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Laboratory Modelling and Analysis of Displacement Pile in Different Geometries on Alluvial Soils

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Abstract

Alluvial soils are weak soils that require precautions and have disadvantageous engineering characteristics such as low shear strength and bearing capacity, high void ratio, and settlement potential. Different foundation systems are preferred for structures built on these soils to transfer the load effects safely. Pile foundations as deep foundations are classified depending on various parameters such as; material property, application method, and load-bearing method. In this study, cylindrical and square concrete piles with different cross-sections and lateral areas were placed in the alluvial soil. The natural alluvial soil taken from İzmir province, Balatcik location was placed in a displacement-controlled pile model unit with a unit weight of ≈ 17 kN/m3. The manufactured concrete piles were driven into the soil with a Standard Proctor hammer. Tensile effects were applied at different time intervals to examine long-term and short-term behavior. As a result of experiments, load-displacement (p-y) and displacement-time (y-t) graphs were drawn. When the displacement piles were examined under long-term tension, it was seen that the cylindrical piles displaced the most. Square piles with the same cross-sectional area as cylindrical piles made less displacement. All studies were modeled 1:1 as numerical and compared with experimental results. Numerical investigations revealed that under long-term effects, the highest displacements were observed in cylindrical piles, while the lowest displacements were in square piles with equal cross-sectional area as cylindrical piles. Under short-term tension effects, investigations showed that the highest bearing capacity, according to both experimental and numerical results, was in square piles which have an equal cross-sectional area with cylindrical piles. Studies showed that the experimental and numerical results for pile behavior were compatible.

1. Introduction

With the assistance of advancing technology in the contemporary world, safer techniques have started to be employed in the construction of complex structures. Particularly in regions where weak bearing capacity soils are present, urbanization has increased and has contributed to the growth of the population. In terms of geotechnical engineering, alluvial soils, considered problematic and extensively studied by numerous researchers, exhibit distinct behavioral characteristics including weak bearing capacity, high void ratio, and low shear strength [1], [2]. In regions where weak soil layers such as alluvial soils, which are considered geological formations not yet fully formed, are present, there has been an increasing inclination towards deep foundations in planned constructions to ensure structural safety [3], [4], [5]. Pile foundations, which are a type of deep foundation, provide the opportunity for safe designs by transferring the superstructure load to soil layers with high bearing capacity, both under dynamic and static loads, thereby offering support to the superstructure [6]. This allows for secure designs under both dynamic and static loading conditions.

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Piles, in general, is construction element used in situations such as taking part in; weak or compressible soil layers under the foundation, the failure to transfer the horizontal, compression, and tension loads on the foundation safely to the soil layers, the danger of shrinkage in the soil layers, excavation near an existing structure in the future, soil layers that are likely to swell or collapse within the effective depth [7]. Piled systems especially, are encountered in special applications where the structure is under tension loads, such as wind turbine foundations and offshore oil refineries [8] ,[9]. To ensure compliance checks of pile designs, field tests are conducted after construction to measure the performance of the pile. However, this practice can sometimes lead to issues due to time and economic constraints. As a result, numerical and laboratory-based model studies have gained momentum for determining pile behavior depending on various parameters [10], [11].

In studies conducted by various researchers on the behavior of piles under tensile loading, it has been understood that parameters such as; pile installation method, friction mechanism between the pile and the soil, duration of load application, pile surface roughness, and pile dimensions have significant effects on pile behavior [12], [13]. In the method, which is described as displacement pile and causes displacements within the soil during the application, laboratory studies have shown that the effect of the pile-soil friction mechanism increases, leading to a 1.33 times increase in shaft resistance [14]. It has been reported that as the duration of applied load on the pile increases, there is an increase in shaft resistance of the pile and subsequently an increase in pile bearing capacity [15]. This phenomenon highlights the significant role of the friction mechanism in pile behavior. When examining the behavior of piles with different surface roughness under tensile loading, it is observed that there is a proportional relationship between surface roughness and tensile load. Specifically, as the surface roughness of the pile increases, the tensile bearing load of the pile also increases [16].

Behavioral characteristics obtained from laboratory studies are also investigated on computer-based models using the Finite Element Method (FEM), which is a numerical analysis technique [17], [18]. This allows for exploring the behavior of the examined system in a computational environment. The similarity between the obtained laboratory data and the generated model validates the reliability and consistency of engineering designs. Nowadays, numerous engineering software utilize scientific foundations by drawing from existing studies and methods in the literature [19]. This approach helps to establish robust scientific frameworks for these software applications. Hence, the alignment of laboratory study results with models created in a numerical environment holds significant scientific importance.

In this study, the behaviors of concrete displacement piles with different geometries under tensile loading conditions within alluvial soils have been investigated by examining both laboratory and numerical model behaviors. Concrete piles with different cross-sectional properties were placed in a displacement-controlled pile model unit in the laboratory using a Standard Proctor hammer. The study examines the effect of cross-sectional properties on the behavior of piles with equal cross-sectional area and lateral area in different geometries. The importance of the duration of load on pile behavior was explored by analyzing long-term and short-term load effects. The data obtained from laboratory experiments were compared and interpreted with the results from a 1:1 scale experimental system created in a numerical environment.

2. Material and Method

2.1. Alluvial Soil

Alluvial soils are commonly found around geographical formations like rivers and streams. In terms of their composition, alluvial soils can contain clay, silt, sand, gravel, and even organic materials [20]. The alluvial soils used in this study were obtained from the Çiğli-Balatçık region. Çiğli district is located to the north of İzmir and is situated within the edge of the Gediz Delta. Due to the presence of the Gediz River, this region contains significant alluvial soil deposits. The location from which alluvial soils were obtained, the Balatçık region, is depicted in Figure 1.

Figure 1. Alluvial soil location

Alluvial soils were obtained through drilling conducted at İzmir Katip Çelebi University. During the drilling process, soil samples were extracted at every 1.50 meters of depth. These soil samples were packaged and brought to the Geotechnical Laboratory of İzmir Katip Çelebi University for further analysis.

2.2. Concrete Piles

Within the scope of the study, concrete piles with different cross-section properties and geometries were produced. The concrete mortar preparation process was carried out in the laboratories of İzmir Katip Çelebi University according to the relevant regulations and prescriptions. Plywood forms were suitable for predetermined pile dimensions used in the pile manufacture. Plastic pipe material (PVC) was used as a form in the production of cylindrical concrete piles. The information about the piles produced for model studies has been given in Table 1. (L: pile length, L': pile embedded length, D: diameter, L/D: pile length/diameter, L'/D: pile embedded length/diameter).

Table 1. Engineering properties of piles

Pile Type	Cylinder	Square Type 1	Square Type 2
Material	Concrete	Concrete	Concrete
Diameter / Side Length (mm)	45	35	40
L (mm)	400	400	400
L' (mm)	250	250	250
L'/D	5.5	6.3	5.5
L/D	8.9	10.1	8.9
Cross-section area (mm^2)	1600	1225	1600
Lateral area (mm^2)	56550	56000	64000
Frictional lateral area (mm^2)	35340	35000	40000

2.3. Displacement – Controlled Pile Model Unit

Within the scope of the study, a displacement-controlled pile model unit was produced in the laboratory. Plywood formwork materials were used in the manufacture of the pile model unit. During the pile application, horizontal displacements (stretches) were prevented by bonding the unit wall (Figure 2.). In this way, only vertical displacements were allowed to occur. Periodic checks were made to detect out-of-plane deformations that may occur in the pile model unit forms during the experiments. Information about the pile model unit manufactured within the scope of the study has been shown in Table 2.

Figure 2. Displacement-controlled pile model unit

Table 2. Pile model unit information

Parameters	Unit
Material	Timber plywood
Thickness (mm)	20
Width (mm)	400
Length (mm)	595
Height (mm)	577

2.4. Other Equipment

To conduct the tensile tests, a pulley-based tensile testing apparatus was manufactured. This apparatus was manufactured using components such as a steel cage element that was used as a framework, a pulley rail system, Medium-Density Fiberboard (MDF) support pieces, steel hooks, and anchors (Figure 3.).

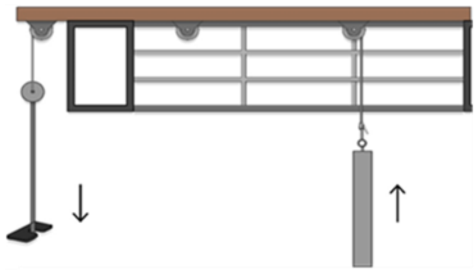

Figure 3. Tensile experiment apparatus

2.5. Laboratory Experiments

In order to determine the geotechnical index properties of alluvial soil; Specific Gravity Test, Fall Cone Test, Plastic Limit Test, Direct Shear Test, Sieve Analysis, Hydrometer, and Proctor Tests were conducted according to regulations. The specific gravity of alluvial soil was determined using the Pycnometer Method [21]. The specific gravity test involved using a 50g sample passing through a No. 4 sieve, along with distilled water and a vacuum pump. Dry and Wet Sieve Analyses were performed to obtain particle size distribution [22] ,[23]. The Hydrometer Test was conducted due to the high fine content of the soil [24]. The Standard Proctor Test was carried out to determine the optimum water content and maximum dry unit weight of the alluvial soil [25]. The results curve from the Standard Proctor Tests were generated using Method A. The Fall Cone Method was conducted to determine the liquid limit values of the alluvial soil [26]. The plastic limit value of the soil was determined using the method specified in the relevant regulation [27]. The soil classification of the alluvial soil was determined using the Unified Soil Classification System (USCS) [28].

2.6. Tensile Behavior Investigation

In order to examine pile behavior in a laboratory setting, various researchers have created small-scale models [29], [30]. The created systems generally consist of a sand tank, pile element, and loading apparatus. In this study, a soil model unit and concrete pile manufacturing were conducted to examine the behavior of piles under tensile effects. Using the established loading and monitoring system, the behavior of the piles under tensile loading was investigated.

Soil unit weight for soil placement in the pile model unit was adjusted at the level of approximately 17 kN/m3 (±0.20)) as the maximum dry unit weight corresponding to the optimum water content obtained as a result of the Standard Proctor Test. Before being placed in the soil model unit, the unit was divided into 50 mm equal layers. Since the target unit weight was 17 kN/m3 (±0.20), the required soil weight for each layer was calculated (Equation 1.).

$$17\frac{kN}{m^2} * 0.05 * 0.04 * 0.0595 * \frac{1000}{9.81\frac{m}{s^2}} = 0.2kN \quad (1)$$

A Standard Proctor hammer was used for the compaction of the soil. To achieve the compaction as described in Equation 1, 10 blows of the Standard Proctor hammer were applied to an area of 0.04 m2. In this way, an application was made by the determined soil unit volume weight. The piles were placed in the displacement-controlled pile model unit using the driving method (Figure 4). Considering the method of application, the piles were displacement piles. The piles placed in the soil were positioned in such a way that the distance from the pile center to the boundary edge in cohesive soils is at least 3 times the pile diameter [31]. During the application of the piles to the soil, it was checked whether there was any inclination in the pile axis at intervals each of 50 mm depth. The experiment was repeated if any inclination was detected during pile driving.

Figure 4. Displacement pile application process

It is known that the soil at the tip of the pile is somewhat compressed during pile placement due to the constant fall energy applied. In order not to affect the experimental results, the displacement-controlled pile model unit was emptied after each displacement pile test. The water content of the samples taken at every 50 mm depth from the test soil was checked. After the losses detected in the water content were compensated, the soil was recompressed and placed in the model unit by the calculations.

During the long-term tensile tests, the test piles were examined under constant stress for 24 hours. After the first 24 hours were completed, the tensile stress on the piles was increased and the displacement values were recorded. Reading of values during tensile tests; 5-minute intervals in the first 6 hours, 15-minute intervals in the 6-12 hour period, and 30-minute intervals in the 12-24 hour period. Pile tension tests were repeated at least 4 times for all piles, and continuity was ensured in the experimental results.

During the short-term tensile tests, incremental loads were applied to the test piles at frequent intervals. The piles were examined for 30 minutes under the applied tensile effects, and the start and end readings were obtained. Behavior results of piles under short-term effects were obtained with the pile tensile test carried out in the laboratory. Information about the short and long-term tensile tests within the scope of the study has been shared in Table 3.

Table 3. Short and long-term loading data

Parameters	Short term loading	Long term loading
Loading type	Tensile force	
Total phases	14	2
Stress duration (min)	30	1440
Stress increments (kPa)	3.1	12.3
Initial stress (kPa)	6.2	18.5
Final stress (kPa)	49.3	30.8

To facilitate comparison and interpretation of the displacement values obtained as a result of the pile tensile tests, normalization was performed (Equation 2). Normalized displacement values were obtained using Equation 2. Given in the formula; Δ (mm) represents the displacement as a result of the tensile effect, D (mm) represents the pile diameter and η represents normalized displacement. Since there are piles with different geometric shapes, the diameter value in the equation is calculated as the equivalent diameter for piles other than cylindrical piles.

$$\eta = \frac{\Delta}{D} \times 1000 \quad (2)$$

2.7. Numerical Analysis

The study system, which was modeled and tested in the laboratory, was modeled as a numerical using finite element method software, and numerical analyses were performed. The analysis model was on a 1:1 scale of the model used in the laboratory. The experimental soil was Mohr-Coulomb, and the experimental piles were modeled as volume elements. Experimental results in the laboratory were used to define the material parameters. The existing concrete parameters (C30) were used by modeling the pile elements with the 'Linear-Elastic' and 'Non-porous' material models accepted in the literature [32]. The model information of numerical analyses has been shared in Table 4. Boundary conditions for the numerical model to be compatible with the real model; the xz-plane was fixed in the y-direction, the yz-plane was fixed in the x-direction, the upper surface was free, and the bottom surface was fixed in all directions. In the analyses, the long-term tensile loads applied to the piles were examined by defining the dynamic function. Short-term tensile effects were defined as point load step by step by increasing the load. The solution of the analysis system was carried out using 'stage construction'. Experimental results were reported by obtaining time-normalized displacement and load-settlement curves.

Table 4. Numerical model information

Numerical Analyses		
Model	Scale	1:1
	Soil Mesh Size (cm)	3.5-4-4.5
	Pile Mesh Size (cm)	3.5-4-4.5
Soil	Material Model	Mohr-Coloumb
	Drainage Type	Drained
Concrete Pile	Pile Model	Volume Element
	Material Model	Linear-Elastic
	Drainage Type	Non-Porous

Table 5. Alluvial soil geotechnical index parameters

Soil geotechnical parameters	
Liquid limit (LL)	29
Plastic limit (PL)	NP
Plasticity index (PI)	-
Fine content (-No.200) %	96
Maximum dry unit weight (kN/m^3)	17
Natural unit weight (kN/m^3)	19.8
Optimum water content (%)	16.5
Specific gravity (G_s)	2.7
Unified Soil Classification System (USCS)	ML
Cohesion (kPa)	28
Internal friction angle (°)	33

3. Results and Discussion

3.1. Geotechnical Index Parameters Experiment Results

The shear parameters, specific gravity, particle size distribution, limit values, optimum water content, and unit weight of alluvial soil were obtained through laboratory tests. Based on the test results, it was determined that the alluvial soil exhibits non-plastic (NP) behavior. From tests conducted to determine the particle size distribution of the soil, it was found that the finest content of the soil is 96%, and the soil composition is 5% sand, 25% clay, and 71% silt.

Considering the consistency limit values and particle size distributions, the classification of the alluvial soil was determined as “ML”, which stands for “ fine-grained less sandy, low plasticity clayey silt” according to the Unified Soil Classification System (USCS). The geotechnical parameters of the soil have been presented in Table 5.

3.2. Pile Tension Test and Numerical Results

The behavior of displacement piles in various geometries with different cross-sectional and lateral areas under the effect of tension was investigated by long and short-term tension tests in the laboratory. Time-displacement curves were drawn to understand the behavior of piles under long-term effects. It aimed to find the ultimate capacities of the piles in the soil with short-term tensile tests. The experimental results were interpreted using the 'Tangent Method', which was accepted as a reliable approach [33]. By using finite element method software, 1:1 scale analyses of the study were carried out in the laboratory environment. Results; time-normalized displacement and load-displacement curves. The results obtained as a result of numerical analyses were compared with the results of experimental studies carried out in the laboratory. The time-dependent experimental normalized displacement values of concrete tension piles with displacement properties under long-term tensile effects have been shown as immediate and long-time displacement with phases in Figures 5, 6, and 7.

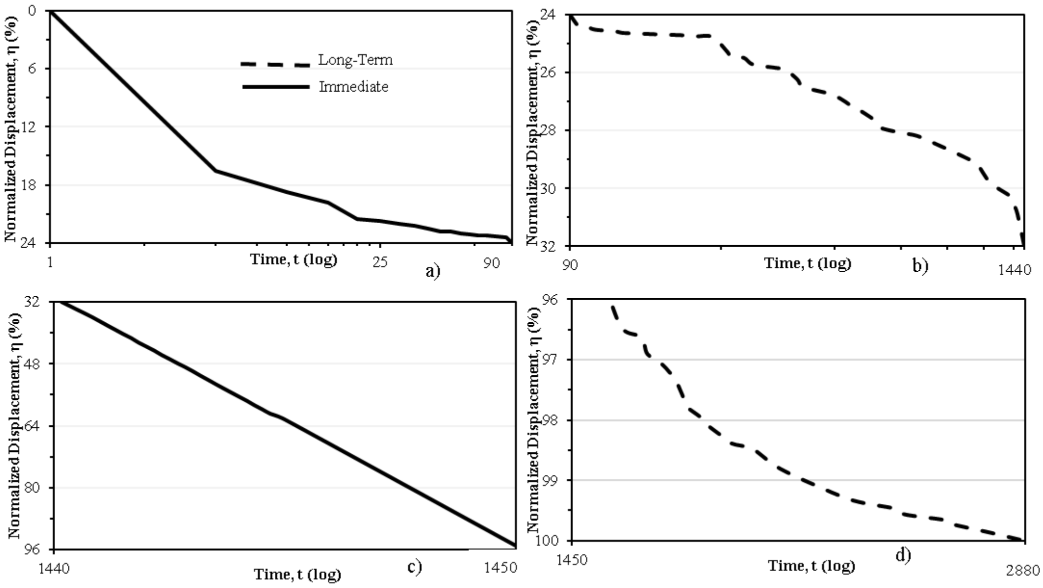

Figure 5. The log(t) – η (%) Curves of Cylinder Piles, a) 1st Phase (Immediate), b) 1st Phase (Long), c) 2nd Phase (Immediate), d) 2nd Phase (Long)

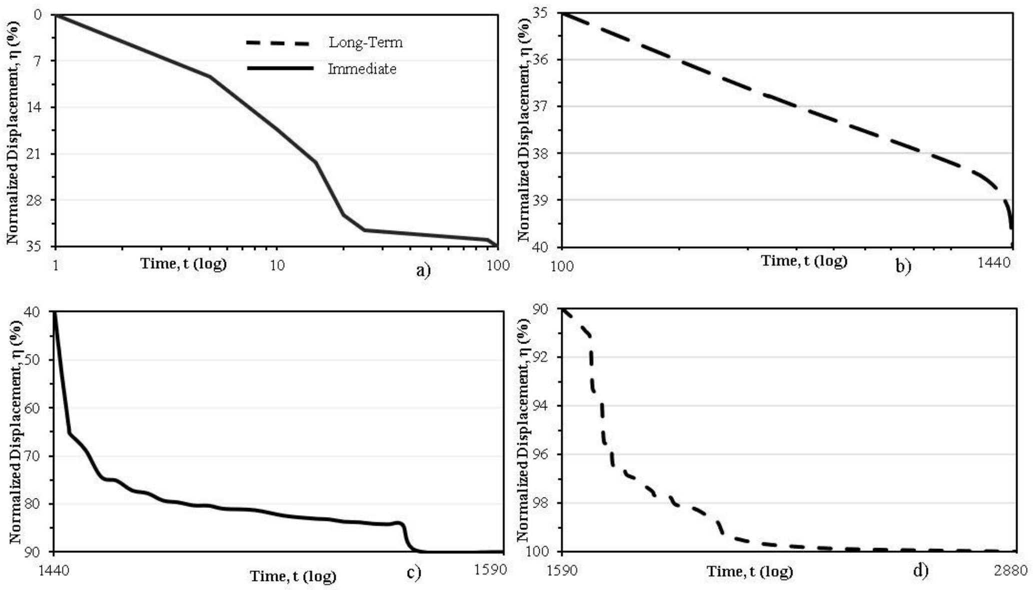

Figure 6. The log(t) – η (%) of 40x40mm Square Piles, a) 1st Phase (Immediate), b) 1st Phase (Long), c) 2nd Phase (Immediate), d) 2nd Phase (Long)

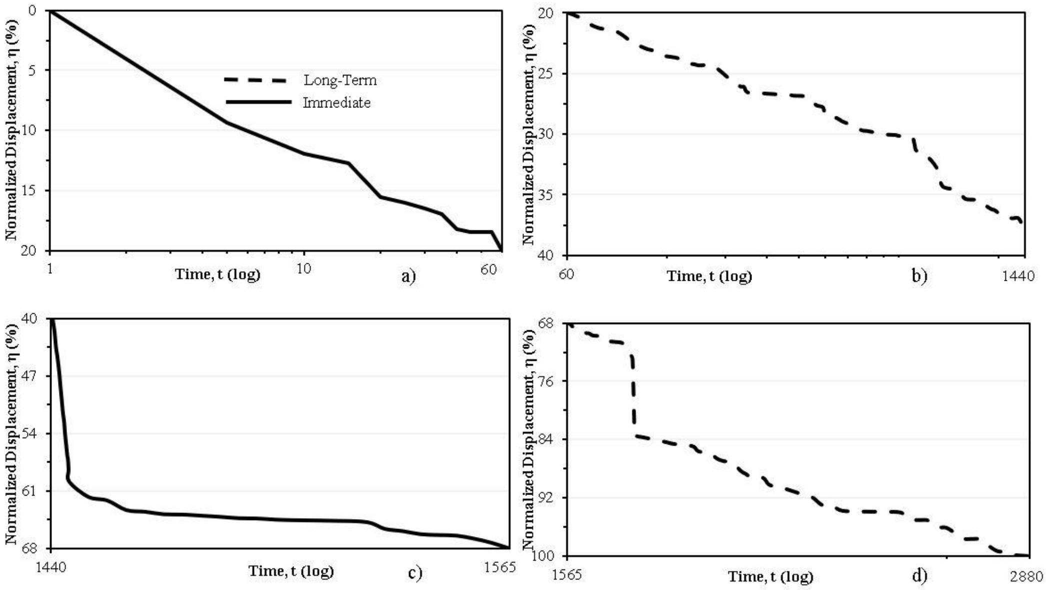

Figure 7. The log(t) – η (%) of 35x35mm Square Piles, a) 1st Phase (Immediate), b) 1st Phase (Long), c) 2nd Phase (Immediate), d) 2nd Phase (Long)

The numerical model results are shown in Figure 8. The data obtained as a result of experimental and numerical analyses were summarized in Table 6. When the time-dependent changes of the normalized displacement values of the piles are examined, it was seen that approximately 25% of the entire displacement occurs, especially in the first 90 minutes following the load increase. When comparing cylindrical and 40x40 mm square displacement piles with an equal cross-sectional area under long-term tension effects, it was revealed that 40x40 mm square piles were exposed to 56% lower displacement.

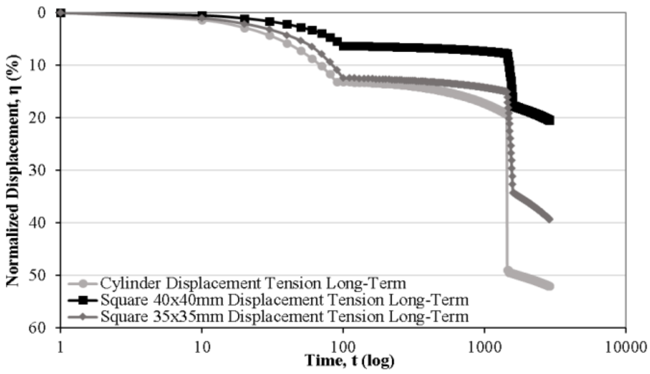

Figure 8. Displacement tension piles numerical results

Table 6. Long-term loading results

Results	Experimental results			Numerical results		
Pile	Cylinder	40x40 square	35x35 square	Cylinder	40x40 square	35x35 square
Tension stress (kPa)	30.84	30.84	30.84	30.84	30.84	30.84
Normalized displacement	48	21	37	52.2	20.2	39.6

It is seen that there were similar behaviors in the studies in the literature on cylindrical and square piles on the determination of the pile-bearing capacity [34]. In this examination, which was carried out by keeping the cross-sectional areas equal, it was understood that the geometric shape has a significant effect on pile behavior. In experimental studies on tension piles of the same geometric shape, it was seen that the increase in the cross-sectional area directly affects the pile-bearing capacity, and the increase in the cross-sectional area was directly proportional to the pile-bearing capacity [35].

When cylindrical and 35x35 mm square displacement piles with equal lateral area were compared, it was seen that 22.9% lower displacement occurs in 35x35 mm square piles. Although cylindrical piles had a larger cross-sectional area compared to 35x35 mm square piles, it was understood that the geometric effect was one of the determining factors in piles under tension effect.

The short-term test results have been given in Figures 9, 10, and 11. As a result of the load capacity determinations of the cylinder and square piles accepted in the literature within the scope of the experiment, different results were obtained from long-term investigations. According to the test results, piles with cylindrical sections, which were exposed to the greatest displacement in long-term tensile effect, were in second place in terms of load-bearing capacity.

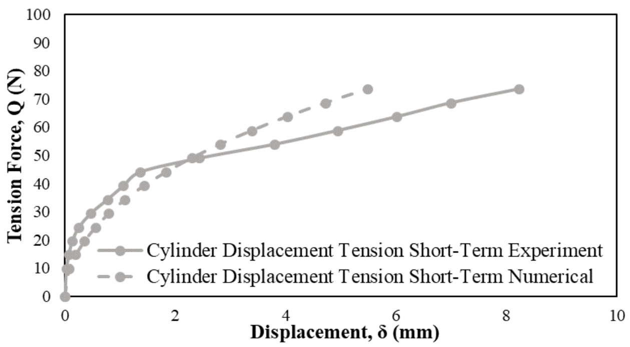

Figure 9. Cylinder displacement piles short-term results

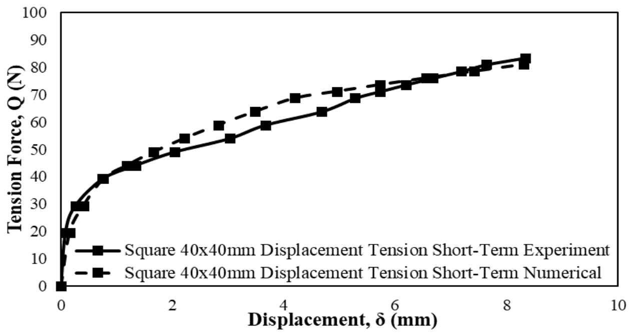

Figure 10. Square (40x40mm) displacement piles short-term results

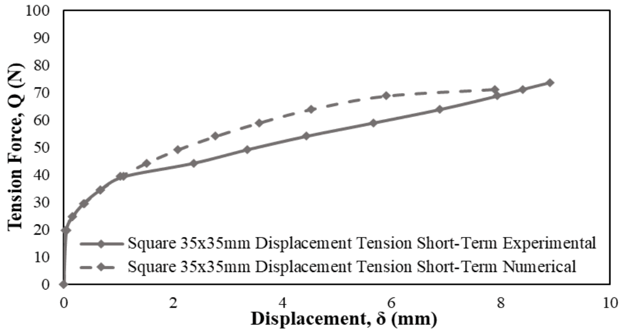

Figure 11. Square (35x35mm) displacement piles short-term results

Low displacement of piles under long-term stress effects compared to piles under short-term effects; could also be explained by the thixotropic property, which was observed in soils with high fine-grain ratio soils. The disturbance of the soil through compaction leads to the alteration of its original structure and can result in sudden drops in its mechanical properties. However, in soils that exhibit thixotropic behavior, ceasing the compaction process can lead to changes in the soil's mechanical properties and a gradual return to its previous strength values [36]. It’s known that a significant portion of soils showing thixotropic behavior are constituted by sediment deposits [37].

As a result of numerical model studies, the displacements around the pile caused by the short and long-term tensile effect applied to the piles have been shown in Figures 12, 13, and 14. As indicated in Figures 13 and 14, it could be seen that under the short-term tensile effects of square piles, the acting load cannot spread around the embedded surface of the pile and the surface friction mechanism could not be activated throughout the embedded depth of the pile. In piles under long-term effects, displacements occurred on the pile surface along the pile embedded depth. This indicates that the long-term effects were transmitted to the pile surface perimeter and the effects were countered by spreading over a much larger area.

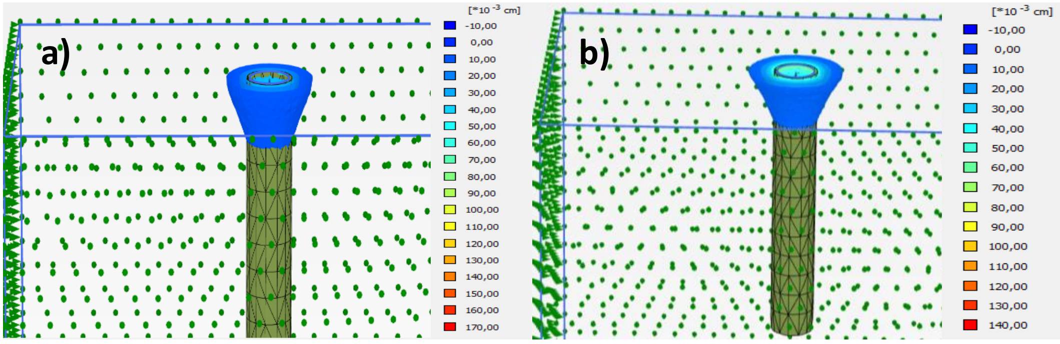

Figure 12. Numerical behavior model of cylinder piles under a) short-term and b) long-term loading

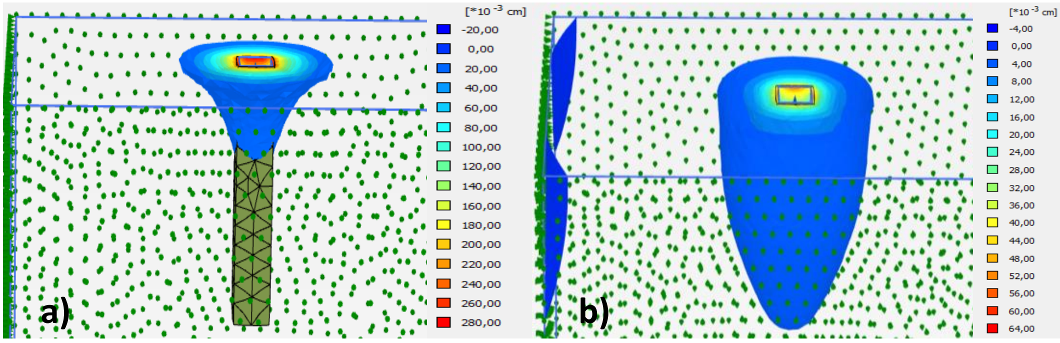

Figure 12. Numerical behavior model of square 40x40mm piles under a) short-term and b) long-term loading

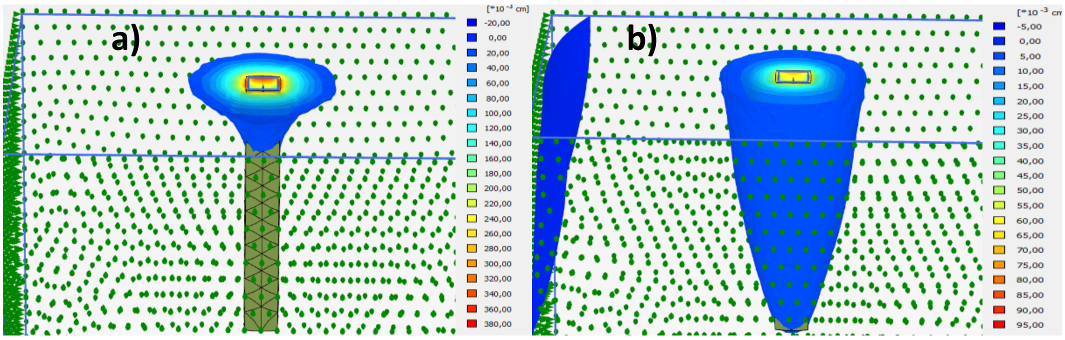

Figure 13. Numerical behavior model of square 35x35mm piles under a) short-term and b) long-term loading

As a result of numerical studies, the soil displacement around different piles, the distribution of soil movement along the length of the pile, and the affected soil surroundings have been examined. The obtained results are presented in Table 7. During the long-term effects, the disturbance range around the pile and disturbance length along the pile have increased compared to short-term loading.

Table 7. Numerical results of soil movement

Pile Type	Short - Term			Long - Term		
	Pile Around Normalized Displacement (η)	Disturbance Range (mm)	Disturbance Length (mm)	Pile Around Normalized Displacement (η)	Disturbance Range (mm)	Disturbance Length (mm)
Cylinder	15.5	250	60	13.33	230	80
40x40 Square	48.78	195	80	8.87	180	270
35x35 Square	65.82	220	120	12.15	180	300

3.3. Discussion

Based on experimental and numerical studies, it has been observed that under long-term tensile effects, the lowest displacements occurred at 40x40 square piles. The results of the numerical analysis support the findings of the experimental studies. When examining the behavior of piles with equal cross-sectional area and equal lateral area, it was observed that cylindrical piles exhibit the highest displacements among the studies.

When examining the effect of cross-sectional properties on the behavior of concrete piles under tensile effects, it was found that the displacement piles with corners had higher tensile load capacities. This observation indicates that the piles with corners exhibit stronger pile-soil interactions due to their shape. The results regarding long-term effects are presented in Table 8.

Table 8. Experimental and numerical comparison of long-term effect

	Equal Cross Section Area		Equal Lateral Area	
Pile	40x40 Square	Cylinder	35x35 Square	Cylinder
Experimental Normalized Displacement, η	21	48	37	48
Square - Cylinder Normalized Displacement Difference (%)	+132.5		+29.7	
Numerical Normalized Displacement, η	20.2	52.2	39.6	52.2
Square - Cylinder Numerical Normalized Displacement (%)	+144		+26.8	
Experimental - Numerical Normalized Displacement Change (%)	-1.06	+3.85	+6.2	+3.85

When comparing the results of pile behavior under short-term effects, it can be observed that 40x40 square-sectioned concrete piles have the highest tensile load capacity. The numerical analysis results were found to be similar to the experimental results. The highest resemblance between experimental and numerical results was observed in cylindrical piles. The results under short-term effects are shared in Table 9.

Table 9. Experimental and numerical comparison of short-term effect

Parameter	Equal Cross Section Area		Equal Lateral Area	
Pile	40x40 Square	Cylinder	35x35 Square	Cylinder
Experimental Q (N)	42	38	36	38
Experimental Q (N) Difference	-9.5		+5.5	
Numerical Q (N)	58	38	44	38
Numerical Q (N) Difference	-34.5		-13.6	
Experimental - Numerical Q (N) Change (%)	+38.1	0	+22.2	0

4. Conclusion and Suggestions

In this study, the behavior of concrete piles with different geometrical properties placed on the soil by the driving method under the effect of tension was investigated. As a result of the experiments, the following results were obtained.

- Studies show that the behavior of piles in long-term applications was different from short-term pile tensile tests. It was understood that the pile-bearing capacity increases with time. It has been observed that the adhesion between the pile surface and the soil increases in direct proportion to time in soils with a high fine grain ratio, and the grains bonding with the pile surface create a surface thickness on the pile surface, improving the surface friction effect over long periods.
- The thixotropic mechanism seen in fine-grained cohesive soils significantly affected the displacement and behavior of the piles depending on the load application time. Under long-term load

effects, the soil gained its initial strength in direct proportion to the time and this mechanism affects the relations between the pile-soil and increased pile bearing capacity.

• When the numerical analyses and experimental study results were compared, the model scale effect was examined. The lab model was a 5.6% scaled version of the field model. In this context, the scale effect directly affected the virtual surface thickness and surface stiffness, especially between the pile surface and the soil. Within the scope of numerical studies, the surface friction coefficient was used by decreasing it by the model scale.

Studies have revealed the effects of tensile load time on pile behavior and the importance of pile geometry. Since there are many parameters affecting the pile behavior, it is understood that results close to the real field behavior will only be possible with experiments to be carried out by focusing on specific points in the laboratory environment. It is understood that the interaction between pile-soil is directly dependent not only on soil shear parameters and pile surface roughness but also on the period of the tension effect and the geometry of the structural pile element. For the pile behavior to converge to the expected behavior in the field, it is of great importance to carry out detailed studies on the scale models to be created in the laboratory environment and to determine the parameters used in numerical analyses specific to the situation.

Contributions of the authors

All authors contributed equally to the study.

Conflict of Interest Statement

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The study complies with research and publication ethics

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