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Effect of Embedded Length on Laterally Loaded Capacity of Pile Foundation

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Abstract

In the analysis of soil-pile interaction under lateral load, the effect of the embedded length of a pile is an important parameter which has a significant influence on its lateral load capacity. This paper investigates the effect of embedded length of a single pile on its ultimate lateral load capacity. In this research, a 30mm steel rod pile was used, and four embedment lengths were selected (250, 300, 350, and 400 mm) for embedment ratios (length to diameter, *L/D*) = 8.3, 10, 11.7 and 13.3, respectively. The pile was embedded in three different relative densities of sand (loose, medium, and dense). The tests were performed using constant rate displacement method. The results indicate that there is an increase in the capacity of laterally loaded pile up to 247% when embedded ratio (*L/D*) increases from 8.3 to 13.3 and when the relative density increases from 12% to 85% there is an increase up to 599% in the resistant capacity of the pile.

Keywords: Laterally loaded pile; Embedded length; Relative density.

1. Introduction

Pile foundations are generally used when the upper soil is weak or due to large applied base loads of engineering structures, that needed to be transferred to a deep, strong stratum or to resist uplift load that developed in engineering structures. In general, most piles are subjected to both lateral and vertical loads. The source of the horizontal loading is probably caused by wind, water pressure, or earth pressure.

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There are situations were piles are subjected to significant horizontal loads, such as piles in wharves and jetties carrying the impact forces of mooring ships. Offshore structures also have to resist horizontal thrusts caused by wind and wave actions [1]. A similar situation exists in transmission tower foundations and tall chimneys where wind exerts large horizontal forces. In all these cases the piles should be designed to withstand these types of loadings. In 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).

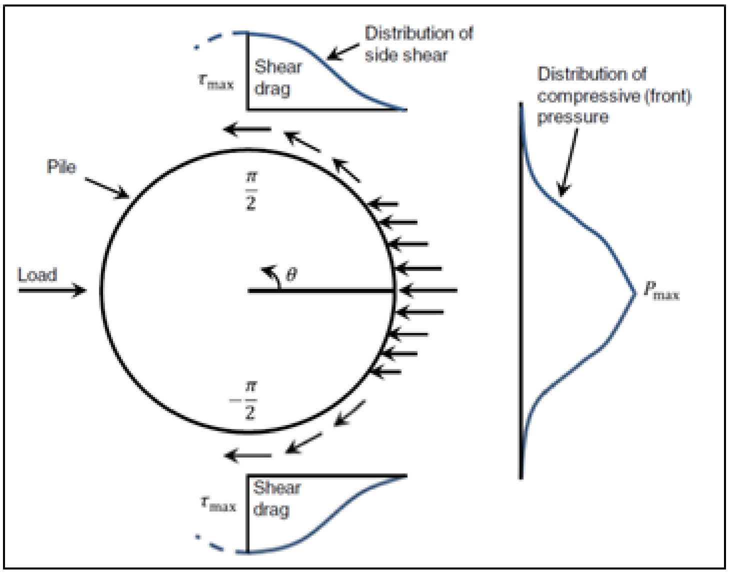

Figure 1: Soil-pile interaction stresses for laterally loaded piles at certain depth [16]

For the ultimate condition, several researchers have proposed methods to predict the ultimate lateral soil-pile interaction pressure (Pu) ([2,3,4,5]). 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) [6], are generally suggested to evaluate the behavior of static laterally loaded piles installed in sandy soils. In the literature, it is clear that most of studies here focused on the ultimate capacity of a single pile in sandy soils. The studies, for example ([7,8,9]), were mainly investigated the effect of slenderness ratio (pile length / pile diameter), which differs from study the effect of embedded length of pile. Much less information is available regarding the effect of embedment length on the behavior of laterally loaded piles. A few researchers have observed that the main dominant layer that controls the behavior of laterally loaded pile is first 3~4 times of pile diameter [10,11,12]. Shazzath Hossain and Mohammad (2014) affirmed these observations by stating that, by removing 1.5m topsoil of the pile, the lateral capacity of the pile reduced to half for a given pile head displacement compared with full soil depth [13]. Regarding the effect of relative density, researchers have been investigating the relationship between relative density (Dr) and horizontal modulus of subgrade reaction (Kh) of a soil using a back analysis based on deflection data from horizontal loading tests of piles, and they found that there is a strong relation between Dr and Kh, and the Relative density of the upper layer has enormous effect on the pile response [10]. Moreover, Wakil (2013) found that the rate of increase of loose sand, with L/D = 2.00 and 3.00 is 235% and 357% compared to 200% and 300% of medium density sand and 35% and 77% of dense sand [14]. The present study aimed to investigate the effect of embedded length on capacity of laterally loaded pile foundation by carrying out laboratory tests on a single pile with varying ratios of embedded length to diameter (L/D = 8.3, 10, 11.7 and 13.3) using three different relative densities Dr=12, 58, 85.

2. Theoretical background

Its possible to predict the lateral soil-pile interaction pressure (p) using several proposed models by researchers such as ([2,3,4,5]). One of the early researchers who studied the behavior of laterally loaded pile was Brinch Hansen (1961), which he defined the soil-pile interaction pressure (p) as a function of the effective earth pressure (K_q) and effective vertical stress (σ_v') [2], as shown in Figure 2. Hansen proposed equations 1 and 2 for calculation soil resistant pressure (p) and ultimate capacity of laterally loaded pile (P_u) respectively.

$$p = \sigma_v' K_q B = \gamma' L K_q B \qquad (1)$$

$$P_u = \left[\frac{2L^3 - 3L^2 + 4x^3}{6(e+x)}\right] * \gamma' K_q B \qquad (2)$$

where: (B) is diameter of the pile, (L) is embedded length of the pile, (e) is eccentricity of loading, (x) is point of rotation of the pile, and (γ') is effective unit weight of the soil In 1964, Brom modified Hansen's proposed equations by assuming that the pile rotates around its tip, and the ultimate soil pressure (p) equals three times the coefficient of passive earth pressure (K_P) as shown in Figure 2, he proposed equation 3 for calculation ultimate pile capacity [3]. Brom's theory, despite its simplification, but it entirely neglected the effect of soil blow actual point of rotation by assuming the pile will rotate around its tip.

$$p = 3\sigma_v' K_p B = 3\gamma' L K_p B \qquad (3)$$

$$P_u = \frac{\gamma' L^3 K_p B}{2(e+L)} \qquad (4)$$

In 1981, Meyerhof by conducting a set of experiments, and measuring actual soil pressure distribution along the length of rigid piles using pressure transducers, he modified Brom's theory through considering the effect of soil below point of rotation (x), taking into account the effect of active earth pressure (K_a), and introducing pile shape factor (S_{bu}) into ultimate piles capacity as shown in equations 5-6 [4].

$$p = \sigma_v'(K_p - K_a)\, S_{bu} B = \gamma' L (K_p - K_a)\, S_{bu} B \qquad (5)$$

$$P_u = \gamma' L^2 (K_p - K_a)\, r_b S_{bu} B \qquad (6)$$

where:

$$r_b = \frac{1}{1+1.4\frac{e}{L}} \qquad (7)$$

It's worth mentioning that all the above-mentioned researchers did not take in to account the effect of pile lateral displacement and they underestimated the lateral capacity of the pile, therefore, American Petroleum Institute (API) [6] from 1990 to 2014 conducted enormous researches to observe and predict the behavior of laterally loaded piles. They concluded that the main dominant factors contribute to the ultimate pile capacity are modulus of subgrade reaction of the pile and piles lateral displacement. Based on these findings API proposed equation 8 to calculate pile ultimate capacity (P_u).

$$P_u = (C_1 z + C_2 B)\sigma_v' = (C_1 z + C_2 B)\gamma' \, L \qquad (8)$$

where:

$$C_1 = tan\left(\frac{\pi}{2} + \frac{\emptyset}{2}\right)\left\{K_p \, tan\frac{\emptyset}{2} + 0.4\left[tan\,\emptyset\, sin\left(\frac{\pi}{2} + \frac{\emptyset}{2}\right)\left(\frac{1}{cos\frac{\emptyset}{2}} + 1\right) - tan\frac{\emptyset}{2}\right]\right\} \qquad (9)$$

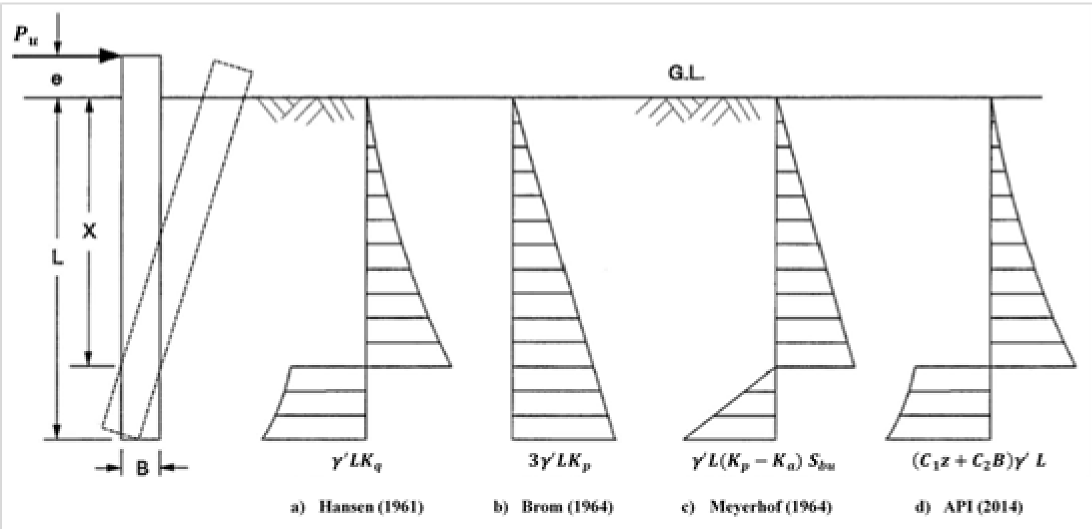

Figure 2: Soil pressure distribution under lateral load [5]

$$C_2 = K_P - K_A \qquad (10)$$

3. Test set-up and procedure

3.1. Material used

A solid steel rod pile with a diameter of 30 mm and height of 450 mm used in this study. The reason of choosing this type of material and its dimensions, are to minimize any pile deflection during the experiments and produce linear displacement as shown in Figure 2.

The soil used in the experiments was air-dried sand brought up from Kasnazan district in Erbil city-Iraq. To produce repeatable preparation of the soil samples, a selected range 0.2 mm to 0.075 mm was chosen form the sieves. The grain size distribution curves for the selected materials obtained using sieve analysis are shown in Figure 3. Table 1 summarizes the physical properties of the sand. The tests were performed according to ASTM specifications.

3.2. Sand deposit preparation

The sand deposit was prepared in a glass box with dimension of 300 × 300 × 450 mm as length, width, and depth, respectively, as shown in Figure 4. Three relative densities were chosen (12, 58, and 85%), this means that the weight required to achieve the relative density is predetermined since the unit weight and the volume of the sand are predetermined. The whole weight of the sand in each box was divided into equal parts (2 cm height of each layer). The soil of each layer was compacted to a predetermined depth. After completing the final layer, the top surface leveled to obtain a flat surface.

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 (max.) kN/m^3	13.38		
Minimum unit weight, γ_d (min.) kN/m^3	16.85		
*D*10, *D*30, *D*60 (mm)	0.13	0.166	0.199
Relative density, %	12	58	84.5
Dry unit weight (γ_d) kN/m^3	13.72	15.2	16.2
The angle of internal friction (Ø), deg.	28	33	38

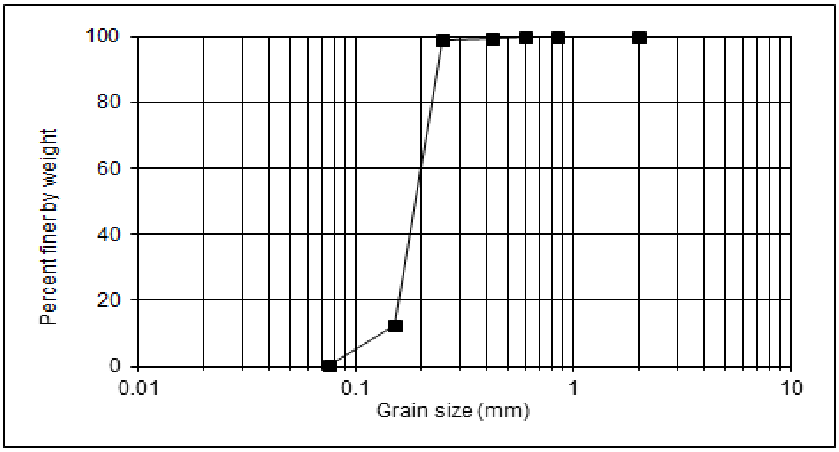

Figure 3: Grain size distribution of sand

3.3. 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 4. 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.

3.4. Model test and test procedure

After completion of the process of installation of the pile with desired density (loose, medium, and high) then the glass box fixed in position in such a manner that the center of the loading shaft coincides with the center of the pile model as shown in Figure 5. Two LVDTs were placed at the top part of the pile, one of them fitted above of the loading shaft (see Figure 5), and the second one was fitted at the bottom of the loading shaft. Both of the LVDTs were measured displacement of the pile at the top part of it. This type of arrangement of the LVDT's allows tilting angle of the pile to be calculated from the displacement measurements.

This Followed by putting two LVDTs on top and bottom of the loading shaft, so that not only displacement of the pile can be measured, but also the tilting angle can be observed.

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

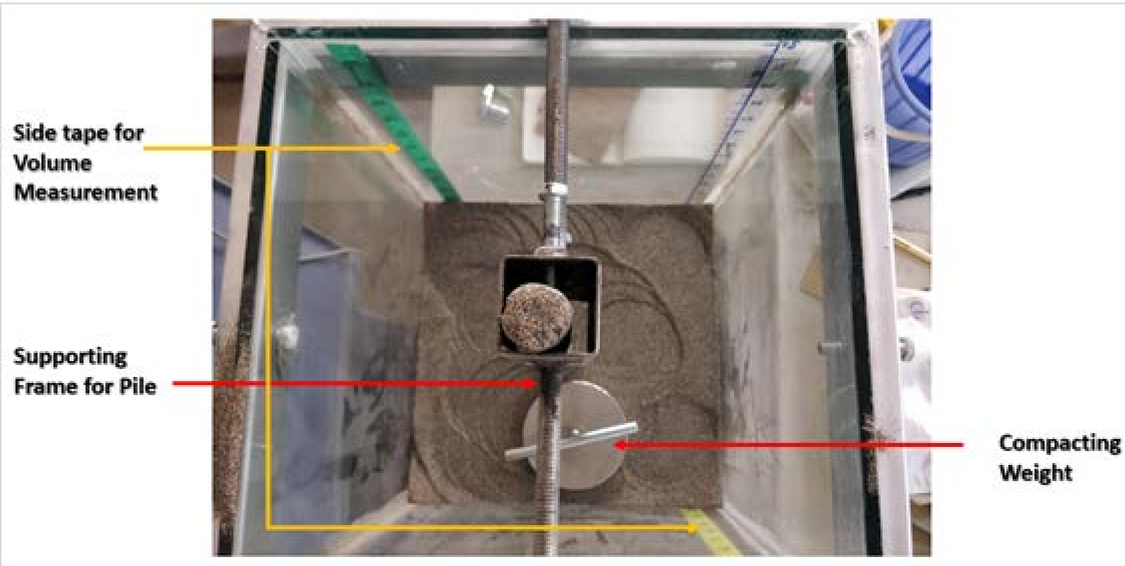

Figure 4: Layering soil in the glass box

4. Test results and discussion

4.1. Model test results

All pile model tests were performed on dry sands subjected to a lateral static load using different relative densities. Following paragraphs show the discussion of these 12 tests.

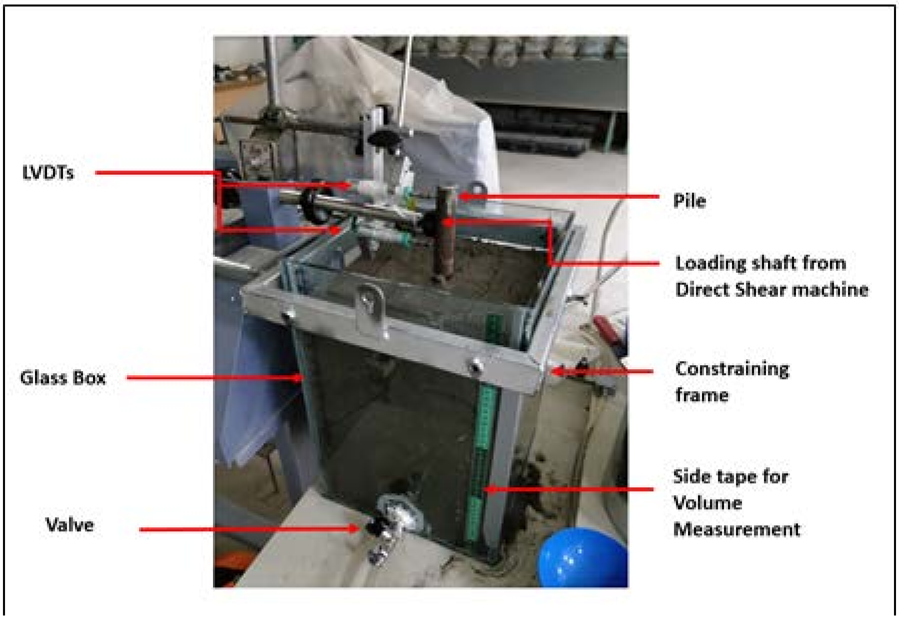

Figure 5: Installation of pile models

4.2. Effect of relative density

Figure 6 shows the effect of relative density (Dr) on the capacity of lateral loaded pile. It can be noticed from Figure 6 that increasing Dr from loose to medium increased the load capacity of the pile by the value of 121%, the value of 121% is the average value of pile lateral load capacity in medium density sand for all L/D, whereas increasing Dr from loose to dense increased the load capacity of the pile by the value of 599%, the value of 599% is the average value of pile lateral load capacity in high density sand for all L/D, (see also Table 2). This can be attributed to the fact that, firstly the relative stiffness ratio and horizontal subgrade reaction of soil increased as the relative density increased [15], secondly compacted soil particles did not 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. Inspection of Figure 6 also shows that, for medium density sand, the average increase in the capacity of the pile is 84% for both (8.3 and 10 L/D), whereas the average increase for both (11.7 and 13.3 L/D) is 158% when compared to loose sand (see Table 2). In dense sand for all embedment ratios, the average value of increase in the capacity of the pile was 600% compared to loose sand. It can be concluded that, in medium density the capacity of the laterally loaded pile significantly increases in higher value of L/D compared to lower value of L/D, whereas the capacity of the laterally loaded pile in dense sand, almost equally increased for all value of L/Ds.

4.3. Effect of embedment length-to-diameter ratio

The effect of the embedment length on the capacity of laterally loaded piles was studied using four different L/D ratios (8.3, 10, 11.7, and 13.3). Figure 6 shows the response of the laterally loaded pile in sands with different embedment lengths to pile diameter ratio (L/D) at different relative density (loose, medium, and dense).

It can be noted that the pile capacity against laterally loading is very sensitive to change in L/D. For loose, medium and dense sand increasing L/D from 8.3 to 13.3, result of 160%, 247% and 127% increase of the piles lateral capacity, respectively (see Table 3). These observations show that the main dominate layer that controls the behavior of laterally loaded pile is first 3~4 times of pile diameter ([10,11,12]).

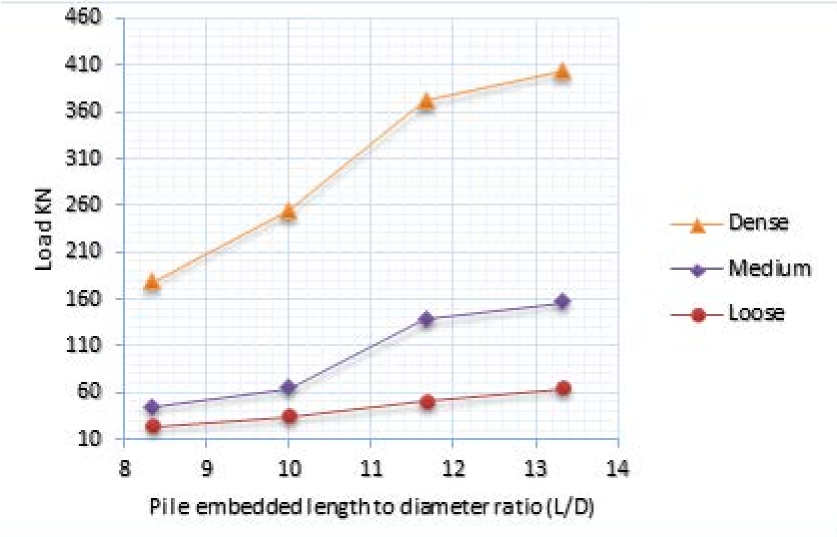

Figure 6: Pile embedment length Vs Load

Table 2: Percent of increment of pile lateral capacity, compared to loose sand

Density	Embedment ratio (L/D)			
	8.3	10	11.7	13.3
Medium (%)	82	86	173	143
Dense (%)	614	629	629	523

Table 3: Percent of increment of pile lateral capacity, compared to L/D= 8.3 embedment length

Density	Embedment ratio (L/D)		
	10	11.7	13.3
Loose (%)	40	104	160
Medium (%)	43	205	247
Dense (%)	43	108	127

4.4. Comparison between test results and proposed models from the literature

In this study, five different methods (see theoretical background) have been used to analysis laterally loaded pile foundation. The comparisons are shown in Figures 7, 8, and 9 between the test results and proposed method predictions.

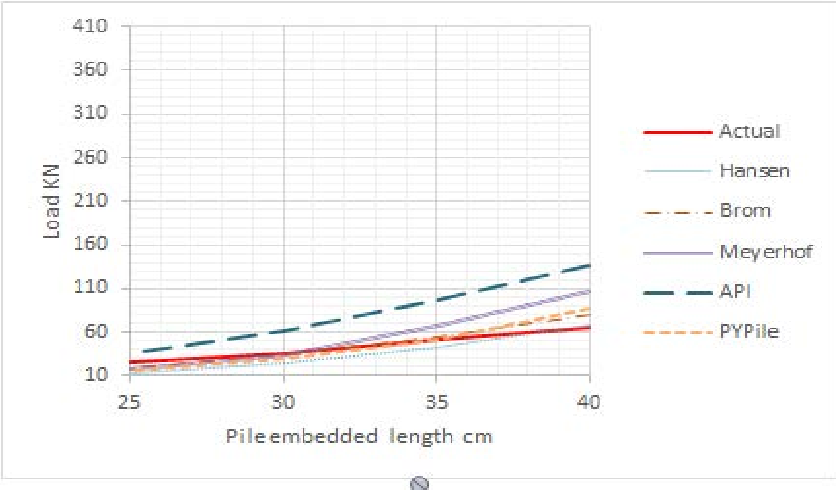

Figure 7: Pile Embedded length Vs Load (Loose sand)

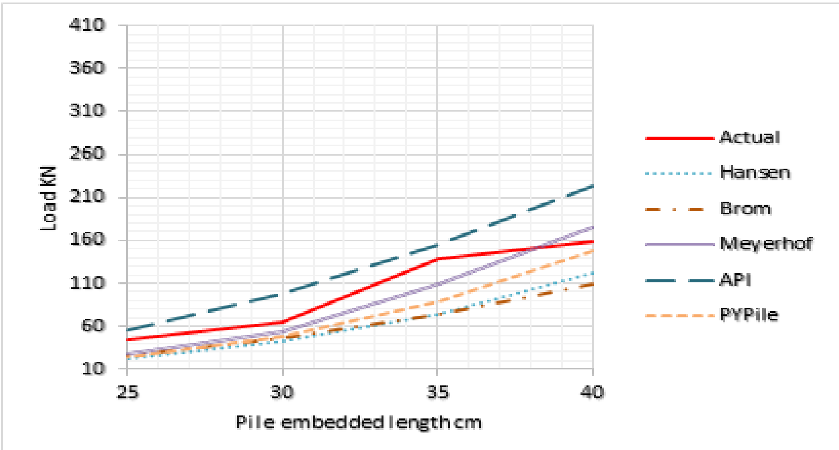

Figure 8: Pile Embedded length Vs Load (Medium sand)

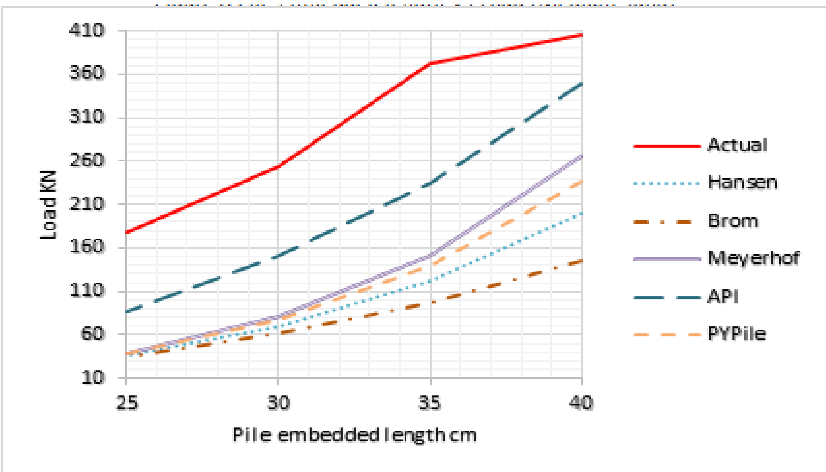

Figure 9: Pile Embedded length Vs Load (Dense sand)

Form the set of the curves, it can be clearly noted that for loose sand, the Brom method predicted more realistic results compared to API and Meyerhof methods. For medium density sand, both API and Meyerhof method predicted more realistic results compared to other methods. In dense sand situation (as shown in in Figure 7, 8, and 9) all methods underestimated the capacity of the pile by average of 60%. Based on the above interpretations it can be noted that the p-y curve (API, 2014) predicts more realistic results to the actual data in this study compared to other methods.

5. Conclusion

Based on the results of 12 pile tests on a laterally loaded pile foundation embedded in the sand in different densities with different embedment ratio, 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 121% and 599% increment for medium and high density, respectively, compared to the loose sand.
2. The upper soil layer has a significant impact on the lateral capacity of the pile, and it is clearly observed when comparing the capacities of pile for L/D =13.3 with 8.3.
3. The variation of the embedded ratio (*L/D*) has a higher impact on the resistance of laterally loaded pile in medium sand, (247%) compared to the laterally loaded pile capacity in dense sand (127%).
4. In loose sand, almost all models overestimated the capacity of laterally loaded pile, whereas in medium density; some of the models (such as API) over estimated and some of the models (such as Brom) underestimated the pile capacity. Contrary, in dense sand, all the models underestimated the capacity of the laterally loaded pile.

Figure 7 Pile Embedded length Vs Load (Loose sand)

Figure 8 Pile Embedded length Vs Load (Medium sand)

Figure 9 Pile Embedded length Vs Load (Dense sand)

Acknowledgements

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