BEHAVIOUR OF PILES SUBJECTED TO LATERAL FORCES IN COHESIVE SOIL

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ABSTRACT: Although piles are elements designed primarily to support vertical loads, They are subjected to horizontal loads by serval sources such as earthquake, wind, impact loads and lateral earth pressure. Large number of studies have been carried out to investigate the effect of different parameters on the behavior of piles. These parameters are summarized as i) effect of pile diameter, ii) angle of the pile with the vertical, iii) piles slenderness ratio and soil type. In the present study an experimental program was carried out to identify the deflection of vertical and inclined piles subjected to a lateral force in cohesive soil. The experimental program comprised pile lateral load tests performed on model of single pile driven in cohesive soil. Using the experimental model results, relations were utilized to estimate the lateral deflection of piles.

Keywords: pile – lateral load – lateral displacement-surrounding soil- Boundary effect

Notation:

L = embedded Length of pile

e = distance between pile tip and ground surface

D = pile diameter

P = lateral load

y = lateral displacement

L/D = slenderness ratio

θ = Pile inclination angle to the vertical direction

INTRODUCTION

Horizontally loaded piles is an important topic of study, The horizontal Load affects the horizontal displacement of the piles and surrounding soil. This horizontal displacement must be taken into consideration in the design process. Lateral loads are imposed on soils and geotechnical structures by serval sources such as earthquake, wind, impact loads and lateral earth pressure. Design of foundation system for structures subjected to lateral loads is a principal issue in the geotechnical engineering. Safety against geotechnical failure, structural failure and excessive deflections should be taken into consideration in the design of piles where lateral loads are expected.

The analysis methodologies of laterally-loaded piles have been evolved over time from the empirical and limit state methods (Broms; 1964a)[1] until reaching the p-y (load-transfer) methods (Matlock,1970[2]; Reese et al.; 1975)[3]. Poulos and Davis[4] (1980) discussed “The theoretical approach of prediction the pile deformation and load capacity”. Behzad, et al. (2014)[5] discussed the performance of laterally loaded piles. They considered the soil-pile interaction and they concluded that "there are different parameter that should be taken into consideration during the design, such as i) initial field stress around the pile and ii) soil-pile interface characteristics. Sheng Luo (2018)[6] discussed the effects of the model boundaries on the pile behavior. He concluded that soil domain diameter should be larger than 15D (i.e. D= the pile diameter) and depth needed to exceed 1.67L (i.e. L= the embedded depth of pile). That was considered sufficient to avoid the interference of the model boundaries in the pile behavior Ahmed Youssef [7], et al. concluded that Soil liquefaction brings about the reduced shear stiffness, which may relax the local section forces of piles around the softened foundation. On the others hand, globally magnified is the overall deformation of liquefied foundation, which may lead to damages of piles especially around the point of stiffness change like support, joints and interfaces between soil layers of different mechanics. This trade-off observed in dynamic soil-pile tests can be simulated by considering nonlinear path-dependency of soil, steel and reinforced concrete,Saleh, A. (2015)[8] concluded that Increase of strength and stiffness of soil increases the load carrying capacity, decreases ground displacement and causes a shallower depth for plastic hinge for tested pile Mi (Michael) Zhou et.al(2017)[9] concluded that “The effect of the ratio of Young’s modulus of soil to undrained shear strength of clay Es/su was shown to have a significant influence on the boundary effect” R. Ayothiraman & A. Boominathan[10] concluded that “Consistency of clay and pile length significantly influences the natural frequency of the soil–pile system. Though the natural frequency substantially increases with pile length and shear modulus of clay at low magnitude of dynamic load”

In this study, an experimental program was carried out to model and identify the deflection of vertical piles and inclined piles subjected to lateral loads. Different soil types, pile diameter, pile length and pile inclination angle were considered. Through the parametric study.

Experimental Work

Tank model

The test setup consists of cylindrical tank 80 cm height and 30 cm diameter. Poly Propylene pipes were used for piles having diameters of 2, 2.5 and 3.2 cm with different lengths. The ratio between the tank diameter and pile diameter was large enough to ensure that there was no boundary effect. The test setup included also wire, pulley and weights to apply horizontal loads, Figure 1. The horizontal loading was applied to the pile using a pulley and external vertical loads connected with wire to the pile top. Dial gauges were used to measure the deflection of the pile.

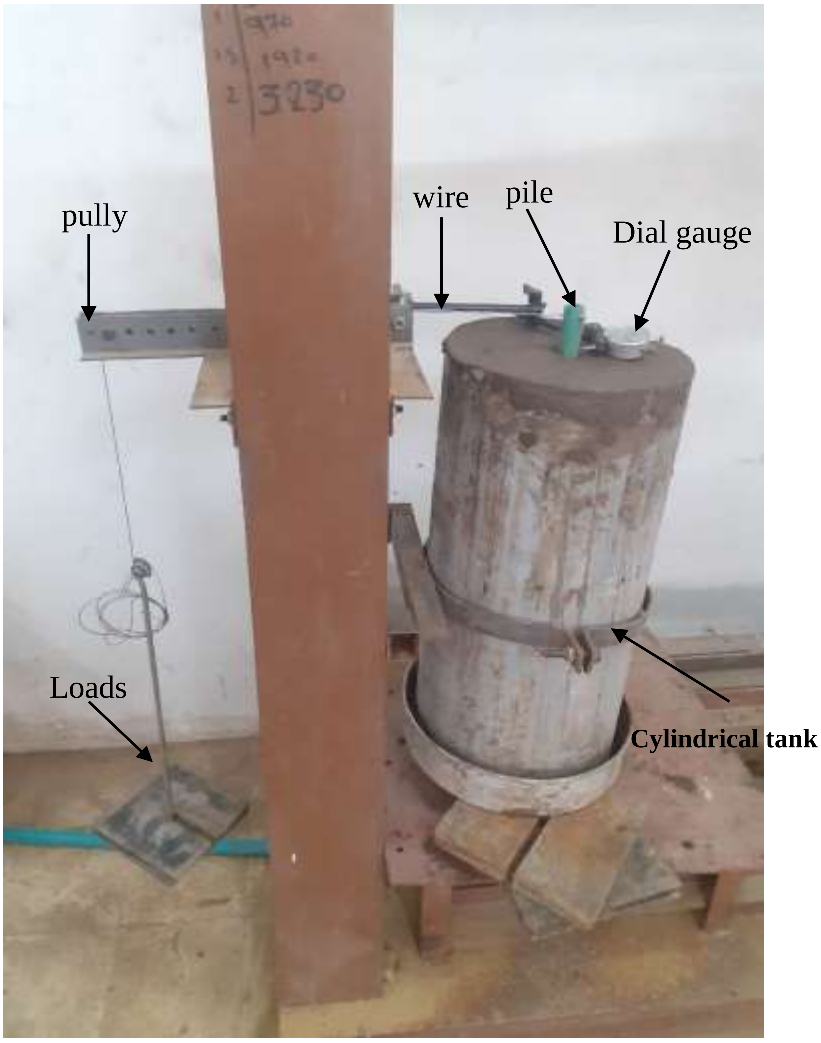

Fig (1): Test setup

Soil Used in Model Tests

In the present study, both clay and silt were used to represent cohesive soil. In all tests soil was fully saturated and loaded by a pre-consolidation stress of (1 Kg/cm^2). Soil was first dried, grinded, and then mixed with water to form a slurry. The slurry was poured in the tank and left to settle. The tank had a perforated bottom, perforated cap and filter paper, used as to allow for consolidation as double drainage. After 24 hours, incremental loading was carried out to the top surface of the soil above the cap. Each increment was 0.1 Kg/cm2, and time interval was minimum 48 hours, in order to allow soil to consolidate under the applied load. Furthermore, settlement was observed, and the new increment was added after confirming no more settlement occurred. Incremental loading was continuing till the sample reached consolidation stress of 1 kg/cm^2. This process was repeated for each test to obtain uniform soil formation for all tests. Soil parameters were determined by laboratory tests following the Egyptian Code. Table (1) summarize the test results.

Table (1) : Soil parameters

Parameters	Soil (1)	Soil (2)	Test Type
Shear strength (cu) – kg/cm2	0.43	0.62	Unconfined test
Specific Gravity	2.68	2.68	
Maximum bulk density (g/cm3)	1.756	1.88	Proctor test
Liquid limit	45	55	Atterberg limits
Plastic limit	23	26	Atterberg limits

Testing Program:

Tests were carried out to investigate the pile behavior under lateral loads. Different parameters were considered to study the soil displacement at ground surface. A total number of 44 tests were carried out. Table (2) presents the testing program.

Table (2) : Testing program

Parameters	
Pile diameter (cm)	2 , 2.5 , 3.2
Pile Length (cm)	25, 35 , 45
Pile inclination angle to the vertical direction (degree)	0, 11 , 15 , 18
Load eccentricity	2.5, 5

Results and Discussions

The experimental work presented in this study is part of a study to investigate the behavior of the vertical and inclined piles in cohesive soil under horizontal loads. The following results will present how the different parameters as the pile diameter, length and inclination will affect the soil displacement at ground surface.

Effect of the slenderness ratio (L/D)

According to Broms (1964), the slenderness ratio equals to the ratio between the embedded depth of pile (L) and the pile diameter. Its increase has a positive effect on pile lateral capacity. Tests have been carried out to study the effect of slenderness ratio on the pile deflection. Fig (2.1)and Fig (2.2) present the load- displacement curves.

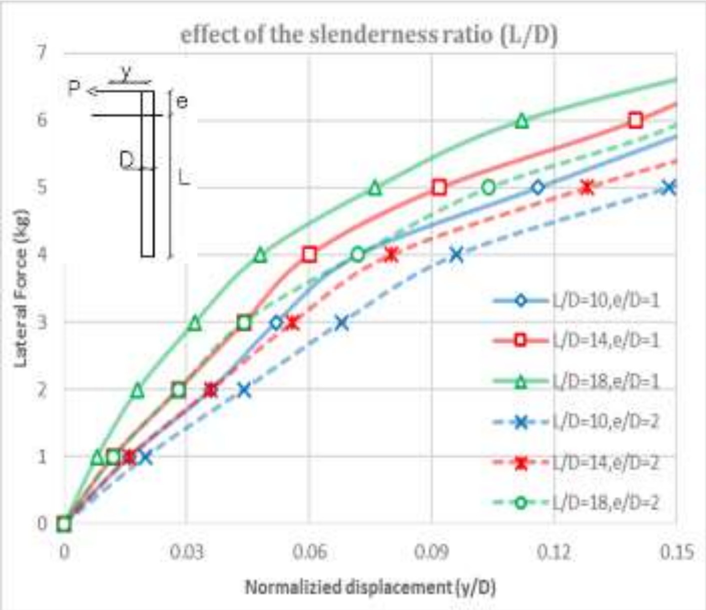

Fig (2.1): Load- displacement curves for vertical pile embedded in Soil (1) . (Pile diameter = 2.5cm)

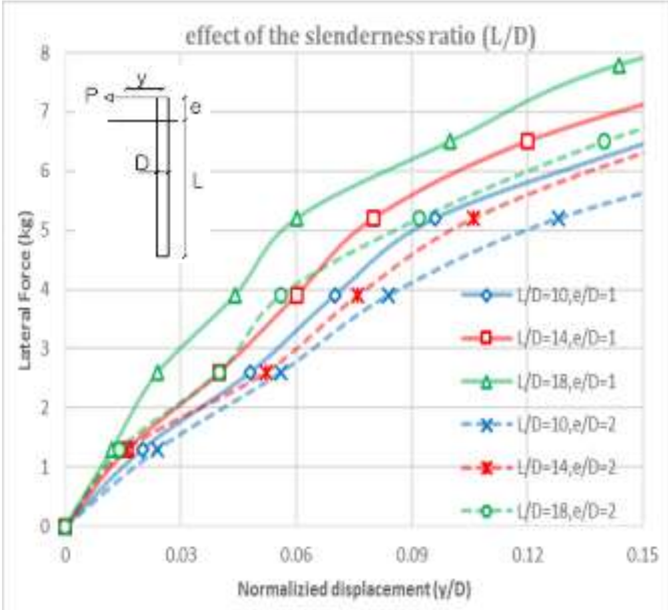

Fig (2.2). Load- displacement curves for vertical pile embedded in Soil (2). (Pile diameter = 2.5cm)

From Figs (2.1 & 2.2), it is noticed that:

Increasing the slenderness ratio decreases the soil displacement under the same (horizontal) HZ load. For the same slenderness ratio, increasing the eccentricity leads to increase in the soil displacement. This is shown in both clay and silt soil.

For Soil (1) and (e/D)= 1, increasing the slenderness ratio (L/D) from 10 to 14 increases the pile load capacity by 8.7%

For Soil (1) and (e/D)= 1, increasing the slenderness ratio (L/D) from 14 to 18 increases the pile load capacity by 5.9%

For Soil (1) and (e/D)= 2, increasing the slenderness ratio (L/D) from 10 to 14 increases the pile load capacity by 6.9%

For Soil (1) and (e/D)= 2, increasing the slenderness ratio (L/D) from 14 to 18 increases the pile load capacity by 10.2%

For Soil (2) and (e/D)= 1, increasing the slenderness ratio (L/D) from 10 to 14 increases the pile load capacity by 10.8%

For Soil (2) and (e/D)= 1, increasing the slenderness ratio (L/D) from 14 to 18 increases the pile load capacity by 11.3%

For Soil (2) and (e/D)= 2, increasing the slenderness ratio (L/D) from 10 to 14 increases the pile load capacity by 12%

For Soil (2) and (e/D)= 2, increasing the slenderness ratio (L/D) from 14 to 18 increases the pile load capacity by 6.3%

For (e/D)= 1, increasing the slenderness ratio (L/D) from 10 to 18 increases the pile load by 14% for Soil (1) and 23% for Soil (2). For (e/D) = 2 the values are 20% for Soil (1) and 18% for Soil (2). However, Increasing the eccentricity (e/D) from 1 to 2 decreases the pile load by 15% for Soil (1) and 16% for Soil (2).

Effect of the pile inclination angle (θ)

Tests were carried out to study the effect of pile inclination angle on the soil displacement. Fig (3.1) & Fig (3.2) present the load-displacement curves for inclination angles.

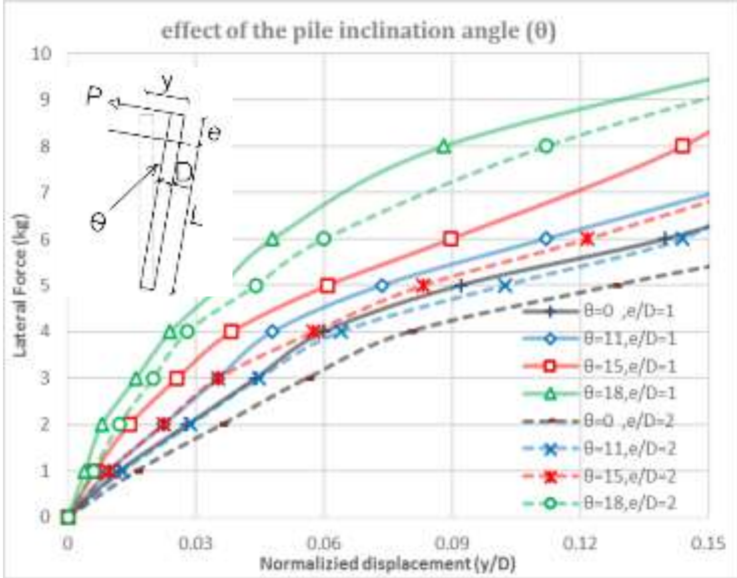

Fig (3.1). Load- displacement curves for inclined pile embedded in Soil (1). (Pile diameter = 2.5cm)

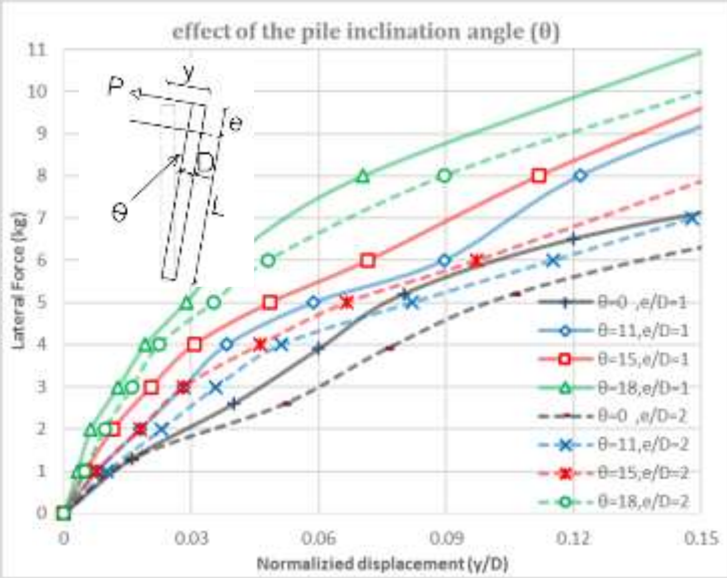

Fig (3.2). Load- displacement curves for inclined pile embedded in Soil (2). (Pile diameter = 2.5cm)

From Figs (3.1) & (3.2), it is noticed that: The selected direction for inclination is opposite to the applied load. It can be seen that increasing the inclination angle leads to a decrease in the soil displacement under the same horizontal load. The same behavior is found for (e/D) = 1 and (e/D) = 2. However, increasing the load eccentricity (e/d) increases soil displacement.

For Soil (1). and (e/D)= 1, increasing the pile inclination angle (θ) from 0 to 11 increases the pile load capacity by 12%

For Soil (1). and (e/D)= 1, increasing the pile inclination angle (θ) from 11 to 15 increases the pile load capacity by 19.4%

For Soil (1) and (e/D)= 1, increasing the pile inclination angle (θ) from 15 to 18 increases the pile load capacity by 13.9%

For Soil (1) and (e/D)= 2, increasing the pile inclination angle (θ) from 0 to 11 increases the pile load capacity by 16.7%

For Soil (1) and (e/D)= 2, increasing the pile inclination angle (θ) from 11 to 15 increases the pile load capacity by 7.9%

For Soil (1) and (e/D)= 2, increasing the pile inclination angle (θ) from 15 to 18 increases the pile load capacity by 33%

For Soil (2) and (e/D)= 1, increasing the pile inclination angle (θ) from 0 to 11 increases the pile load capacity by 28.9%

For Soil (2) and (e/D)= 1, increasing the pile inclination angle (θ) from 11 to 15 increases the pile load capacity by 4.9%

For Soil (2) and (e/D)= 1, increasing the pile inclination angle (θ) from 15 to 18 increases the pile load capacity by 13.5%

For Soil (2) and (e/D)= 2, increasing the pile inclination angle (θ) from 0 to 11 increases the pile load capacity by 11.1%

For Soil (2) and (e/D)= 2, increasing the pile inclination angle (θ) from 11 to 15 increases the pile load capacity by 12.9%

For Soil (2) and (e/D)= 2, increasing the pile inclination angle (θ) from 15 to 18 increases the pile load capacity by 26.6%

For (e/D) = 1 increasing the pile inclination angle (θ) from 0 to 18o increases the pile load by 50% for Soil (1) and 57% for Soil (2). For (e/D) = 2 the values are 70% for Soil (1) and 61% for Soil (2). Also, increasing the eccentricity (e/D) from 1 to 2 decreases the pile load by 14% for Soil (1) and 18.5% for Soil (2).

Effect of the pile diameter (D)

Tests were carried out to study the effect of the pile diameter on the soil displacement. Fig (4.1) & Fig (4.2) present the load- displacement curves.

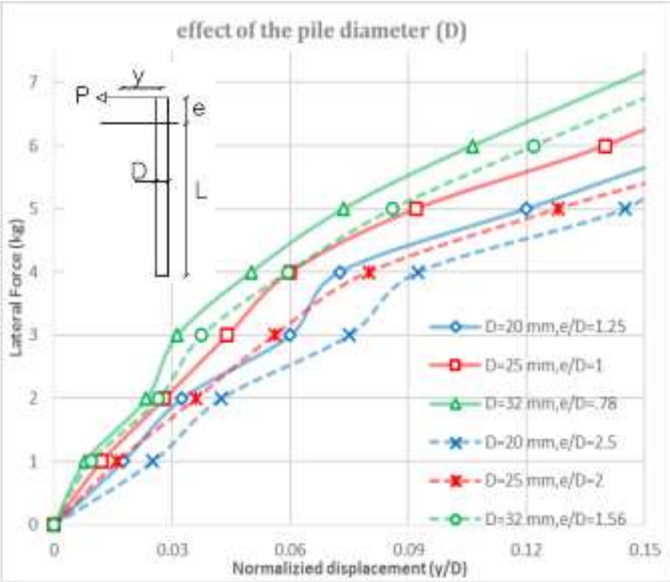

Fig (4.1). Load- displacement curves for vertical pile embedded in Soil (1). (Pile length = 35 cm)

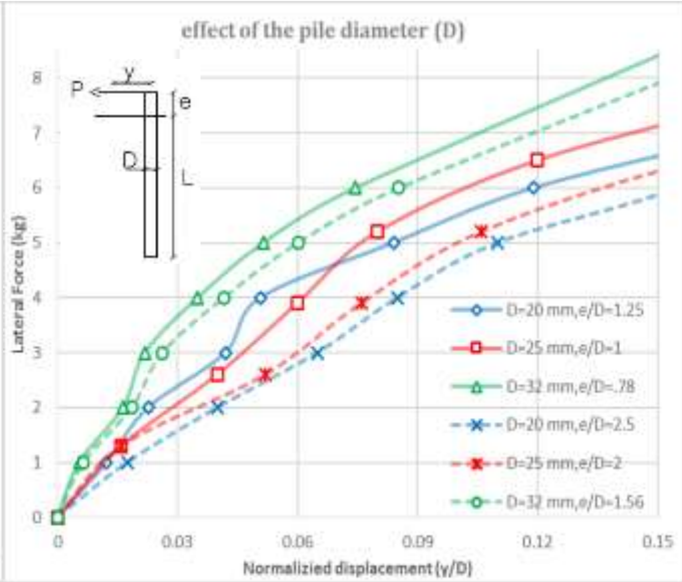

Fig (4.2). Load- displacement curves for vertical pile embedded in Soil (2). (Pile length = 35 cm)

From Fig (4.1) & Fig (4.1), it is noticed that:
As is expected, increasing the pile diameter decreases the displacement under the same horizontal load. Furthermore, this increase in the pile diameter reduces the effect of the load eccentricity on the obtained soil displacement. The same behavior is obtained for both clay soil and silt soil

For Soil (1). and (e/D)= 1.25 to 1, increasing the pile diameter (D) from 20 to 25 increases the pile load capacity by 10.6%

For Soil (1). and (e/D)= 1 to 0.78, increasing the pile diameter (D) from 25 to 32 increases the pile load capacity by 15.2%

For Soil (1). and (e/D)= 2.5 to 2, increasing the pile diameter (D) from 20 to 25 increases the pile load capacity by 4.2%

For Soil (1). and (e/D)= 2 to 1.56, increasing the pile diameter (D) from 25 to 32 increases the pile load capacity by 25%

For Soil (2). and (e/D)= 1.25 to 1, increasing the pile diameter (D) from 20 to 25 increases the pile load capacity by 7.7%

For Soil (2) and (e/D)= 1 to 0.78, increasing the pile diameter (D) from 25 to 32 increases the pile load capacity by 18.3%

For Soil (2) and (e/D)= 2.5 to 2, increasing the pile diameter (D) from 20 to 25 increases the pile load capacity by 7.7%

For Soil (2) and (e/D)= 2 to 1.56, increasing the pile diameter (D) from 25 to 32 increases the pile load capacity by 25.4%

For (e/D)= 1.25 to 0.78, increasing the pile diameter (D) from 20 to 32 mm increases the pile load by 30% for Soil (1), and 33% for Soil (2). For (e/D) = 2.5 to 1.56 the values are 31% for Soil (1) and 35.5% for Soil (2). However, doubling the eccentricity (e/D) decreases the pile load by 12% for Soil (1) and 11% for Soil (2).

Effect of the pile length (L)

Tests were carried out to study the effect of the pile length on the soil displacement. Fig (5.1) & Fig (5.2) present the load- displacement curves.

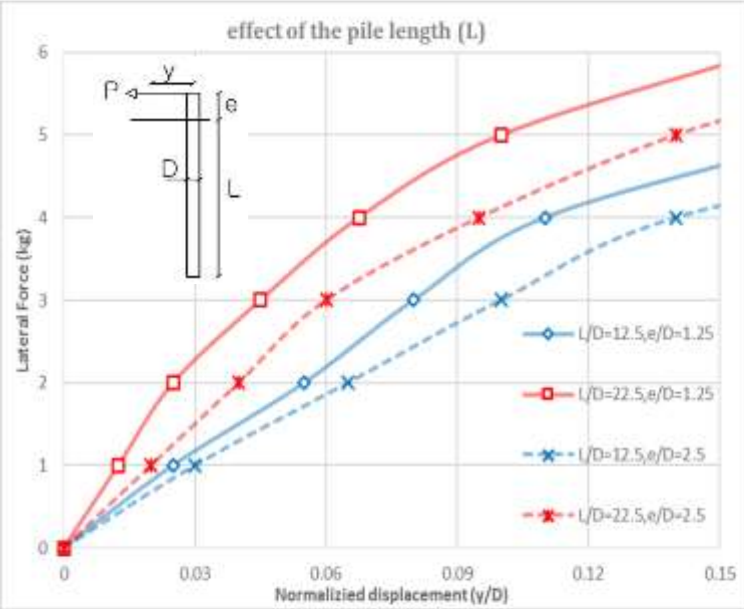

Fig (5.1). Load- displacement curves for vertical pile embedded in Soil (1). (Pile length = 35 cm)

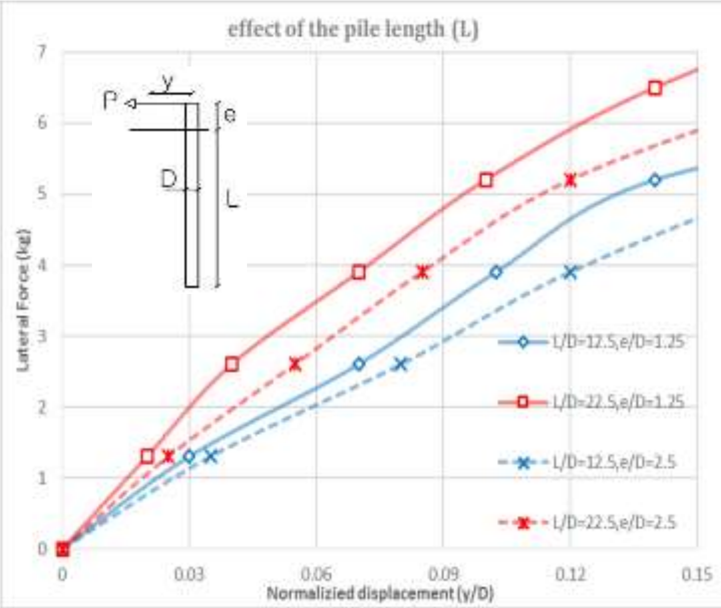

Fig (5.2). Load- displacement curves for vertical pile embedded in Soil (2). (Pile length = 35 cm)

From **Figs (5.1) and (5.2),** it is noticed that:

Pile length is selected to obtain short piles (i.e. L/D=12.5) and long piles (i.e. L/D=22.5).

For Soil (1) and short pile, increasing the eccentricity (e/d) from 1.25 to 2.5 increases the pile load capacity by 26.2%

For Soil (1) and Long pile, increasing the eccentricity (e/d) from 1.25 to 2.5 increases the pile load capacity by 24.9%

For Soil (2) and short pile, increasing the eccentricity (e/d) from 1.25 to 2.5 increases the pile load capacity by 26.2%

For Soil (2) and Long pile, increasing the eccentricity (e/d) from 1.25 to 2.5 increases the pile load capacity by 26.3%

Increasing eccentricity form (e/d) form 1.25 to 2.5 leads to decrease of the pile load for short piles by 12% in Soil (1), and 13% in Soil (2), and for long piles 11.5% in Soil (1) and 15% in Soil (2).

Conclusions

Based on the results of the carried out experimental work, it is concluded that:

- For (e/D)= 1, increasing the slenderness ratio (L/D) from 10 to 18 increases the pile load by 14% for Soil (1) and 23% for Soil (2). For (e/D) = 2 the values are 20% for Soil (1) and 18% for Soil (2). However, Increasing the eccentricity (e/D) from 1 to 2 decreases the pile load by 15% for Soil (1) and 16% for Soil (2).

- For (e/D) = 1 increasing the pile inclination angle (θ) from 0 to 18o increases the pile load by 50% for Soil (1) and 57% for Soil (2). For (e/D) = 2 the values are 70% for Soil (1) and 61% for Soil (2). Also, increasing the eccentricity (e/D) from 1 to 2 decreases the pile load by 14% for Soil (1) and 18.5% for Soil (2).

- For (e/D)= 1.25 to 0.78, increasing the pile diameter (D) from 20 to 32 mm increases the pile load by 30% for Soil (1), and 33% for Soil (2). For (e/D) = 2.5 to 1.56 the values are 31% for Soil (1) and 35.5% for Soil (2). However, doubling the eccentricity (e/D) decreases the pile load by 12% for Soil (1) and 11% for Soil (2).

- Increasing eccentricity form (e/d) form 1.25 to 2.5 leads to decrease of the pile load for short piles by 12% in Soil (1), and 13% in Soil (2), and for long piles 11.5% in Soil (1) and 15% in Soil (2).

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