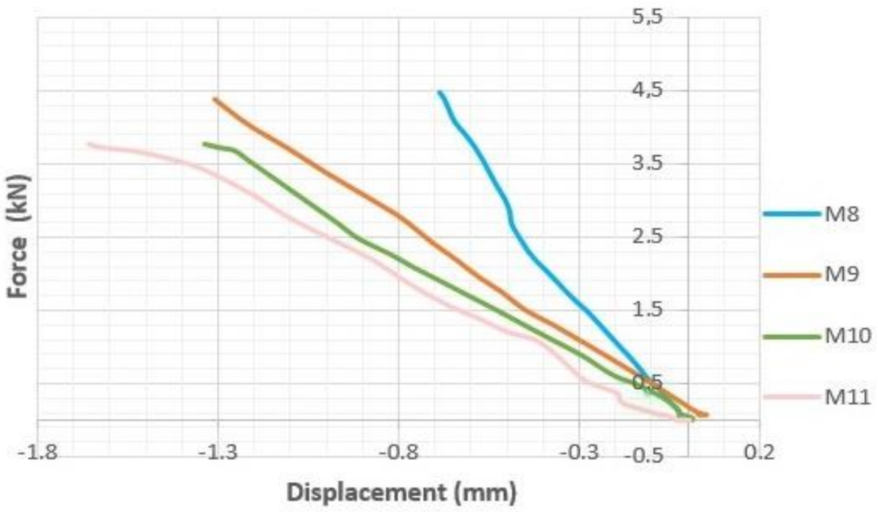


Figure 7. Graphs for the Saturated Soil

In models M8-9-10-11 pile behaviour during liquefaction is investigated for %100 saturated soil with 200 mm buried depth conditions. Load-displacement graphs of the piles for the saturated and liquefied conditions are presented in Figure 7.

The increase in the soil relative density affects the pile carrying capacity positively in the saturated soils as well as it can be seen in Figure 7. However, maximum capacity values for dry soil conditions are resulted higher than of the saturated soil conditions. Increase in the soil saturation seems to negatively affect the lateral confinement effect on the piles in other words the pile support conditions even under static loading conditions. This condition can be explained by pore water decreasing the friction resistance of grains and easing the relative movement of soil grains (Marzulli et al., 2021). Marzulli et al. (2021), have performed shear tests for dry and wet conditions on different sized two soil samples. From the results, it has been observed that the friction between the grains is shown to decrease while water is present in the soil. Friction angles are detected higher in the dry condition compared to the wet condition for the same grain size. When the behavior in saturated soil and the behavior in liquefied conditions are compared, it can be seen that dynamic loading effect is pulling down the pile capacity value to beneath all of the saturated conditions and the reference specimen.

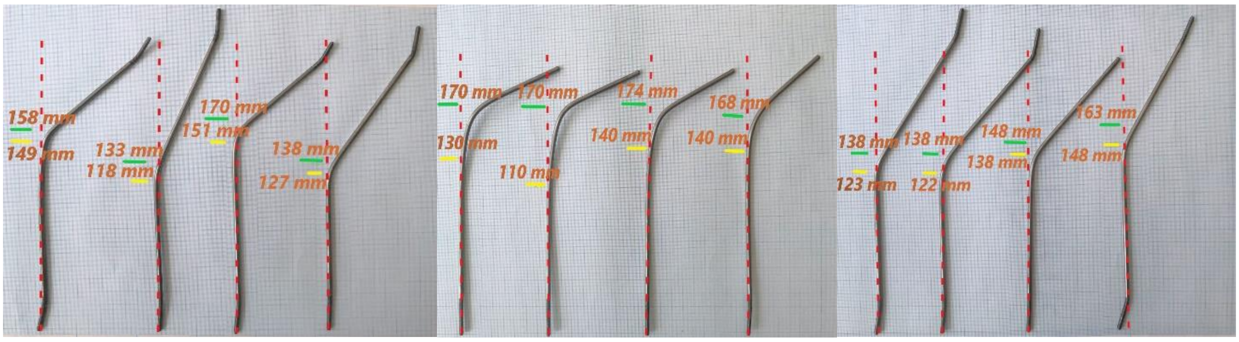
Bhattacharya (2003), has mentioned that the liquefaction in the soil due to seismic activity caused plastic deformation on the upper part of the piles for one third of pile total length. The results has shown that the buckling points are at the 1/3 L height which is in accordance with the literature. The buckling heights (distance between pile buckling points and the floor) are presented in the Table 4.

Table 4. Pile Buckling Lengths

	Load (kN)	Sand Fill (mm)	Pile Length	Distance of Pile Buckling Points to the Floor (mm)
M1	407	-	220	130
M2	1118	300	220	172
M3	873	300	220	163
M4	632	300	220	162
M5	551	300	220	151
M6	523	200	160	134
M7	444	200	160	112
M8	446	200	160	114
M9	445	200	160	115
M10	377	200	160	113
M11	376	200	160	133

From the Table 4 effects of soil fill, soil relative density, saturation degree and the dynamic effect on the pile buckling length can be seen. It is seen that the distance of the buckling failure location from the lower end of the pile is maximum in the M2 model test. Due to decrease in the soil relative density, this distance shifts towards to the mid point of the pile length. In other words this specimen approaches the buckling behavior of the reference specimen. Buckling lengths obtained for specifically saturated and liquefied conditions show that the effect of lateral confinement decreases/diminishes for soil-pile interaction and the pile buckling lengths approach to the reference specimen. Post loading condition of pile systems are presented in Figure 8 for dry soil, saturated soil and the liquefied soil conditions. Presented models are chosen to demonstrate the pile buckling shapes. In the images; M2 is for dry soil, M8 is for saturated soil and M11 is for liquefied soil condition. Through investigating the Figure 8, it can be stated that the piles buckle on their middle point and go into the failure mode. In the M11 model test, lateral load caused by the dynamic effect is seen to be effective on the buckling behavior. This condition can be supported also by the fact that the capacity obtained for the M11 model has resulted lower than of the reference specimen.

When the post-loading behavior of the M2 model (the highest soil relative density ratio and the pile buried depth conditions) is investigated, it can be seen that the collapse is not focused to a point but happens rather ductile. This situation clearly shows the effect of soil confinement on the piles that are forced to lateral buckling under vertical load.



M2 M8 M11

Figure 8. Buckling heights

CONCLUSION

In this study, effects of soil relative density, soil saturation and consequently lateral confinement effect of the soil on the piles are investigated for cohesionless soils. Obtained deformation shapes and buckling length of piles in soils that may liquefy under dynamic forces are seen to be in accord with the literature.

Conclusions from the pile-soil model tests are given below.

- Structural capacity of the piles in cohesionless soils is in direct proportion to the soil relative density.
- For soils with same relative density, as the pile buried depth increases, pile structural capacity increases aswell. This conclusion is specifically important for pile foundations of offshore and coastal structures and end bearing piles surrounded by soils with potential for liquefaction along the pile length.
- Comparison of the results of models for dry and saturated soils with same soil relative density has shown that the increase in the soil saturation has lead to a decrease in the structural capacity of the pile system. The increase in the soil saturation leads to frictional resistance of soil particles to decrease thus the effect of soil lateral confinement on piles decreases. This condition directly affects the pile support conditions thereby pile carrying capacity and the buckling behavior.
- By socketing pile bottom end to a hard soil and the upper part to a rigid plate, lateral movement is limited and the pile resistance for lateral loads is increased thus affecting the buckling behavior positively. In addition, due to lateral confinement effect of the soil surrounding the pile being determinant on the support conditions, the buckling point shifts towards upward as the confinement effect increases.
- Investigating the load-displacement graphs has shown that as the lateral confinement effect of the soil surrounding the pile increases, the pile buckling behavior tends to be more ductile. Considering this condition for pile system design may lead to a safer and more economic solutions.

From the tests, the maximum load pile can carry before the buckling and the buckling length are observed to be correlated with; soil saturation degree, relative densities, pile buried depth and pile end boundary conditions. In this study, soil condition, pile type and size are kept fixed for the tests therefore it can be stated that the obtained data is limited by the study conditions. By diversing the pile types and the soil conditions and improving the test setup to reflect the effect of soil stresses, further research may provide more realistic contribution to both practice and the literature.

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Conflict of Interest

The article authors declare that there is no conflict of interest between them.

Author’s Contributions

The authors declare that they have contributed equally to the article.

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