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Ultimate capacity of laterally loaded pile foundation in dry and saturated layered soils

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Abstract

The behavior of the laterally loaded pile is significantly affected by the surrounding soil, weather the sand is dry or fully saturated, and these two conditions have a crucial role in the pile-soil interaction. This paper examines the behavior of the ultimate capacity of laterally loaded single pile in layered soils in dry sand and fully saturated sand. In this research, a 30mm steel rod pile model was used in one layer and two-layered soil in dry and fully saturated condition. In one layer soil, the pile was embedded in three different relative densities of sand (loose, medium and high density) however in the two-layered soil the pile was embedded in soils with loose to dense ratios (L/D = 0.5, 1, and 2). All tests were performed using constant rate displacement method. The results indicate that there is a decrease in the capacity of laterally loaded pile up to 25%, and 19% for fully saturated soil compared to dry soil in one layer and two-layered soil, respectively.

Keywords: Laterally loaded pile, Fully saturated; Layering, Relative density.

I. INTRODUCTION

Pile foundation is commonly used when building structures have to transfer superstructure loads from weak strata or through water to stiffer or more compact and less compressible soil. In most cases, piles are subjected to lateral load as well as vertical load.

The source of laterally loaded that act on the piles may come from winds, water forces, ship impact, surge, swing, and sway of ships, ship mooring, ice thrust, force acting railway on bridge, ice thrust, force acting railway on bridge, soil flow, earthquake force.

Vertical pile resists horizontal loads or moments by deflecting until the necessary reaction in the surrounding soil is mobilized. This lateral load resistance of pile foundations is critically important in the design of structures under loading from earthquakes, soil movement, waves, etc. According to Poulos and Davis, 1980 [1], the maximum deflection of the pile is the major criterion in the design.

The piles transfer the load of the superstructure through two ways: (a) Shear generated along the surface of the pile due to soil–pile friction; (b) Point resistance due to the bearing of the pile at its bottom. The behavior of the foundation under such loading conditions depends on the relative stiffness of the pile and the soil.

In the design process of laterally loaded pile foundation, both ultimate conditions and serviceability limits should be considered. However, many researchers who are investigating the behavior of short, stiff laterally loaded piles have focused on the ultimate condition and the maximum soil-pile interaction pressure (Pmax, shown in Figure 1).

For the ultimate condition, several researchers have proposed

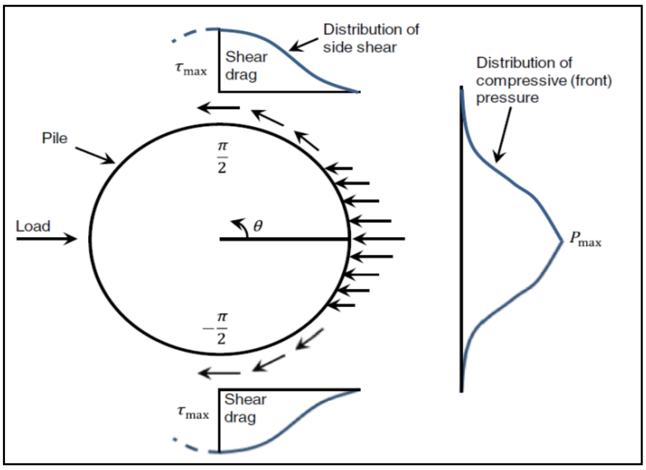

Figure 1 Soil-pile interaction stresses for laterally loaded piles at certain depth [12]

methods to predict the ultimate lateral soil-pile interaction pressure (Pu) (Hansen and Christensen, 1961 [2], Broms, 1964 [3], Meyerhof, Mathur and Valsangkar, 1981 [4], and Prasad and Chari, 1999 [5]). These methods define the ultimate soil-pile interaction pressure as a function of the effective vertical stress and the coefficient of passive pressure. The most common method used in practice to estimate soil resistance is Brom's method, which assumes that the pile rotates around its tip, and the ultimate soil pressure equals three times the passive pressure.

The p-y curve method is also, commonly used method to study the reaction of pile foundation which a laterally loaded pile considered as a beam on an elastic foundation, and for the soil is replaced by an arrangement of independent narrowly spaced springs. The p-y curve, with recommendations of the American Petroleum Institute (API) is suggested to evaluate the behavior of static laterally loaded piles installed in sandy soils [6].

In the designing process of the laterally loaded pile, accurate groundwater level information is needed for the estimation of soil densities, determination of effective soil pressures, and preparation of effective soil pressure diagrams. This information is vital for performing foundation design.

When a dry soil changes to fully saturated this can change the effective stresses leading to different soil behavior, such type of change in the field have to be carefully studied and monitored because it may change the deep foundation response to loads, as well as the soil-pile interaction.

In recent years numerous studies have focused on the effect of soil saturation on the behavior of laterally loaded pile for example, Chik et al., 2009 [7], Hamilton, 2014 [8], Mahmood, Salim and Abood, 2018 [9], and Uddin and Islam, 2010 [10] found that the case of dry soil condition gives more resistance than the other three soil cases. Chik et al., 2009 found that the lateral pile response influenced by the water table elevation significantly increases the capacity in dry soil condition and marginally decrease the capacity in fully saturated soil [7]. Taha et al., 2009 found that for the same loading, the fully saturated case showed a 63% increase in the lateral displacement compared to the dry case [11].

From the literature, it is clear that most of the studies focused on the behavior of pile in one layered soil and very few studies investigated the effect of saturation on the capacity of laterally loaded of pile foundation in layered soil.

The present study aimed to investigate the effect of saturation on the capacity of laterally loaded of pile foundation in layered soil by carrying out laboratory tests on a single pile in one layered and two-layered soil with different relative densities (loose, medium, and high density).

II. TEST SET-UP AND PROCEDURE

II.I Materia used

In this study, a solid steel rod pile with a diameter of 30 mm and height of 450 mm used. This type of material and its dimensions were chosen to minimize any pile deflection during the experiments and achieve linear displacement throughout the entire pile length.

The soil used in the experiment was air-dried sand brought from Kasnazan district in Erbil city-Iraq. A selected range of sand from 0.2 mm to 0.075 mm was chosen from sieves to produce repeatable preparation of the soil samples. The grain size distribution curves for the selected materials obtained using sieve analysis are shown in Figure 2. Table 1 summarizes the physical properties of the sand. The tests were performed according to ASTM specifications.

II. II Materia used

Three relative densities (12, 58, and 85 %) were selected for one-layered soil, and two relative densities (12 and 85 percent) were selected for two-layered soil, which means the weight required to achieve the relative density is predetermined as the unit weight and sand volume are predetermined. In each box, the entire weight of the sand was divided into equal parts (2 cm of each layer height).

For dry soil preparation, the air-dried soil was used, but for fully saturated condition the soil was prewetted with 1.3 kg water added for every 10 kg of soil, Then the layers were compacted to a predetermined depth till reaching 30 cm depth. After completing the final layer, the top surface leveled to obtain a flat surface.

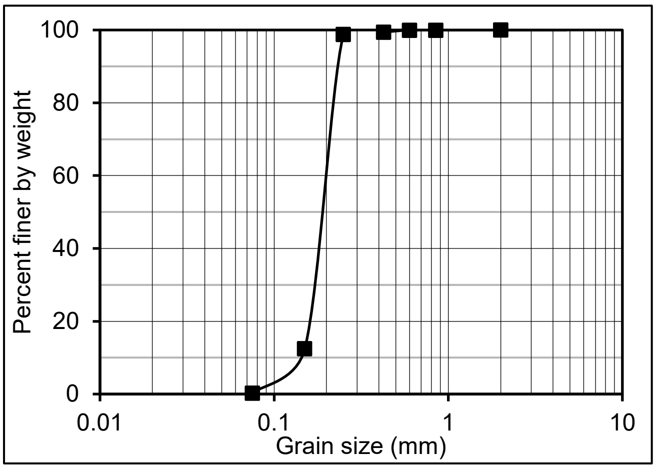

Fig. 2 Grain size distribution of sand

Table 1 Physical properties of the used sand

Parameter	Values		
Coefficient of uniformity, Cu	1.524		
Coefficient of curvature, Cc	1.069		
Classification (USCS)	SP		
Specific gravity, *Gs*	2.73		
Maximum unit weight, γ_d kN/m^3	13.38		
Minimum unit weight, γ_d kN/m^3	16.85		
*D*10, *D*30, *D*60 (mm)	0.13	0.17	0.2
Relative density, %	12	58	84.5
Dry unit weight (γ_d) kN/m^3	13.72	15.2	16.2
Angle of internal friction (Ø), deg.	28	33	38

II. III Installation of pile

The pile was lowered to the required depth then fixed from the top to the glass box through steel frame so that the pile did not move during sand deposit preparation layers, as shown in Figure 3. After the completion of the process of layering the fixing frame was removed so that it was possible to apply lateral load to the pile with a free head condition.

II. IV Model test and test procedure

Once the installation process of the pile has been completed with the desired density (loose, medium and high), the glass box is then fixed in position so that the center of the loading shaft coincides with the center of the pile model as shown in

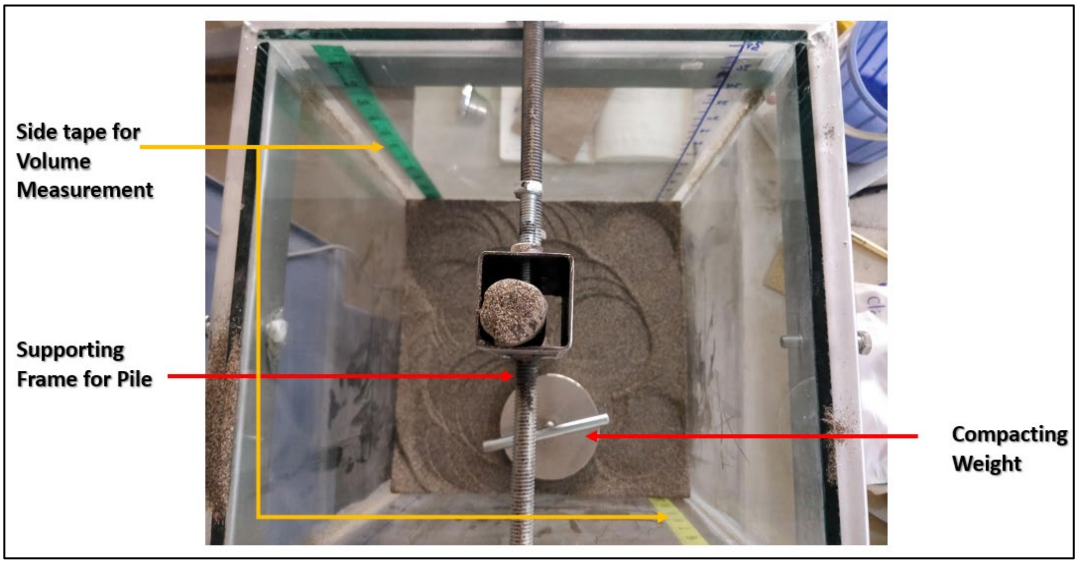

Fig. 3 Layering soil in the glass box

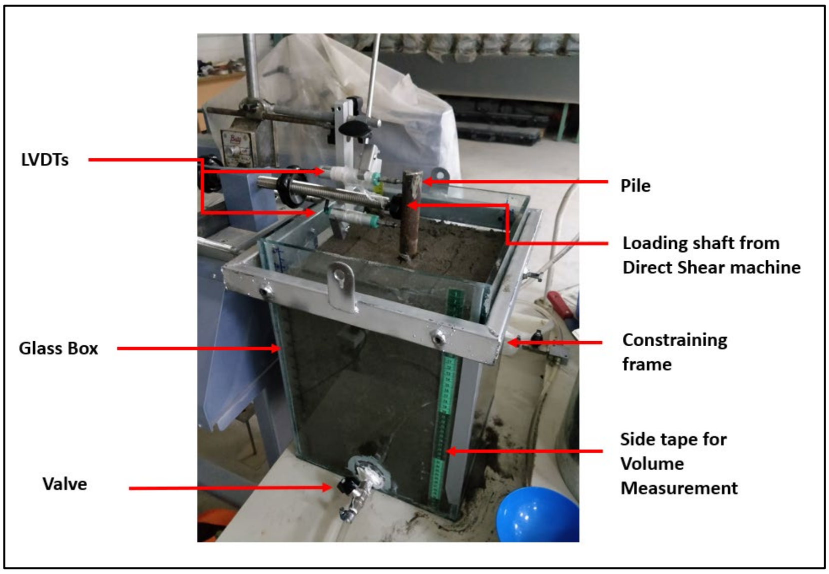

Fig. 4 Installation of pile models

Figure 4. Two LVDTs were placed at the unembedded portion of the pile, one of them fitted above the loading shaft (see Figure 4), and the second one was fitted at the bottom of the loading shaft. Both LVDTs were measured displacement of the pile at the top part of it. This type of layout of the LVDT's allows calculating the pile's tilting angle from the displacement measurements.

The tests were performed using strain-controlled technique by applying static load at a rate of 0.5 mm/min, employing direct shear loading device. The loading continued till the 20 mm displacement reached.

III. TEST RESULTS AND DISCUSSION

III.I Model test results

All pile model tests were performed on dry and saturated sands subjected to a lateral static load using different relative densities. Following paragraphs show the test results and the discussion of these 14 tests from which seven were dry and the other seven were fully saturated.

III. II Effect of relative density

Figure 5 shows the effect of relative density (Dr) on the capacity of the one-layered lateral loaded pile in dry and fully saturated soil. It can be noticed from Figure 5 that in dry soil, increasing Dr from loose to medium increased the load capacity of the pile by the value of 86%, whereas increasing Dr from loose to dense increased the load capacity of the pile by the value of 629%, (see also Table 2). For fully saturated soil, increasing Dr from loose to medium increased the load capacity of the pile by the value of 114%, whereas increasing Dr from loose to dense increased the load capacity of the pile by the value of 632%, This can be attributed to the fact that, firstly the relative stiffness ratio and horizontal subgrade reaction of soil increased as the relative density increase, secondly the close percentage of change between dry and fully saturated soil in dense state can be explained by the fact that in the compacted soil, particles cannot move as easily as the loose sand particles and the degree of interlocking between particles in dense and medium sands are more than loose sand.

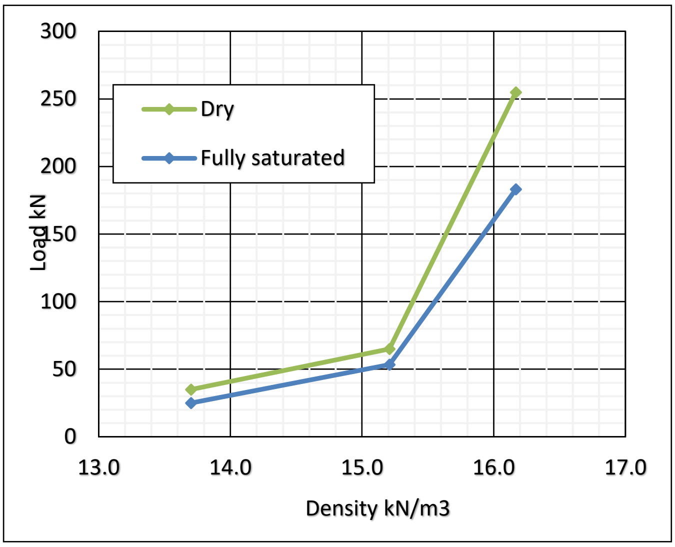

Fig. 5 Relative density vs load for one layered soil

Table 2 Percentage of change compared to loose

Density	Saturation condition	One Layer	Two Layer
Medium	Dry	86%	72%
	Saturated	114%	82%
Dense	Dry	629%	153%
	Saturated	632%	168%

III. III Effect of layering

Figure 6 and 7 show the effect of layering on the capacity of the laterally loaded pile in dry and fully saturated soil, respectively. It can be observed from figure 6 (dry condition) that changing layering of the soil from one layer with relative densities loose, medium, and high, to the two-layer with loose to dense ratios L/D = 2, 1, and 0.5 will cause 46%, 34%, and -49% change, respectively (see also Table 3). This behavior also can be identified in fully saturated condition figure 7, which in this condition the percentage of change will vary slightly, 58%, 34%, and -42% when changing from one layer two-layer with same relative densities for the dry condition.

These characteristics can be attributed to the difference of densities between the two layers, which for dry and fully saturated soil have averagely same percentage of increase, 52%, and 36% in case of L/D = 2 cm, and L/D = 1, compared to loose and medium densities respectively. Also, in case of L/D = 0.5, same behavior can be observed for both dry and fully saturated

Table 3 Percentage of change of two layer compared to one-layer soil

Loose to Dense ratio (L/D)	Dry	Saturated	average
2	46%	58%	52%
1	35%	34%	34%
0.5	-49%	-42%	-46%

condition which causes averagely 42% decrease in the capacity of the latterly loaded pile compared to high-density soil.

III. IV Effect of Saturation

Figure 5 and 8 show the effect of fully saturated condition of soil on the capacity of the laterally loaded pile in one layer and two-layered condition, respectively. It can be observed from figure 8 (one layered soil) that fully saturated condition decreases the capacity of the pile by 29%, 18%, and 28% for loose, medium, and high relative densities respectively (see Table 4).

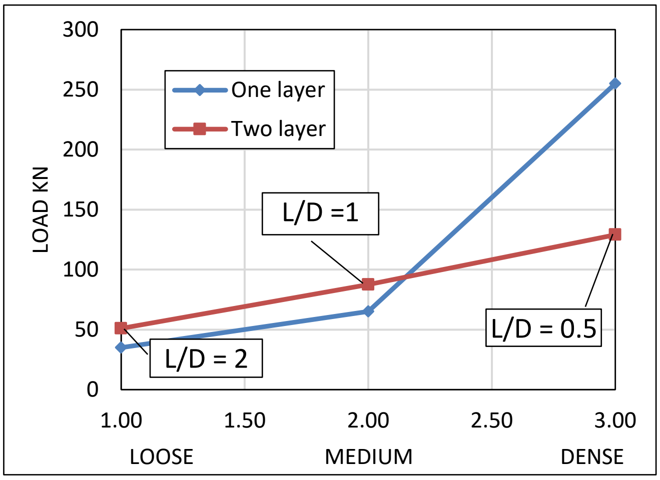

Fig. 6 Relative density vs load for dry condition

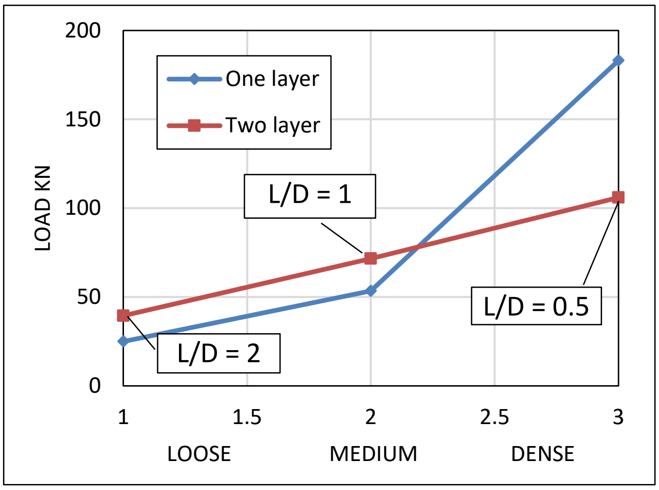

Fig. 7 Relative density vs load for Fully saturated condition

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Also form figure 5 it can be noted that fully saturated condition decreases the capacity of the pile by 23%, 18%, and 18% for L/D = 2, 1, and 0.5 respectively (see Table 4).

These characteristics of decreasing capacity of the pile by averagely 25%, and 18% for one layered and two-layered soil respectively occurs because in the fully saturated condition the effective stress of the soil decrease and the particles moving become more easily due to the presence of water.

Table 4 Percentage of change of Saturated soil compared to dry condition

layering		Percentage change	Average
Top	**Bottom**		
Loose 30cm		-29%	-25%
Medium 30cm		-18%	
Dense 30cm		-28%	
Loose 20cm	Dense 10cm	-23%	-19%
Loose 15cm	Dense 15cm	-18%	
Loose 10cm	Dense 20cm	-18%	

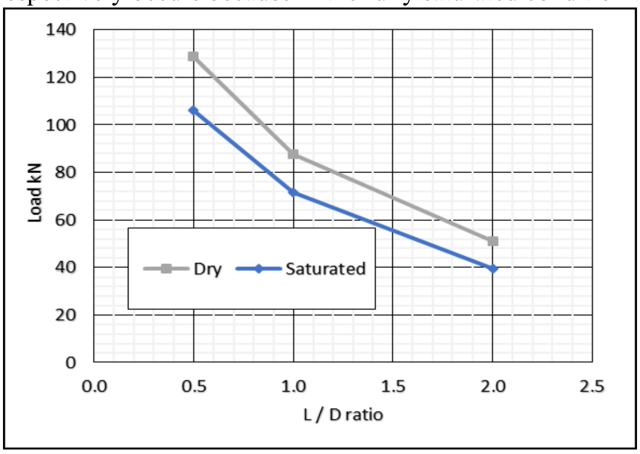

Fig. 8 L/D vs load for two layered soil

III. V Comparison between test results and proposed models from the literature.

In this study, five different methods have been used to analysis laterally loaded pile foundation in dry and fully saturated conditions. The comparisons are shown in Figures 9, 10, 11, and 12 between the test results and proposed method predictions.

From the set of the curves of one-layered soil (see Figures 9, and 10), it can be noted that for loose, and medium condition Meyerhof and Broms gives more realistic (averagely they underestimated the results by 16%, and 22%, respectively) as shown in Table 5, and for high relative density condition the API method gives more realistic results than other methods (averagely it underestimate by 44%). Overall the API method gives more accurate results than other methods and it overestimates by 17%.

From the set of the curves of two-layered soil (see Figures 11, and 12), it can be noted that for L/D = 2 Meyerhof and Broms gives more realistic (averagely they underestimated the results by 9%, and 12%, respectively) as shown in Table 6, and for L/D = 1 cm, and L/D = 0.5 layers the API method gives more realistic results than other methods (averagely it underestimate by 9%). Overall the API method gives more accurate results than other methods and it overestimates by 19%.

Based on the above interpretations it can be noted that the p-y curve (API, 2014) overall predicts more realistic results to the actual data in this study compared to other methods. It can also be observed that there are no such differences between the methods for predicting the capacity of the pile in dry and fully saturated condition.

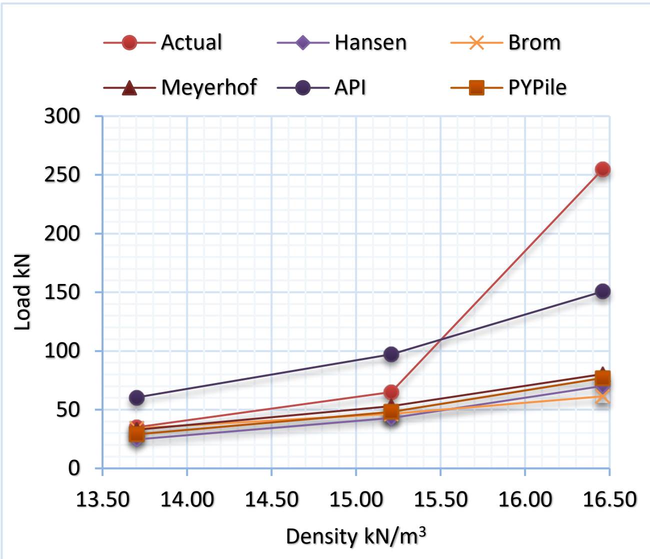

Fig. 9 Comparison between test results and five proposed models in dry condition for one layer.

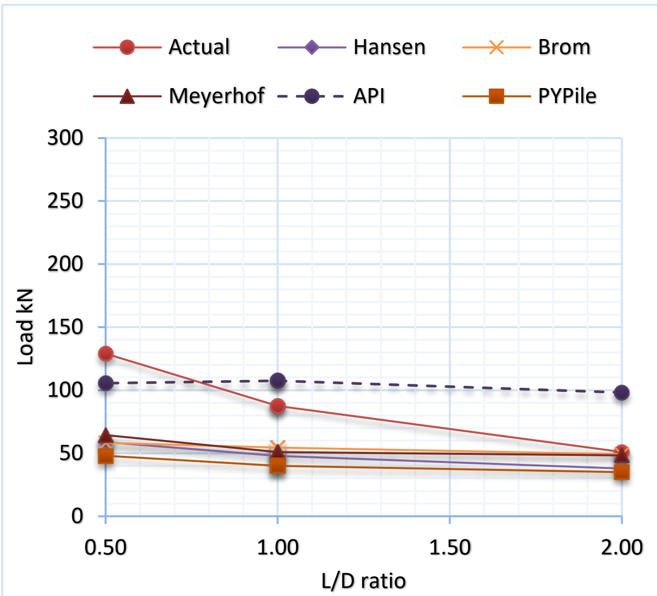

Fig. 10 Comparison between test results and five proposed models in Dry condition for two layered soil.

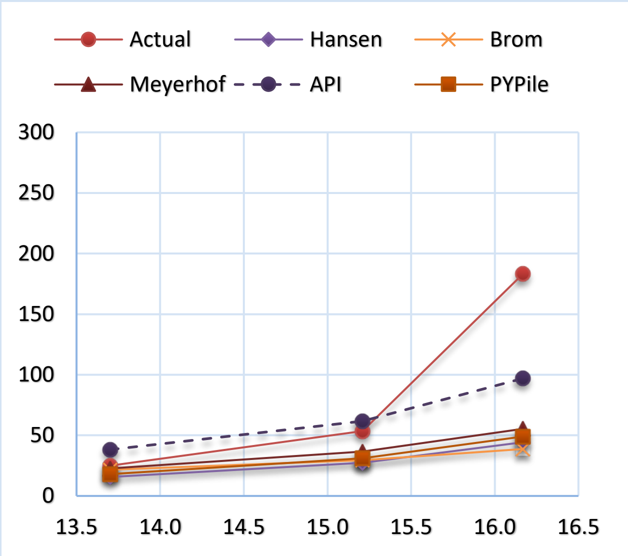

Figure 11 Comparison between test results and five proposed models in Saturated condition for one layer.

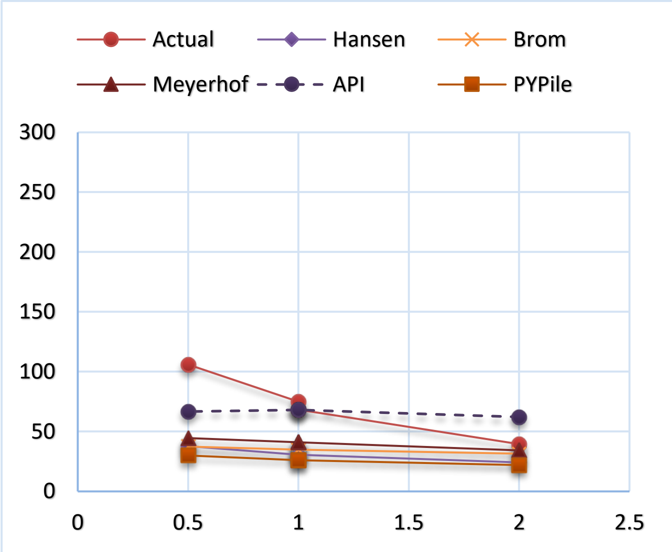

Figure 12 Comparison between test results and five proposed models in Saturated condition for two layered soil.

Table 5 Percent of change between test results and five proposed models in one layer.

One layer		**Loose**		**Medium**		**Dense**	**Average**	
Method	**Dry**	**Sat.**	**Dry**	**Sat.**	**Dry**	**Sat.**	**loose + medium**	**Dense**	**All**
Hansen	-30%	-37%	-34%	-49%	-72%	-76%	-38%	-74%	-50%
Brom	-2%	-13%	-29%	-45%	-76%	-79%	-22%	-77%	-41%
Meyerhof	-6%	-9%	-18%	-31%	-68%	-70%	-16%	-69%	-34%
API	73%	53%	50%	15%	-41%	-47%	48%	-44%	17%
PYPile	-17%	-28%	-26%	-42%	-81%	-73%	-28%	-77%	-45%

Table 6 Percent of change between test results and five proposed models in two layers.

L/D	**2**		**1**		**0.5**		**Average**		
Methods	**Dry**	**Sat.**	**Dry**	**Sat.**	**Dry**	**Sat.**	**L=20 cm**	**L=15, 10 cm**	**All**
Hansen	-26%	-39%	-45%	-57%	-54%	-64%	-32%	-55%	-48%
Brom	-3%	-20%	-38%	-51%	-55%	-65%	-12%	-52%	-39%
Meyerhof	-5%	-13%	-42%	-43%	-50%	-58%	-9%	-48%	-35%
API	92%	57%	23%	-5%	-18%	-37%	75%	-9%	19%
PYPile	-31%	-44%	-54%	-64%	-63%	-72%	-38%	-63%	-55%

IV. CONCLUSION

Based on the results of 14 pile tests on a laterally loaded pile foundation in the dry and fully saturated sand with different densities, the following conclusions are drawn:

1. Changing in relative density of the soil has a great influence on the capacity of laterally loaded pile up to 168% and 632% increment for one layer and two-layered soil, respectively, compared to the loose sand.
2. The soil layering has major influence on the capacity of the pile up to 52% increase compared to loose soil and 46% decrease compared to dense soil.
3. By fully saturating the soil the capacity of the laterally loaded pile was decreased by 25%, and 19% for one layered and two-layered soil, respectively.
4. In one layer and two-layered soil for both dry and fully saturated soil, all models underestimated the capacity of laterally loaded pile except the API model which overestimate it, in case of loose and medium density soil in one layer and L/D = 2 cm in case of two-layered soil.

ACKNOWLEDGMENTS

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