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Experimental Investigation of Piles Behavior Subjected to Lateral Soil Movement†

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ABSTRACT

In this study, the behaviour of vertical piles installed to increase slope stability under lateral soil movement is observed by model tests conducted in a specially built large scale shear box in the geotechnics laboratory of Yıldız Technical University. Laboratory model tests were carried out on sandy soil slopes stabilized with piles. A row of four 800 mm long aluminum pipes with a diameter of 35 mm and wall thickness of 5 mm were used. Pile heads were connected to each other by means of an aluminum beam. Single row was subjected to loading due to lateral soil movement. Deformations and bending moments developed in the pile sections were measured by strain gauges attached at different points along the pile lengths. The results obtained from the experiments are compared with the methods found in the literature to contribute to a better understanding of this complicated geotechnical problem.

Keywords: *Slope stability, lateral soil movement, pile, large scale shear box.*

1. INTRODUCTION

Landslides is among the most complicated subjects of Geotechnical engineering. Slides may occur due to various reasons and in several different forms resulting in colossal material loss and even lead to deaths. Therefore the investigation and prevention of landslides has always been a current issue.

The stability of non-equilibrium slopes could be increased by employing different methods such as changing the geometry of the slope, carrying out surface and subsurface drainage, using soil improvement techniques, installing permanent or temporary retaining structures (walls or bored piles). The first remedy leads to a reduction of the driving forces for failure, the other measures an increase of the resisting forces. Construction of a retaining wall before the sliding mass of soil may be necessary in order to stabilize driving forces. As classical walls require large amounts of excavation, they do not always provide a cost-effective solution. What's more, the mass of soil resulting from excavation may reduce the resisting forces, resulting in a slide of the slope. The great vibrations that form during the construction of a deep sheetpile curtain may decrease safety in a slope. Piles carried across

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the active or potential failure surface can be used efficiently as the retaining element, since they can often be installed without disturbing significantly the equilibrium of the slope.

Piles subjected to lateral soil movements are known as passive and are usually used in a row. With an accurate design, piled stability systems are effective in supporting the slopes and in the prevention of slope movements in poor bearing soils. The transfer of soil loads resulting from lateral soil movements to the piling elements is a complicated issue of soil-structure interaction (it depends on many factors related to deformation and moment features both the soil and the pile). And significant differences among design methods of piled stability point to the fact that improvement mechanisms are not totally understood. The downward soil movement during slope slides bring about lateral load distributions that are difficult to calculate on stability piles. A reliable estimation of these load distributions is important because the effect of piles on the general stability of slopes directly depends on the loading of piles.

All design methods rely on the estimation of the force acting on the row of piles by extending the value that is found for only one pile. Such an approach could be applied for active piles but may not be valid for passive piles because in the case of active piles, the acting lateral forces are predetermined and are not influenced by the existence of the pile. In case of passive piles, the presence of a pile affects the lateral force that acts on the pile. Therefore, at the beginning of the analysis, it is necessary to consider the stability piles one by one in a row.

One of the most important points that have to be solved in the passive piles is the precise estimation of the lateral stress acting on the pile due to soil movements. The calculation of the lateral resistance of piles is possible with the knowledge of the direction and magnitude of the acting lateral force. Due to the complex mechanism of the lateal force resulting from the pile-soil interaction, the lateral forces acting on one pile and pile row could be estimated with experimental methods supposing that the soil around the pile is a visco liquid [1]. However, while overestimating the lateral force may provide uneconomical results in pile stability and provides a higher safety number for slope stability, underestimation of the lateral force leads to results exactly opposite. Ito and Matsui [2] conducted a series of model experiments on this issue. In slope stability analyses, the place of sliding surface could be predetermined thanks to land inspections. There are many factors acting on the pile in such a slope. These factors include the distance of piles, pile head fixity condition, the length of piles on sliding surface, pile diameter and the rigidity of piles.

To provide slope stability, most studies that have been conducted so far have employed both numerical [1-3] and experimental [6-13] methods by using various finite elements programs in order to determine the lateral behavior during soil movement of vertical piles to be install in slope. Because slope safety is directly related to the manner in which piles are loaded, it is important to realistically determine the distribution of loads transferred to the piles from the soil. There are empirical methods based on the field and laboratory experiments [1-2, 13-15] in order to estimate the loads resulting from moving soil mass, analysis methods based on the magnitude and shape of lateral soil displacement, and finite elements methods. However, these methods fail to reflect the changes in the behavior of pile group due to soil properties, the distance between piles, and pile rigidity. For this reason, a generally accepted dimensioning method has not yet been established.

In this study, large-scale model experiments were conducted in order to precisely and orally determine the transfer of soil loads resulting from lateral soil movements to pile elements and the deformations and bending moments developed in pile sections. Based on pile and soil properties, Brinch-Hansen [16], Subgrade Reaction [17-18] and Broms Methods were employed, section of piles deformed by lateral loads were analyzed and the maximum bending moments and points in the pile sections were determined and the results were compared with the experimental results.

2. EXPERIMENTAL WORK

2.1. Large Scale Shear Box

The behavior of vertical piles installed to increase slope stability under lateral soil movement was observed by model tests conducted in a specially built large scale shear box

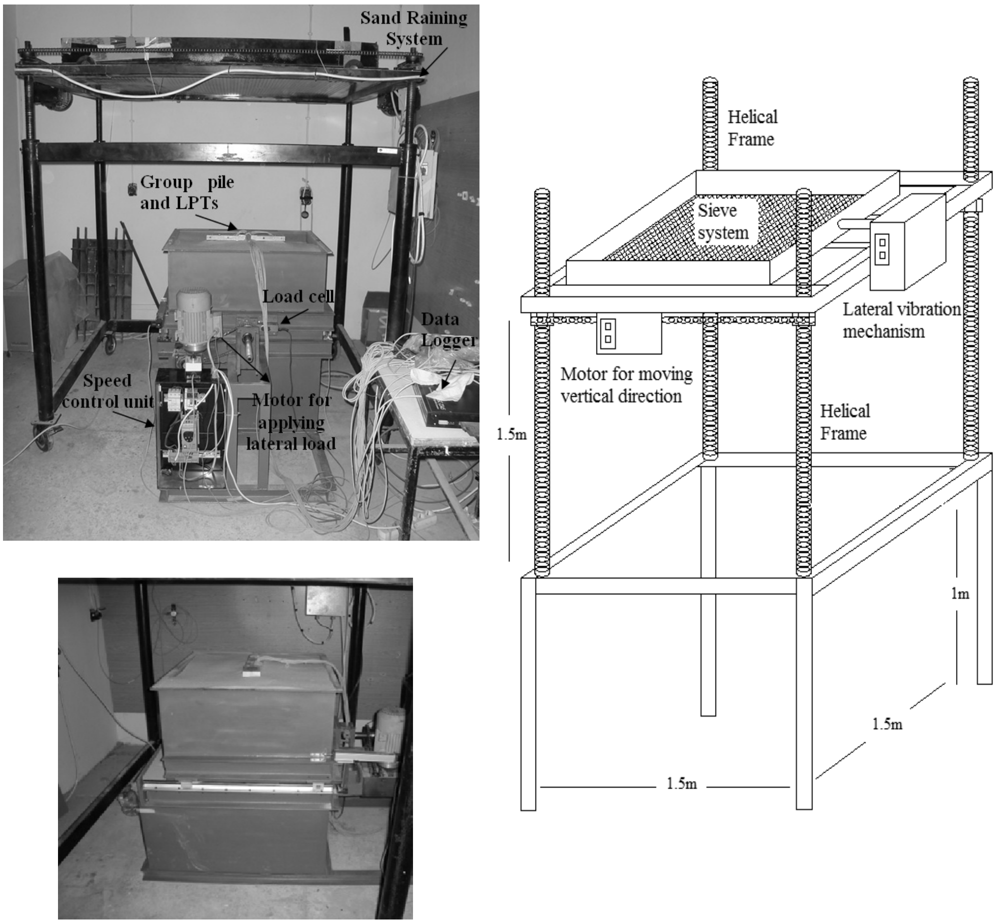


Figure 1. Experimental Setup and Sand Raining Technique

which consists of two different pieces in the geotechnics laboratory of Yıldız Technical University. The shear box apparatus included motor, speed control unit and load cell. The upper box (moveable part) was 77 cm wide, 70 cm long and 45 cm high. The lower box was 77 cm wide, 85 cm long and 45 cm high. The upper box could move above the lower box when the lateral load was applied the upper box by using a motor and a speed control unit (Figure 1). The sand was used for the all model tests. To achieve a uniform deposit with the desired density, the sand raining technique was used. The dimension of this system was 1.5 m x 1.0 m x 1.0 m at base. The sieve system (sieves can adjust different spaces) could be moved along the helical frame by the motor. The vibration system which has adjustable frequency was connected the sieve system. To obtain the desirable density of sand, the sieve system should be run with the controlled velocity and desired vibration frequency. Details of the sand raining technique is shown in Figure 1. Also, to check the desirable density of sand in the shear box, several metal cans placed in the sand bed at different locations and depth during its deposition were done. After the tests, these cans were removed and density of sand was determined and it's compared with the desirable density.

2.2. Properties of Sand

The sand used for all the model tests has Quartz obtained from Şile. Various testing procedures were carried out to determine the grain size distribution curve, specific gravity and maximum and minimum dry unit weights. The results of the grain size distribution is presented in Figure 2. Also, the physical properties of tested sand are shown in Table 1. Also, the direct shear tests were performed to find out the angle of internal friction of sand at the different ralative density.

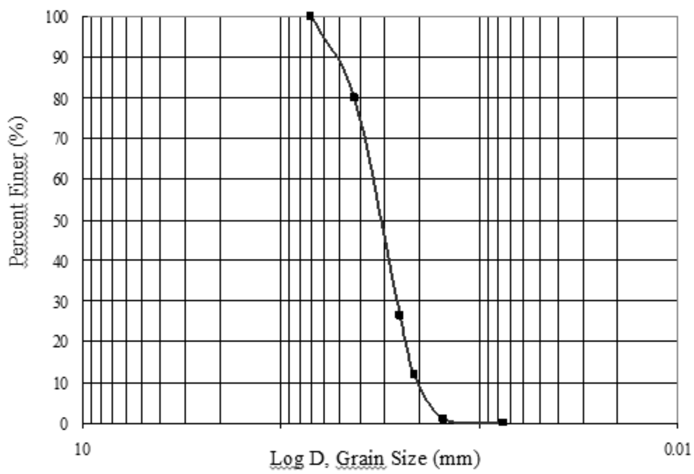


Figure 2. Grain Size Distribution of Sand

Table 1. Physical Properties of Sand

Soil Classification (USCS)	SP
Specific Gravity, G_s	2.65
Mean Partical Size, D_{50} (mm)	0.31
Maximum Void Ratio, $e_{\max}$	0.87
Minimum Void Ratio, $e_{\min}$	0.53
Maximum Dry Unit Weight, $\gamma_{k,\max}$ (kN/m^3)	17.0
Minimum Dry Unit Weight, $\gamma_{k,\min}$ (kN/m^3)	13.9

Table 2. Properties of Strength for Sand

Relative Density, D_r (%)	Angle of Friction, ϕ (^{o})
50	36.7
60	37.4
70	38.5

2.3. Pile Group and Instrumentation

In this study, 800 mm long aluminum pipes with a diameter of 35 mm and wall thickness of 5 mm were used. Fixed head pile group subjected to the lateral load consists of 4 piles in a row. Pile group was installed in the shear box in the perpendicular direction to the direction of the soil movement. As shown in Figure 3, center to center spacing of 2.7 times the pile diameter (s/d=95/35) and this ratio is acceptable value for the pile groups subjected to the lateral soil movement.

In this research, three different instruments were used; (i) strain gauges attached along the pile length, (ii) lineer position transducers (LPT) attached to the pile head and upper shear box, (iii) load cell placed in front of the movable upper shear box. Datas from all these devices were digitally transferred to the data acquisition system.

Pile group was subjected to loading due to lateral soil movement. Deformations and bending moments developed in the pile sections were measured by strain gauges attached at different points along the pile length. Lateral pile head displacement measurements were measured by utilizing LPTs. Strain gauges were attached along the inner surface (same direction) of the pile at different points (Pile 1 (corner pile) and Pile 3 (center pile)) against the soil movement. Pile tips were covered with the shutters. In this way, strain gauges were protected from damages due to sand during the sand raining and lateral soil movement. Instrumentation of pile with the intervals of strain gauges is given in Figure 4. Each pile had 5 strain gauges named G1, G2, G3, G4 and G5 in total. To measure the lateral displacement of the pile cap, two LPT were attached the right and left side of pile cap (LPT1 and LPT2). Also, LPT4 was attached near of the pile tip to measure the potential displacement during the loading. Besides, LPT3 was placed the shear box to determine the relative displacement of the upper box according to the lower box.

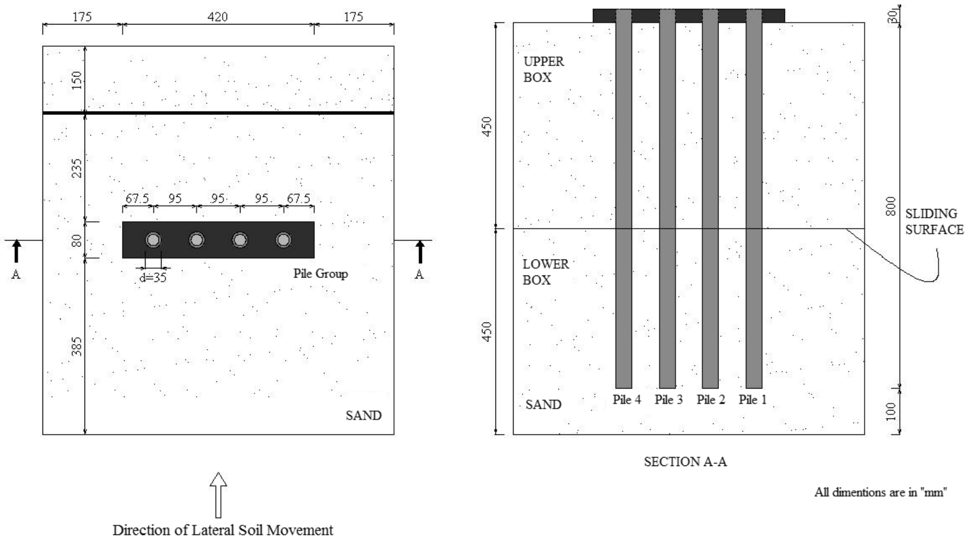


Figure 3. The geometry of pile group investigated

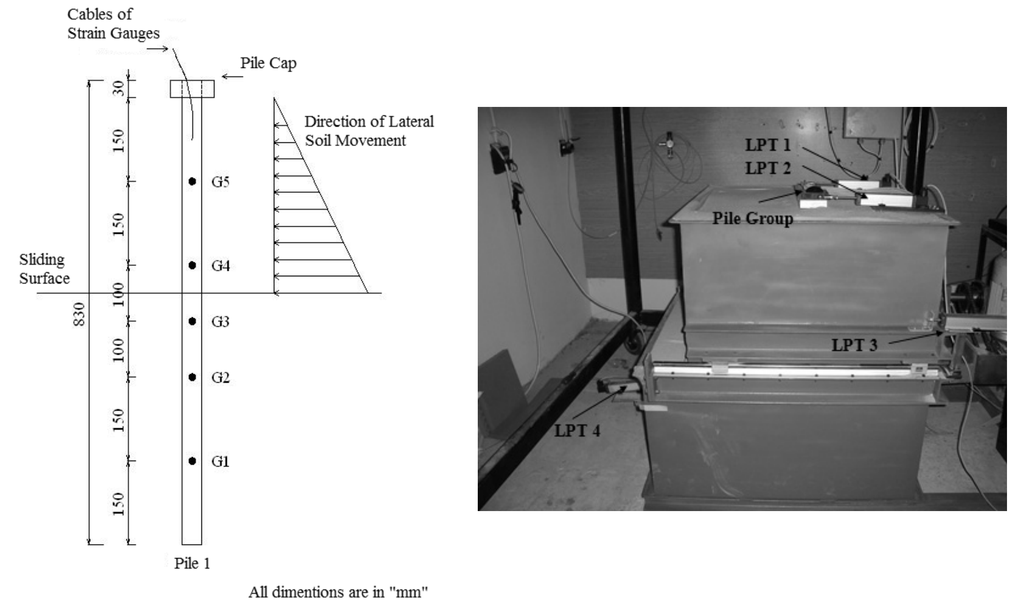


Figure 4. Instrumentation of Model Tests

In the performed tests, to obtain the bending moment behavior of the pile group subjected to lateral soil movement, strain gauges were attached on the surface of the piles named Pile 1 and Pile 3. Gauges were located from under the pile cap to the pile tip depth of 150, 300, 400, 500 and 650 mm respectively. Thus, each pile had 5 strain gauges in total (two strain gauges were attached above the sliding surface and three strain gauges were attached below the sliding surface). For each pile, the bending moment distribution with depth during the loading was determined from the obtained strains. Lateral pile head displacement measurements were done by utilizing lineer position transducers (LPT1 and LPT2). Also, relative displacement measurements were done by using LPT3 placed on upper shear box. Details of tests are given by Özçelik (2007) [20].

3. EXPERIMENTAL RESULTS

Pile group, installed the large scale shear box filled sand (with different relative density (50%, 60% and 70%)) by raining technique, was subjected to lateral soil movement due to moving upper box. After the tests, bending moment distribution and lateral head displecement of piles were obtained. The results are shown in Figure 5-8. It can be seen that the maximum bending moment in the pile section that under the sliding surface increases as the relative density of sand decreases. The maximum bending moment on Pile 1 is higher than the maximum bending moment on Pile 3 as expected for pile groups subjected to lateral soil movement. As shown in Figure 9, for pile group placed in sand with 70% relative density, when the shear box moves 140 mm in the lateral direction, pile head displacement is 35 mm at the final lateral load of 2.21 kN (reading from load cell). For other tests with different relative density of sand, lateral pile head displacement measurements increase as the relative density decreases. As shown in figure, after a little displacement of shear box (~5mm), the value of load reading from load cell do not change, but shear box displecement measurements continue to increase. This indicates that the additional soil movement has no more influence on the load transfer mechanism (between pile and soil) and failed pile element is incapable of carrying additional load.

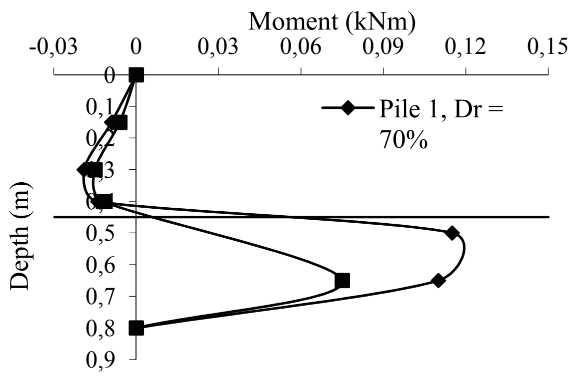


Figure 5. Distribution of Bending Moment (For Dr=70%)

For 70% relative density of sand, it can be seen that, when the pile group's subjected to loading due to lateral soil movement, the maximum bending moment of corner pile (Pile 1) is 0.123 kNm at a depth of 0.55 m. Also, the maximum bending moment of center pile (Pile 3) is 0.075 kNm at a depth of 0.65 m.

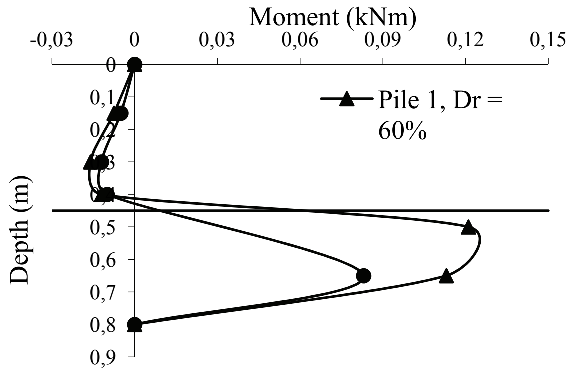


Figure 6. Distribution of Bending Moment (For Dr=60%)

For 60% relative density of sand, it can be seen that, when the pile group's subjected to loading due to lateral soil movement, the maximum bending moment of corner pile (Pile 1) is 0.128 kNm at a depth of 0.55 m. Also, the maximum bending moment of center pile (Pile 3) is 0.083 kNm at a depth of 0.65 m.

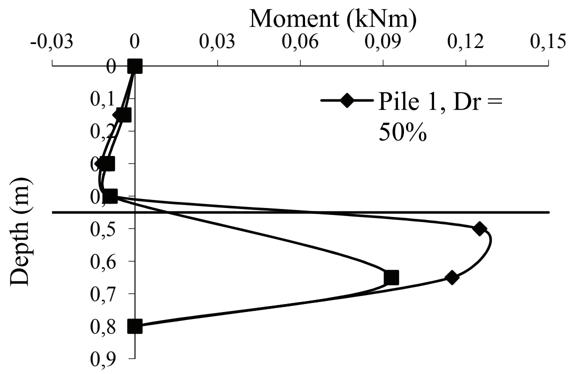


Figure 7. Distribution of Bending Moment (For Dr=50%)

For 50% relative density of sand, it can be seen that, when the pile group's subjected to loading due to lateral soil movement, the maximum bending moment of corner pile (Pile 1) is 0.130 kNm at a depth of 0.55 m. Also, the maximum bending moment of center pile (Pile 3) is 0.093 kNm at a depth of 0.65 m.

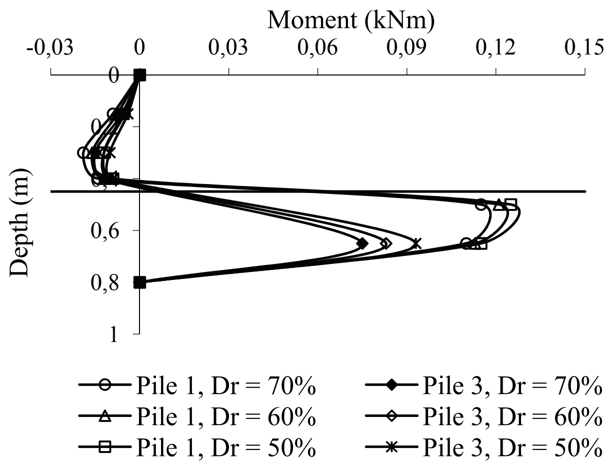
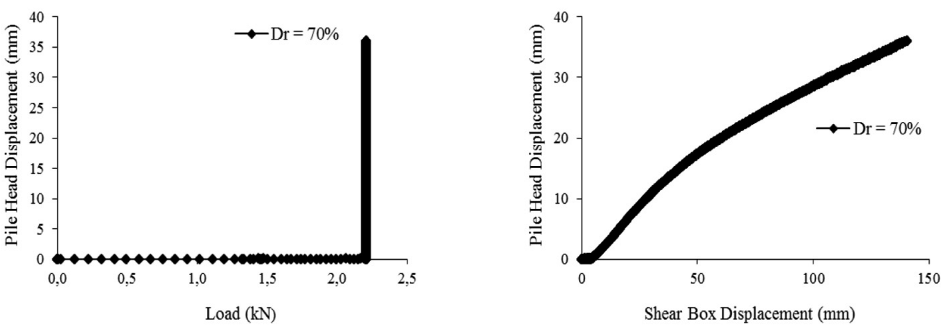


Figure 8. The Comparision of Bending Moment Distributions for Dr= %70, %60, %50



(a) (b)

Figure 9. For D_r = 70% -Relative Density of Sand, (a) Distribution of Pile Head Displacement vs. Load, (b) Distribution of Pile Head Displacement vs. Shear Box Displacement

The summary of the model test results is shown in Table 3 that contain the maximum moment values with depth for corner pile (Pile 1) and center pile (Pile3) at different relative density of sand.

Table 3. The Summary of Results From Model Tests

	$M_{max,1}$ (kNm)	Depth(m)	$M_{max,3}$ (kNm)	Depth(m)	y_x (mm)
D_r = % 70	0.123	0.55	0.075	0.65	35.00
D_r = % 60	0.128	0.55	0.083	0.65	36.34
D_r = % 50	0.130	0.55	0.093	0.65	37.05

The measured load-displacement relationship of the shear boxes indicates the contribution of the pile to the shear strength of the system. It is seen that, the measured loads (by load cell) in case of box filled with sand in a test without piles and with piles until the box movement reach 140 mm. Firstly, load measurements were done by load cell when the lateral soil movement was applied the shear box without piles. Then, load measurements were done when the lateral soil movement was applied the shear box with piles. The difference between the reinforced soil load and the unreinforced soil load, for a given shear box displecement, is the load applied to the pile. The value of total load applied to the pile group, ΔFr, is used for estimating the load distribution along the piles with the increasing lateral translation of soil. A graph of load vs.displacement is shown in Figure 10. In Figure 10, the unreinforced load is 0.96 kN and the reinforced load is 2.21 kN. The load carried by the pile group is 1.25 kN (ΔFr). That value is approximately 0.32 kN for each pile in a group consists of 4 piles in a row.

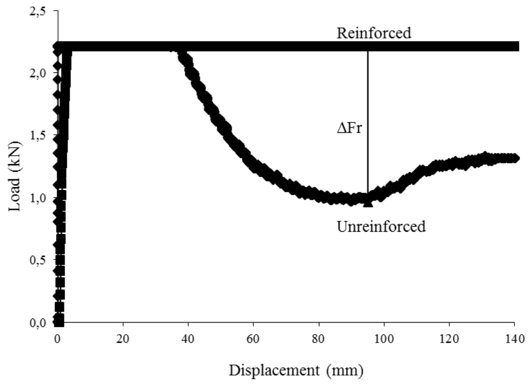


Figure 10. For Dr = %70 of relative density of sand, Graph of Load vs. Shear Box Displacement

3.1. Estimating the Behavior of Piles By Using Empirical Correlations

In this study, lateral reaction force (for a pile section above the sliding surface) exerted on the slope by the pile and maximum bending moment values on Pile 1 and Pile 3 (corner and center piles) were measured by experimental tests. Then, lateral load values (which were corresponding to bending moment values obtained from tests) were calculated via the methods found in the literature. These lateral load values were compared with the lateral load values obtained from experimental tests. As it is known, (the vertical piles subjected to the lateral soil movement in sandy soils), the lateral load acting on pile section above the sliding surface increases linearly with depth from the ground surface to the sliding surface (Figure 4) and the lateral load acts at one-third of the height of the section above the sliding surface. Also, the effect of the ratio of calculated load (by using different methods) – measured load (by experimental tests) was investigated if the lateral load acts at different height of the pile section (getting close to the ground surface).

For a pile in pile group, lateral reaction force exerted on the slope by the pile was measured 0.32 kN by tests. By considering the lateral load acts at one-third of the height of the pile section ($H/3$ = 0.15 m) above the sliding surface (H = 0.45 m), piles (Pile 1 and Pile 3) were analyzed by the Brinch-Hansen, Subgrade Reaction, and Broms methods. The results are shown in Table 4, Table 5 and Table 6. Also, the lateral load values corresponding to maximum bending moment values (for Pile 1 and Pile 3) from tests were calculated by using these methods.

Table 4. The Results By Using Brinch-Hansen Method (Lateral Load Acts at H/3)

	Brinch – Hansen Method			
	M_{max} (kNm)	Depth(m)	The Lateral Load For $M_{max,1}$(kN)	The Lateral Load For $M_{max,3}$(kN)
D_r = 70%	0.386	0.6208	0.640 (loc.: 0.53 m)	0.422 (loc.: 0.51 m)
D_r = 60%	0.336	0.6197	0.646 (loc.: 0.54 m)	0.453 (loc.: 0.51 m)
D_r = 50%	0.298	0.6195	0.648 (loc.: 0.54 m)	0.495 (loc.: 0.51 m)

Table 5. The Results By Using Subgrade Reaction Method (Lateral Load Acts at H/3)

	Subgrade – Reaction Method			
	M_{max} (kNm)	Depth(m)	The Lateral Load For $M_{max,1}$(kN)	The Lateral Load For $M_{max,3}$(kN)
D_r = 70%	0.0688	0.600 (y_x = 3.12 mm)	0.572 (loc.: 0.60 m) (y_x = 5.58 mm)	0.349 (loc.: 0.60 m) (y_x = 3.40 mm)
D_r = 60%	0.0734	0.620 (y_x = 4.45 mm)	0.558 (loc.: 0.62 m) (y_x = 7.76 mm)	0.362 (loc.: 0.62 m) (y_x = 5.03 mm)
D_r = 50%	0.0756	0.632 (y_x = 5.17 mm)	0.551(loc.:0.632 m) (y_x = 8.90 mm)	0.394(loc.:0.632 m) (y_x = 6.36 mm)

For a pile in group, piles were analyzed by considering the lateral load (0.32 kN) acting at $5H/12$ ($5H/12$=0.1875m) of the height of the pile section above the sliding surface (H = 0.45 m). The results are shown in Table 7, Table 8 and Table 9.

Table 6. The Results By Using Broms Method (Lateral Load Acts at H/3)

	Broms Method			
	M_{max} (kNm)	*Depth(m)*	*The Lateral Load For $M_{max,1}$(kN)*	*The Lateral Load For $M_{max,3}$(kN)*
D_r = 70%	0.112	0.750	0.345 (loc.: 0.761 m)	0.234 (loc.: 0.706 m)
D_r = 60%	0.114	0.760	0.349 (loc.: 0.774 m)	0.250 (loc.: 0.724 m)
D_r = 50%	0.116	0.768	0.350 (loc.: 0.783 m)	0.270 (loc.: 0.742 m)

Table 7. The Results By Using Brinch-Hansen Method (Lateral Load Acts at 5H/12)

	Brinch – Hansen Method			
	M_{max} (kNm)	*Depth(m)*	*The Lateral Load For $M_{max,1}$(kN)*	*The Lateral Load For $M_{max,3}$(kN)*
D_r = 70%	0.446	0.6208	0.553 (loc.: 0.53 m)	0.359 (loc.: 0.51 m)
D_r = 60%	0.338	0.6197	0.557 (loc.: 0.53 m)	0.384 (loc.: 0.51 m)
D_r = 50%	0.344	0.6195	0.558 (loc.: 0.54 m)	0.423 (loc.: 0.50 m)

Table 8. The Results By Using Subgrade Reaction Method (Lateral Load Acts at 5H/12)

	Subgrade – Reaction Method			
	M_{max} (kNm)	*Depth(m)*	*The Lateral Load For $M_{max,1}$(kN)*	*The Lateral Load For $M_{max,3}$(kN)*
D_r = 70%	0.0781	0.600 (y_x = 3.47 mm)	0.504 (loc.: 0.60 m) (y_x = 5.47 mm)	0.307 (loc.: 0.60 m) (y_x = 3.33 mm)
D_r = 60%	0.0828	0.620 (y_x = 4.92 mm)	0.495 (loc.: 0.62 m) (y_x = 7.61 mm)	0.321 (loc.: 0.62 m) (y_x = 4.93 mm)
D_r = 50%	0.0849	0.632 (y_x = 5.69 mm)	0.490(loc.:0.632 m) (y_x = 8.71 mm)	0.350(loc.:0.632 m) (y_x = 6.22 mm)

Table 9. The Results By Using Broms Method (Lateral Load Acts at 5H/12)

	Broms Method			
	M_{max} (kNm)	*Depth(m)*	*The Lateral Load For $M_{max,1}$(kN)*	*The Lateral Load For $M_{max,3}$(kN)*
D_r = 70%	0.124	0.750	0.318 (loc.: 0.749 m)	0.214 (loc.: 0.695 m)
D_r = 60%	0.126	0.760	0.324 (loc.: 0.762 m)	0.229 (loc.: 0.713 m)
D_r = 50%	0.128	0.768	0.325 (loc.: 0.771 m)	0.248 (loc.: 0.730 m)

For a pile in group, piles were analyzed by considering the lateral load (0.32 kN) acting at *H/2* (*H/2*=0.225m) of the height of the pile section above the sliding surface (H = 0.45 m). The results are shown in Table 10, Table 11 and Table 12.

Table 10. The Results By Using Brinch-Hansen Method (Lateral Load Acts at H/2)

	Brinch – Hansen Method			
	M_{max} (kNm)	Depth(m)	The Lateral Load For $M_{max,1}$(kN)	The Lateral Load For $M_{max,3}$(kN)
D_r = 70%	0.505	0.6208	0.481 (loc.: 0.52 m)	0.310 (loc: 0.50 m)
D_r = 60%	0.440	0.6197	0.487 (loc.: 0.52 m)	0.332 (loc.: 0.50 m)
D_r = 50%	0.390	0.6195	0.490 (loc.: 0.53 m)	0.366 (loc.: 0.50 m)

Table 11. The Results By Using Subgrade Reaction Method (Lateral Load Acts at H/2)

	Subgrade – Reaction Method			
	M_{max} (kNm)	Depth(m)	The Lateral Load For $M_{max,1}$(kN)	The Lateral Load For $M_{max,3}$(kN)
D_r = 70%	0.0875	0.600 (y_x = 3.83 mm)	0.450 (loc.: 0.60 m) (y_x = 5.38 mm)	0.275 (loc.: 0.60 m) (y_x = 3.29 mm)
D_r = 60%	0.0922	0.620 (y_x = 5.38 mm)	0.445 (loc.: 0.62 m) (y_x = 7.49 mm)	0.289 (loc.: 0.62 m) (y_x = 4.86 mm)
D_r = 50%	0.0943	0.632 (y_x = 6.21 mm)	0.441(loc.:0.632 m) (y_x = 8.56 mm)	0.316(loc.:0.632 m) (y_x = 6.13 mm)

Table 12. The Results By Using Broms Method (Lateral Load Acts at H/2)

	Broms Method			
	M_{max} (kNm)	Depth(m)	The Lateral Load For $M_{max,1}$(kN)	The Lateral Load For $M_{max,3}$(kN)
D_r = 70%	0.136	0.750	0.295 (loc.: 0.738 m)	0.197 (loc.: 0.685 m)
D_r = 60%	0.138	0.760	0.301 (loc.: 0.751 m)	0.212 (loc.: 0.703 m)
D_r = 50%	0.140	0.768	0.302 (loc.: 0.760 m)	0.230 (loc.: 0.720 m)

For a pile in group, piles were analyzed by considering the lateral load (0.32 kN) acting at *7H/12* (*7H/12*=0.2625m) of the height of the pile section above the sliding surface (H = 0.45 m). The results are shown in Table 13, Table 14 and Table 15.

Table 13. The Results By Using Brinch-Hansen Method (Lateral Load Acts at 7H/12)

	Brinch – Hansen Method			
	M_{max} *(kNm)*	*Depth(m)*	*The Lateral Load For* $M_{max,1}$*(kN)*	*The Lateral Load For* $M_{max,3}$*(kN)*
D_r = 70%	0.565	0.6208	0.424 (loc.: 0.51 m)	0.271 (loc.: 0.50 m)
D_r = 60%	0.493	0.6197	0.432 (loc.: 0.52 m)	0.292 (loc.: 0.50 m)
D_r = 50%	0.436	0.6195	0.436 (loc.: 0.52 m)	0.321 (loc.: 0.50 m)

Table 14. The Results By Using Subgrade Reaction Method (Lateral Load Acts at 7H/12)

	Subgrade Reaction Method			
	M_{max} *(kNm)*	*Depth(m)*	*The Lateral Load For* $M_{max,1}$*(kN)*	*The Lateral Load For* $M_{max,3}$*(kN)*
D_r = 70%	0.097	0.600 (y_x = 4.18 mm)	0.407 (loc.: 0.60 m) (y_x = 5.32 mm)	0.248 (loc.: 0.60 m) (y_x = 3.24 mm)
D_r = 60%	0.101	0.620 (y_x = 5.85 mm)	0.404 (loc.: 0.62 m) (y_x = 7.38 mm)	0.262 (loc.: 0.62 m) (y_x = 4.79 mm)
D_r = 50%	0.104	0.632 (y_x = 6.73 mm)	0.402(loc.:0.632 m) (y_x = 8.46 mm)	0.287(loc.:0.632 m) (y_x = 6.04 mm)

Table 15. The Results By Using Broms Method (Lateral Load Acts at 7H/12)

	Broms Method			
	M_{max} *(kNm)*	*Depth(m)*	*The Lateral Load For* $M_{max,1}$*(kN)*	*The Lateral Load For* $M_{max,3}$*(kN)*
D_r = 70%	0.148	0.750	0.275 (loc.: 0.728 m)	0.182 (loc.: 0.676 m)
D_r = 60%	0.150	0.760	0.281 (loc.: 0.741 m)	0.196 (loc.: 0.693 m)
D_r = 50%	0.152	0.768	0.282 (loc.: 0.749 m)	0.214 (loc.: 0.710 m)

4. CONCLUSIONS AND COMMENTS

In this study, the behavior of vertical piles installed to increase slope stability under lateral soil movement is observed by model tests conducted in a specially built large scale shear box in the geotechnics laboratory of Yıldız Technical University. Model tests were carried out on sandy soil with different relative density (Dr = 70%, 60% and 50%). Pile group was subjected to lateral soil movement due to moving shear box and bending moment distributions along the pile length and lateral pile head displacements were measured. The obtained results from tests were compaired with the calculated results by using Brinch-Hansen Method, Subgrade Reaction Method and Broms Method. Based on the results, the following conclusions can be made;

- The maximum bending moment values (obtained from the experiments) along the pile section below the sliding surface increase as the relative density of sand decreases. Also, it is observed that the results by using the Subgrade Reaction Method and Broms Method have similar behavior.
- The distribution of bending moment in the pile group demonstrates that the maximum moment on Pile 1 is higher then Pile 3. This result is an expected result for pile group subjected to the lateral soil movement.
- The lateral pile head displacements obtained from tests are more higher than the results by using other methods at different relative density of sand.
- Performed tests, one type pile section was used with 35 mm of diameter, 5 mm of wall thickness. Also, distance between pile group-box wall was constant. Therefore, change of these parameters were not considered in this recearch. Altough, to determine the effect of variation of these parameters to the pile group and each pile in a group, experimental tests have been continuing in the geotechnics laboratory of YTÜ.
- The total lateral load carried by pile group is 1.25 kN and this value is equal to 0.32 kN for each pile in group. By considering this lateral load value, the pile section above the sliding surface was analyzed according to the lateral load acting at different height of the pile section. From these results, it is observed that the method by dividing the total lateral load of the group by the number of piles was not a right approach. The expected loads (for the lateral load acts at *H/3* and *H/2* of the height of the pile section (*H*) above the sliding surface) were measured for corner pile (Pile 1) and center pile (Pile 3) and the results are summarized as follows.

In the case that the lateral load acts at one-third of the pile section (*H/3*) above the sliding surface (Dr = 70%), the calculated loads (expected loads) corresponding to the bending moment values (measured), by using Brinch-Hansen, Subgrade Reaction and Broms Methods, are given in Figure 10 for corner pile $M_{max,1}$ and center pile $M_{max,3}$.

As shown in Figure 10;

- For Brinch-Hansen Method; the ratio of the calculated load / measured load is equal to 200% (0.640/0.320=2) for corner pile. The ratio of the calculated load / measured load is equal to 132% (0.422/0.320=1.32) for center pile.
- For Subgrade Reaction Method; the ratio of the calculated load / measured load is equal to 179% for corner pile. The ratio of the calculated load / measured load is equal to 109% for center pile.
- For Broms Method; the ratio of the calculated load / measured load is equal 108% for corner pile. The ratio of the calculated load / measured load is equal 73% for center pile.

In the case that the lateral load acts at a half of the pile section (*H/2*) above the sliding surface (Dr = 70%), the calculated loads (by using Brinch-Hansen, Subgrade Reaction and

Broms Methods) corresponding to the bending moment values (measured), are given in Figure 10 for corner pile $M_{max,1}$ and center pile $M_{max,3}$.

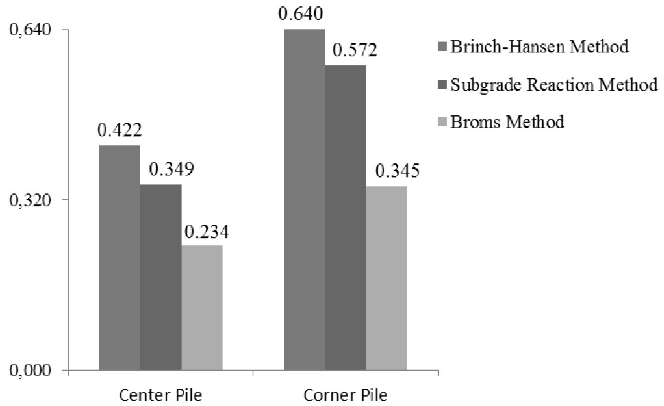


Figure 10. Expected Loads for Corner Pile and Center Pile Section (Load Acts at H/3)

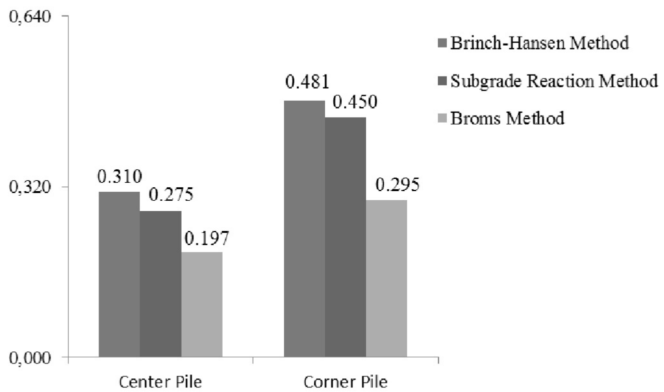


Figure 11. Expected Loads for Corner Pile and Center Pile Section (Load Acts at H/2)

As shown in Figure 11;

- For Brinch-Hansen Method; the ratio of the calculated load / measured load is equal to 150% for corner pile. The ratio of the calculated load / measured load is equal to 97% for center pile.
- For Subgrade Reaction Method; the ratio of the calculated load / measured load is equal to 141% for corner pile. The ratio of the calculated load / measured load is equal to 86% for center pile.

- For Broms Method; the ratio of the calculated load / measured load is equal to 92% for corner pile. The ratio of the calculated load / measured load is equal to 62% for center pile.

In the performed tests, after the lateral soil movement was applied to the shear box under the unreinforced and reinforced conditions, the load carried by the pile group is measured 1.25 kN and that value is approximately equal to 0.32 kN for each pile in a pile group. Also, the maximum bending moment values were measured along the pile length for Pile 1 and Pile 3. Then, lateral load values corresponding to these values (Table 3) were calculated by using Brinch-Hansen, Subgrade Reaction and Broms Methods and calculated loads were compared with the measured loads. The results of the analysis of piles can be summarized as follows (Figure 12-Figure 13).

- Brinch-Hansen method usually estimates over load (both corner pile and center pile). By estimating over load leads to unsafe conditions for slope. Also, the safety against failure of piles leads unecenomic solutions. If the predicted lateral load is less than the real load, it leads to opposite effects.
- The results are close to the right values for center pile by using Subgrade Reaction Method (more 9%). But load is calculated more 79% for corner pile.
- The load is calculated less value for center pile by using Broms Method. But for corner pile, the results are close to the right values. When this method is compared with the other methods, the lateral load value is obtained less than the other method's values.

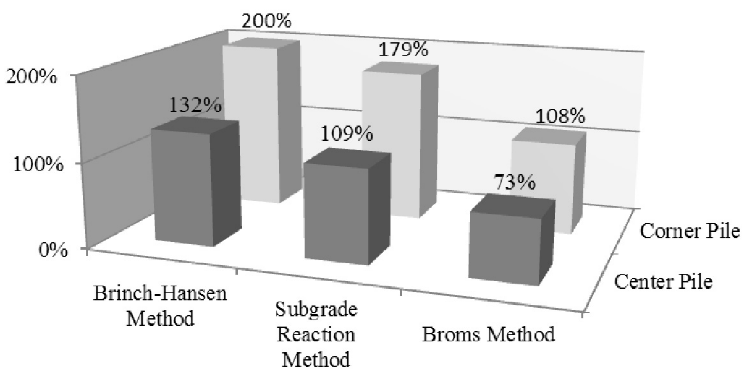


Figure 12. The Comparision of The Ratio of Calculated Load/Measured Load For Corner Pile and Center Pile (Load Acts H/3)

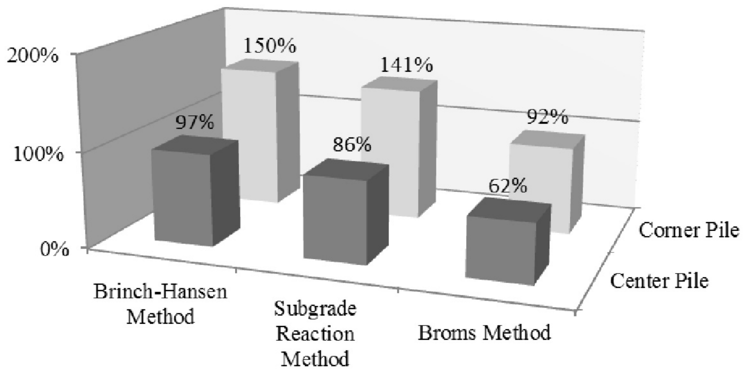


Figure 13. The Comparision of The Ratio of Calculated Load/Measured Load For Corner Pile and Center Pile (Load Acts H/2)

Symbols

USCS : The Unified Soil Classfication System

G_s : Specific gravity

D_{50} : Mean particle size

$e_{\max}$: Maximum void ratio

$e_{\min}$: Manimum void ratio

$\gamma_{k,\max}$: Maximum dry unit weight

$\gamma_{k,\min}$: Manimum dry unit weight

ϕ : Angel of friction

d : Pile diameter

t : Thickness of wall of pile

L : Pile length

S : Center to center spacing of pile

$M_{\max,1}$: Maximum bending moment on corner pile

$M_{\max,3}$: Maximum bending moment on center pile

y_x : Pile head displacement

ΔFr : Total load applied to the pile group

H : Pile section length above the sliding surface

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