The performance of laterally loaded piles in layered sandy soils under variable degree of saturation

Ahmed Hasan[1*], *Rizgar* Hummadi[1], and *Omed* Azeez[1]

[1]Civil Engineering Department, College of Engineering, Salahaddin University-Erbil, Erbil-KRG, Iraq

Abstract. This paper investigates the capacity of a single laterally loaded pile in single- and multi-layered sandy soils under dry, unsaturated and saturated conditions for a wide range of void ratios. Two Linear Variable Differential Transformers (LVDT) were employed to measure lateral displacements. For unsaturated tests, on one layer and two layered sandy soils, suction was controlled using the hanging column technique. Two different suction levels were applied to the soils. The results demonstrated that, the capacity of a single laterally loaded pile in single- and multi-layered sandy soils, under unsaturated conditions, were greater than those in dry and saturated conditions for loose, medium and dense states. Comparison between experimental data for unsaturated tests and several proposed mathematical expressions in the literature for calculating the capacity of a single laterally loaded pile in sandy soils showed a significantly good fit between measured and predicted values of the capacity of the piles where Bishop's stress is used in the expressions instead of effective stress, confirming the importance of inclusion of suction and degree of saturation in mathematical models when unsaturated conditions of soils were investigated.

1 Introduction

It is common practice that piles are often subject to vertical and lateral loads. Lateral loads might cause instability in structures which can be prevented by pile foundations. Examples of lateral loadings could be wind loads, earthquake loads, wave loads, soil active loads and inclined loads [1, 2]. Lateral loads may also occur in the form of impact loads, such as ship collision with a bridge pier [3, 4]. Due to the prevalence of such lateral loads on structures such as high-rise buildings and long-span bridges [5], pile foundation design requires careful consideration and analysis of laterally loaded pile behaviour. In almost all situations, soils surrounding pile foundations are not isotropic, homogenous or saturated/dry over the entire pile profile. In these conditions, the comprehensive evaluation of the behaviour of the pile response is very crucial for designing the foundation and the superstructure to better understand the soil-pile interaction. As in the other structures, the pile foundation design process should also consider both the ultimate limit state and serviceability state [6].

In many situations, piles are placed above the groundwater table (i.e., unsaturated zone) [7] where soils are under unsaturated conditions. The influence of matric suction (i.e., capillary stresses) in the active zone is typically not considered in the conventional design of deep foundations.

The allowable lateral loads on piles are determined from the following two values [8]: the lateral pile load with the factor of safety and the maximum allowable lateral load corresponding to acceptable lateral displacement. Several mathematical expressions have been proposed in the literature to predict the lateral pile load in coarse-grained soils for short and long piles such as Broms [9], Hansen [10], Meyerhof et al. [11] and American Petroleum Institute (API) [12]. The details of the mathematical expression of the API equation are shown below.

The API equation for sandy soils under dry and saturated conditions is given by:

$$P_u = (C_1 z + C_2 D)\,\sigma' \quad (1)$$

where P_u is the resistance in force/unit length for short piles. z is the depth below the surface of the soil. D is the pile diameter. σ' is effective stress. C_1 and C_2 are defined by:

$$C_1 = tan(\beta)\{K_p\, tan(\alpha_1)+0.4\, tan(\varphi)\, sin(\beta)[(1/cos(\alpha_1))+1]-0.4\, tan(\alpha_1)\} \quad (2)$$

$$C_2 = K_p - K_a \quad (3)$$

where $\beta = (45+\varphi/2)$ and $\alpha_1 = \varphi/2$. K_p and K_a are passive and active earth pressure coefficients, respectively.

The P_u in Eq. 1 is for coarse-grained soils under dry and saturated conditions. In the case of soils under unsaturated conditions, Eq. 1 might be able to predict P_u if the σ' changed by Bishop's stress (σ^*)[13]:

$$\sigma^* = (\sigma - u_a) + \chi(u_a + u_w) \quad (4)$$

* Corresponding author: ahmed.hasan@su.edu.krd

where σ is the total stress, u_a is the pore air pressure, u_w is the pore water pressure. χ is a weighting factor ranging between 0 and 1. The value of χ is suggested to equal to degree of saturation S_r for coarse-grained soils [14]. Thus, the σ' in API equation (Eq.1) can be replaced by σ^* to produce:

$$P_{us} = (C_1 z + C_2 D)[(\sigma - u_a) + S_r(u_a + u_w)] \quad (5)$$

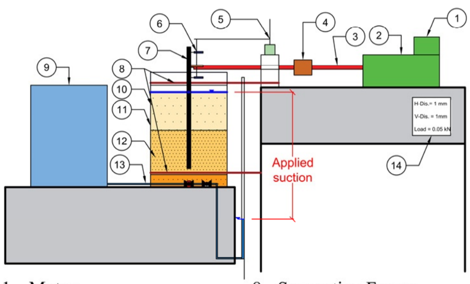
In the current study the major aim is to examine the predictions of Eq. 5 for P_{us} at different magnitudes of pile lateral deformation under unsaturated conditions and then compare the test results and the predictions of the proposed Eq. 5. Other aims are to further investigate the behaviour of pile foundations in unsaturated conditions subjected to lateral loading at different levels of suction and relative densities, in one- and two-layered soil beds.

2 Methodology and research design

2.1 Materials and test programme

The soil used in this study was taken from Kasnazan district in Erbil City -Iraq. This particular sand was chosen because it is a clean and naturally round. The sandy soil is classified as poorly graded sand (SP) according to Unified Soil Classification System (USCS). To produce repeatable preparation of the soil bed and eliminate any further effects that may occur during the bed preparation, the soil was sieved to get particles from 0.25 - 0.075 mm (fine sand). Table 1 summarizes the physical properties of the sand.

To study the behaviour of laterally loaded pile foundation, a solid steel rod used as a pile with diameter, D=30 mm, and length, L=450 mm (see, Fig. 1). The reason for choosing this rigid steel rod with these dimensions is to minimize any pile deflection during the experiments and to produce linear displacement.



1. Motor
2. Loading Gear
3. Loading Shaft
4. Load Cell
5. Magnetic holder
6. LVDT
7. Pile
8. Supporting Frame
9. Water Tank
10. Loose Sand
11. Glass Box
12. Dense Sand
13. Pipes
14. Display Unit

Fig. 1. General layout of the used equipment

A test box (container) with 300mm width, 300mm length, and 450 mm depth was manufactured (see, Fig. 1) in such a way to be convenient to study the behaviour of laterally loaded piles in dry, saturated and unsaturated conditions and to avoid boundary effect. To ensure the fixity of the test box during loading, the top and bottom of the box were fixed to the loading machine, as shown in Fig. 1. Two holes having 12 mm were made above 10mm from the bottom of the test box to control water level, degree of saturation and suction inside the soil. The holes were located in opposite directions from each other to allow a smooth flow of water into and out of the test box. The holes were connected to a T-shape connector. The first hole connected to the water tank to supply water to the test box and to raise the water level in the soil, and the second hole connected to a negative pressure gauge and burette for applying suction in the soil.

Table 1. Physical properties of the dry sandy soil

Density	Parameter	Value	ASTM No.
	Specific gravity, G_s	2.73	ASTM D854
	D_{10} (mm)	0.13	ASTM D422
	D_{30} (mm)	0.166	
	D_{60} (mm)	0.199	
	C_u	1.524	
	C_c	1.069	
	USCS	SP	ASTM D2487
	Minimum unit weight (kN/m^3)	13.38	ASTM D4254
	Maximum unit weight (kN/m^3)	16.85	ASTM D4253
Loose	Relative density (%)	12	
	γ_d (kN/m^3)	13.72	
	e	0.95	
	S_r (%)	72.4	
	The angle of internal friction (φ^o),	27.5	ASTM D3080
Medium	Relative density (%)	58	
	γ_d (kN/m^3)	15.2	
	e	0.76	
	S_r (%)	77.5	
	φ^o	32.2	
Dense	Relative density (%)	84.5	
	γ_d (kN/m^3)	16.2	
	e	0.65	
	S_r (%)	77.7	
	φ^o	36.5	

The process of applying suction in the soil inside the box requires a high air entry disk (HAED) to be fixed at the bottom of the box but due to the large size of the box, it was difficult to fit HAED into it. Thus, a sand filter layer was placed at the base of the box, as suggested by Shwan [15]. One of the crucial properties of the filter layer is to have a higher air entry value than the soil. This was achieved using a smaller particle size compared to the soil [16]. In this study, a selected range of fine sand particles, from 150µm to 75µm was chosen for the filter layer. The G_s, C_u and C_c for the filter layer were 2.731, 1.417 and 0.933, respectively.

A load cell (3000 N max.), and two LVDT's were used for measuring the applied load and lateral displacement, respectively. The lateral load was applied to the pile using a stepper motor from a direct shear apparatus (see, Fig. 1). The pile was loaded at a rate of 0.016 mm/s. The loading was stopped after the displacement of the pile reached 20 mm. The loading of the pile was displacement controlled and the applied load was recorded using data acquisition in the loading machine.

Table 2 shows the test programme followed in the current work. The letters D, S, and U represent dry, saturated and unsaturated soil conditions, respectively. For example, the code of Test U10(0.5) means that the test is performed on unsaturated soils when 10 kPa suction was applied in layered soil with L_1 to L_2 ratio of 0.5 and U5D indicates that the test is performed on unsaturated soil when 5 kPa suction was applied in a dense soil layer with pile embedded length of 30cm.

Table 2. Test programme followed in the study

Test code	Top layer state (L_1)	Bottom layer state (L_2)	Pile embedment length (cm)		L_1/L_2	Suction (kPa)
			L_1	L_2		
D(0.5)	Loose	Dense	10	20	0.5	0
D(1)			15	15	1	0
D(2)			20	10	2	0
S(0.5)			10	20	0.5	0
S(1)			15	15	1	0
S(2)			20	10	2	0
U5L	Loose	-	30	-	-	5
U5M	Medium	-	30	-	-	5
U5D	Dense	-	30	-	-	5
U5(0.5)	Loose	Dense	10	20	0.5	5
U5(1)			15	15	1	5
U5(1.5)			15	10	1.5	5
U5(2)			20	10	2	5
U5(2.5)			25	10	2.5	5
U5(3)			30	10	3	5
U10(0.5)			10	20	0.5	10
U10(1)			15	15	1	10
U10(2)			20	10	2	10

2.2 Soil bed preparation

The target densities were obtained inside the test box in different saturated conditions following the procedure performed by Shwan [15] as below:

1-Placing a sand filter layer at the bottom of the test box, then cyclic saturation and desaturation of the filter performed. When water flow out without air bubbles in the pipe, this indicated that the filter was fully saturated.

2- The soil bed prepared (in 2-cm layer) for saturated and unsaturated conditions similar to the filter layer (except in dry condition). The unsaturated soil is reconstituted in saturated condition, and then de-saturated in order to ascertain the soil is on the main drying retention curve.

3- On completion of the soil bed, the suction (5 kPa or 10 kPa) applied by the hanging column technique (HCT), see Fig. 1.

4- During suction application, the top of the soil layer was covered with two layers of plastic nylon sheets, to prevent evaporation.

2.3 Suction control and measurement

The water retention curves (WRC) for the soils and the filters in this study were obtained using the filter paper method (FPM). Fig. 2 shows the WRC for the soils along with their fitted curves from the proposed model by Fredlund and Xing [17]. The WRC for the filters were determined by following a similar way but their WRC curves are not presented here. Figure 2 shows three different air entry values for loose, medium and dense sands, as expected, with three corresponding residual suctions.

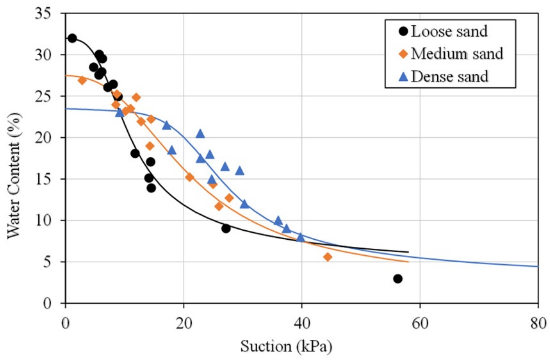


Fig. 2. WRC for sandy soil at different densities with fitting curves by Fredlund and Xing Model [16]

The levels of suction (5kPa and 10 kPa) were applied on the soils; therefore, the required depths were 0.51 m and 1.02 m below the surface of the soil. After several preliminary tests of the burette lowering and checking the water level every 3 hours, it was found that an equilibrium time of 1 day was suitable for the sand used in this study for both levels of suction.

3 Test results

Fig. 3 shows a comparison between the measured values of the ultimate lateral load resistances of the piles, which obtained by double tangent method at various lateral deformations under dry, saturated and unsaturated conditions for layered soils with 0.5, 1 and 2 (L_1/L_2 ratios). Inspection of Fig. 3 shows that the capacity for dry soils is higher than that for saturated soils. Furthermore, the capacity is highest when the soils were under unsaturated conditions. This can be attributed to the influence of suction which provides additional normal forces between individual soil particles, and hence apparent cohesion. Moreover, the higher the suction was the higher becomes the capacity of the laterally loaded pile. It can also be seen from Fig. 3 that the trend of changing the capacity of the laterally loaded pile for dry and saturated soils was different from unsaturated soils, confirming the importance of including the principles of unsaturated soil mechanics in analysing and designing infrastructures.

Figs. 4 to 7 show the measured values of the resistance of the laterally loaded pile for all unsaturated tests listed in Table 2, under different levels of applied suctions (5kPa and 10kPa) and different levels of lateral deformations (5%, 10%, 15% and 20% of the 30mm diameter of the pile). The figures also show their corresponding predicted values using Eq. 1 and Eq. 5.

Eq. 1 has been selected in this study based on research performed by Omed et al. [18] on the same sandy soils, suggesting that the equations proposed in the literature by Broms [9], Hansen [10] and Meyerhof et al. [11], consistently underestimated the capacity of the laterally loaded pile, under one layer and two layered conditions. They also observed that the predicted values of the laterally loaded pile by Eq. 1 were the most reliable ones compared to the equations proposed by Broms, Hansen and Meyerhof et al.

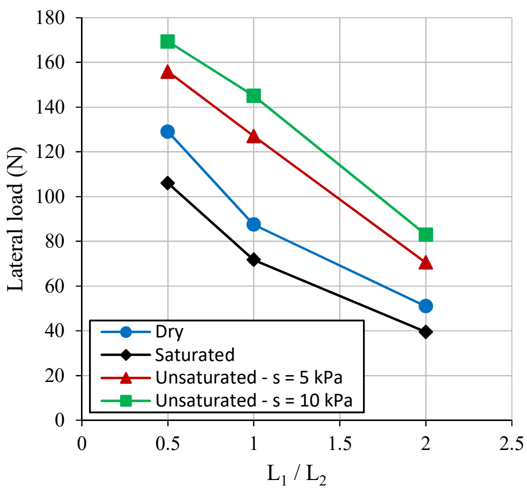


Fig. 3. The measured values of the maximum capacity of the laterally loaded pile for tests under dry, saturated and unsaturated conditions

3.1 Influences of relative density

Figs. 4 to 7 show the influence of relative density of one layer of sandy soils on the capacity of the laterally loaded pile at 5%, 10%, 15% and 20% lateral deformations for Tests U5L, U5M and U5D. Inspection of Fig. 7 shows that changing in the relative density of the sand from loose to dense state has a significant influence on the increase of the lateral loaded pile capacity up to 216% for unsaturated soils when 5kPa suction was applied in one layer soil bed. Figs 4 to 7 also show that by increasing lateral deformation from 5% to 20%, the lateral load applied to the pile was almost double for tests U5L, U5M and U5D. It can also be seen from Figs. 4 to 7 that the trend of increasing the lateral loaded pile capacity is almost linear when the relative density increased from loose to dense at all levels of lateral deformation.

3.2 Influence of suction and soil layering

The influence of suction level on the capacity of laterally loaded pile was examined using hanging column technique. Inspection of Figs. 4 to 7 shows that the capacity of laterally loaded pile increases with increasing applied suction from 5kPa to 10kPa in Tests U5(0.5) and U10(0.5) respectively, by an average value of 31%. Declined trend was observed in Tests U5(0.5), U5(1) and U5(2). Similar trend was also noted in Tests U10(0.5), U10(1) and U10(2).

Nine Tests were performed including U5(0.5), U5(1), U5(1.5), U5(2), U5(2.5), U5(3), U10(0.5), U10(1) and U10(2), in order to observe the influence of changing of thickness of the first soil layer on the capacity of the laterally loaded pile. The capacity of the laterally loaded pile for all nine tests was recorded at pile lateral deformations of 5%, 10%, 15% and 20%. It is observed from Figs. 4 to 7 that the capacity of the laterally loaded pile decreased as the L_1/L_2 increased up to (2). This is also true for Tests U10(0.5), U10(1) and U10(2). However, the capacity of the laterally loaded pile started gradually to increase after the value of L_1/L_2 exceeded 2 in Tests U5(2.5) and U5(3). The above observations were consistent when the pile deformed laterally at 5%, 10% and 15%. This trend was different at 20% lateral deformation (see Figs. 4 to 7). This can be attributed to the fact that the large deformation of the soil surrounding the pile led to a change in void ratio, thus, the degree of saturation. This subsequently changed the level of the matric suction in the surrounding soils. However, the value of S_r was considered constant. It was difficult to track changes of S_r due to the limited ability of the test apparatus. Due to changing layering conditions of the soil from one layer (dense) to two layers (loose layer/dense layer = 0.5) the pile lost approximately half of its strength (see, for example, Fig. 7). It can be deduced from the previous observations that, the layer that dominates the capacity of the pile is the upper layer up to 3 ~ 4 of the diameter of the pile.

3.3 Comparison between current test results and proposed models

Under unsaturated conditions, soil tests last long time, require complicated and valuable equipment. Therefore, it is highly recommended to propose a robust mathematical expression for the prediction of the behaviour of the laterally loaded pile. For this purpose, the measured values of the capacity of the laterally loaded pile from all unsaturated tests in Table 2 were compared to the predicted ones from Eq. 1 in Figs 4 to 7. Inspection of Figs. 4 to 7 shows that Eq. 1 consistently underestimated the capacity of the laterally loaded pile at lateral deformations 5%, 10%, 15% and 20% for all the tests. This was because Eq. 1 has been proposed for dry and saturated soil conditions. That is why Bishop Stress (σ^*) is used instead of effective stress (σ') in Eq. 1 to produce Eq. 5 for soils under unsaturated conditions.

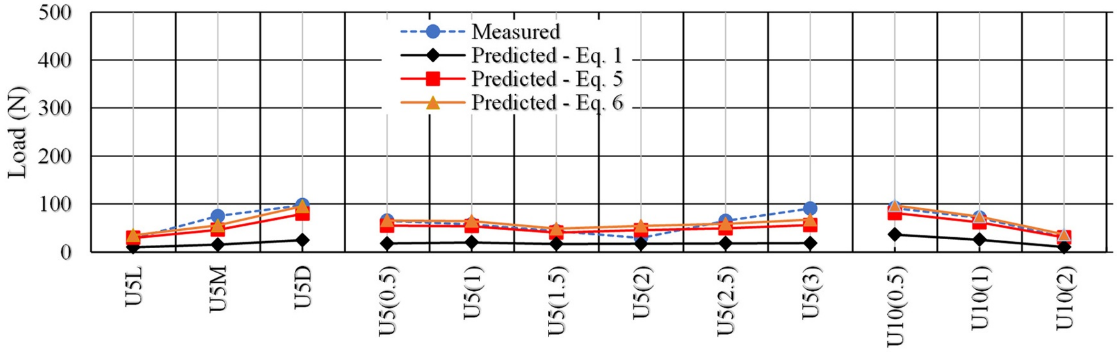


Fig. 4. Measured and predicted values of the lateral load at 5% lateral deformation by Eq. 1, Eq. 5 and Eq. 6 (α = 1.20)

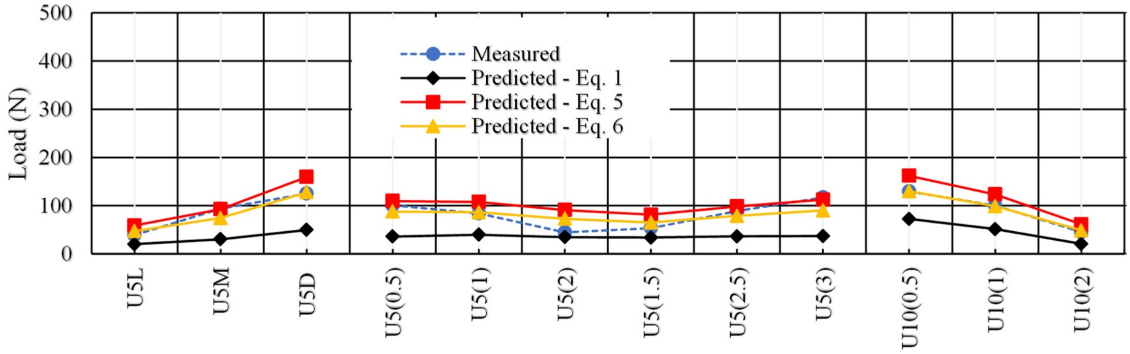


Fig. 5. Measured and predicted values of the lateral load at 10% lateral deformation by Eq. 1, Eq. 5 and Eq. 6 (α = 0.80)

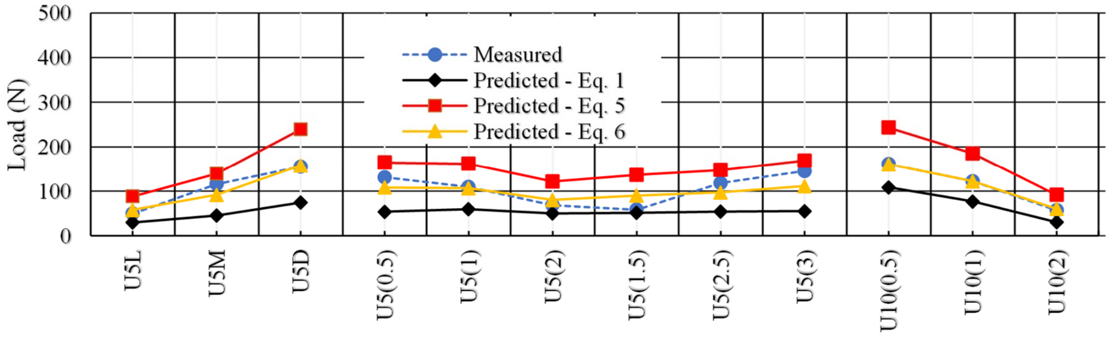


Fig. 6. Measured and predicted values of the lateral load at 15% lateral deformation by Eq. 1, Eq. 5 and Eq. 6 (α = 0.66)

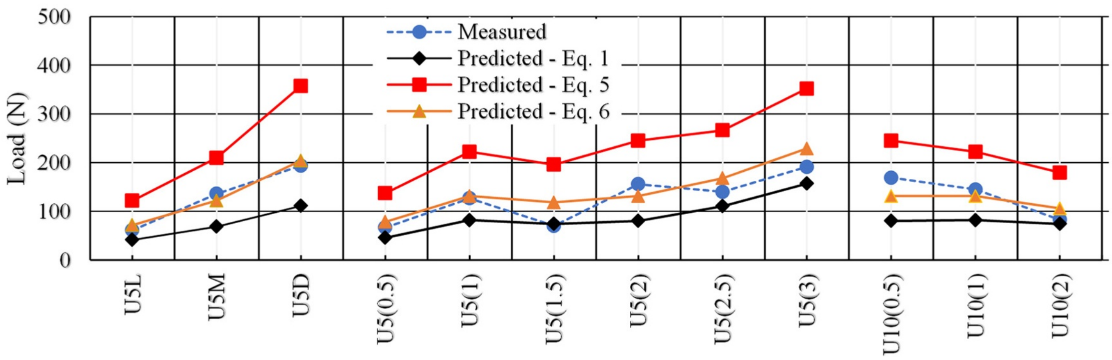


Fig. 7. Measured and predicted values of the lateral load at 20% lateral deformation by Eq. 1, Eq. 5 and Eq. 6 (α = 0.40)

Comparison between predicted values of the laterally loaded pile from Eq. 5 and the measured values for all tests presented in Figs 4 to 7 shows that Eq. 5 consistently overestimated, expect at 5% lateral deformation. This overestimation gradually increased when the lateral deformations increased. A modification of Eq. 5 was performed by including the parameter α in the second part of Bishop's stress in Eq. 5 by:

$$P_{us} = (C_1 z + C_2 D)[(\sigma - u_a) + \alpha S_r (u_a + u_w)] \quad (6)$$

Inspection of Figs. 4 to 7 shows that when the predicted values of P_{us} in Eq. 6 and measured values of P_{us} are compared at a certain value of lateral deformation of the pile, a particular value of α parameter should be proposed. It can be observed from Figs. 4 to 7 that the values of the α are 1.20, 0.8, 0.66 and 0.40 at pile lateral deformations of 5%, 10%, 15% and 20% for all the tests, respectively. The values of α were optimised using solver technique in MS Excel software.

The performance of Eq. 6 was examined by comparing the measured data and predicted ones by Eq. 6 for the 12 tests as shown in Figs. 4 to 7. The values predicted by Eq.6 match measured values excellently for one layer soil in Tests U5L, U5M and U5D. Furthermore, Eq. 6 was also gives a high performance when it predicted values compared to the recorded ones in two layered soils in Tests U10(0.5), U10(1) and U10(2). Predictions of Eq. 6 are less accurate when they compared to the measured values in Tests U5(0.5), U5(1), U5(1.5), U5(2), U5(2.5) and U5(3), particularly, at 15% and 20% of the lateral deformations of the pile.

Based on the optimization of the values of parameter α at different levels of lateral deformations (*LD*) of the pile, a linear relationship has proposed (see, Fig. 8) between them having coefficient of determination (R^2) of 0.96 by:

$$\alpha = -0.05\,LD + 1.4 \quad (7)$$

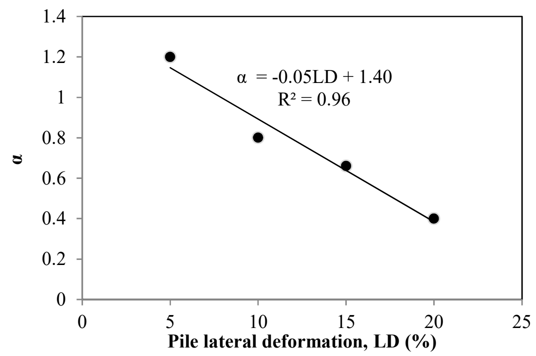


Fig. 8. Variation of α against pile lateral deformation

4 Conclusions

The following conclusions can be suggested from the test results and the proposed mathematical expression:

1- It was found that increasing relative density of the sandy soils has a significant improvement of the lateral loaded pile capacity up to 216% for unsaturated soils when 5kPa suction was applied in one layer of soil.

2- The Modified The API equation (Eq. 5) consistently overestimated, under unsaturated and saturated conditions, expect at 5% lateral deformation.

3- Including the α parameter into Bishop's stress in Eq. 6 gives excellent results compared to measured ones for one layer and two layered for sandy soils under unsaturated conditions.

4- Further investigation is necessary to confirm the application of the α parameter by applying higher values of matric suction (more than 10 kPa) to the layered sandy soils.

References

1. C.-C. Fan, J. H. Long, Comput. and Geotech., **32** (2005).
2. S. Ahmed,M. Sadique, V. Sawant, Inter. J. of Ad. Resea. In Sci. & Eng., 6 (2017)
3. M. Budhu, Soil Mechnics and Foundations, John Wiley & Sons., (2010)
4. W. F. Vanimpe, L. C. REESE, *Single piles and pile groups under lateral loading*, CRC press (2010)
5. H. Kim ,M. Prezzi , R. Salgado, Canad. J. of soil sci., **97**, (2016)
6. L. Bowles, *Foundation analysis and design*, McGraw-hill, (1996)
7. D. G. Fredlund, N. R. Morgenstern, J. of Geotech. and Geoenvi. Eng., **103**, (1977)
8. S. Prakash, H. D. Sharma, *Pile foundations in engineering practice*, John Wiley & Sons, (1990)
9. B. B. Broms, J. Soil Mech. Found. Div., 90, (1964)
10. B. J. Hansen, Danish Geotech. Inst., (1961)
11. G. Meyerhof , S. Mathur , A. Valsangkar, Canad. Geotech. J., **18**, (1981)
12. API RP2A-WSD, American Petroleum Institute Washington, DC., (2011)
13. A. W. Bishop, Teknisk Ukeblad, **39**, (1959)
14. E. E. Alonso, J.-M. Pereira, J. Vaunat, S. Olivella Geotechn., **60**, (2010)
15. B. Shwan, PhD, University of Sheffield, (2015)
16. W. T. Hong, Y. S. Jung, S. Kang, J. S. Lee, Materials, **9**, (2016)
17. D. G. Fredlund, A. Xing, Canad. Geotech. J., **31** , (1994)
18. O. Azeez, R. Hummadi, A. M. Hasan, Int. J. Eng. Res. Tech. (2019)