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Effect of Soil Degree of Saturation on Pile Load Capacity at Different Slenderness Ratios

Lateef J. Mohammed Saeed*, Qutaiba G. Majeed and Qassem H. Jalut

Department of Civil Engineering, University of Diyala, 32001 Diyala, Iraq

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ABSTRACT

The conventional methods follow in designing piles adopt the assumption of saturated condition of soil depending on soil parameters at saturated condition while at most cases the whole piles or part of them lays in unsaturated soil zone, thus the estimated pile capacity will be far of the real. This issue made the need to study the pile capacity at unsaturated condition and compare it with saturated condition. This study is performed to investigate the behavior of single pile inserted in clay soil at different degrees of saturation. The test was performed under axial compression loads by using different degrees of saturation (100,80,60,40%). A pile of 14x14 mm cross section with different slenderness ratios (L/D) (24,30,36) employed in the study. The impact of saturation degree, matric suction and slenderness ratio on pile load capacity is examined. The results illustrate that pile capacity influenced considerably by the saturation degree, matric suction, and slenderness ratio. The results showed that when saturation degree reduced from 100% to (80,60,40%), bearing capacity of pile increased for all L/D used. An example ultimate capacity of pile with L/D (24) increased (380, 512, 63%) by decreasing degree of saturation from 100 % to(80 ,60 ,40%) respectively, this means the pile capacity increased about four times by decreasing Sr. from 100 % to 80 % , five times by decrease Sr. from 100% to 60 % and little increase (63 %) in pile capacity by decreasing Sr. to 40 %.A close results had been observed at L/D 30 and 36. The effect of increasing slenderness ratio had been studied at different saturation degrees, an example by increasing L/D from 24 to 30 pile capacity increased (11.45, 10.2, 25, 32.5%) at Sr.(100 ,80 ,60 ,40%) respectively.

1. Introduction

Pile foundations are embedded within the ground to transfer heavy loads from the structure above to the soil below, and to reduce the amount of settlement. These foundations are commonly used for structures like tall buildings, bridges, and retaining walls; sometimes they have to deal with both vertical and horizontal forces at the same time.

Often, the whole pile or part of it is in soils that are not fully saturated. However, designing piles often follows the rules of soil mechanics for saturated soils, which do not consider the impact of matric suction in soils that are not fully saturated. Because of this, the ability of the piles to carry loads and their settlement behaviour may not be predicted accurately, [1].

Many researchers have been interested in how matric suction affects the shear strength of soils in partially saturated condition, [2-5].

The shear strength of a soil influenced clearly by matric suction, which leads to support more load [6,7].

The design of structures based on soil mechanics for saturated soils is under estimated

* Corresponding author.
E-mail address: latif-jassim@uodiyala.edu.iq
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by using saturated design criteria, the approach of unsaturated criteria, which considers that the pores media has two fluid phases, represent more reliable behaviour of soil under different saturation degrees, [8].

Some researchers studied the influence of degree of saturation and matric suction on pile behaviour practically or theoretically or by combining both of them, most of these researchers made their searches on sand and little of them studied the influence in clay soil which is the more difficult section, however more studies needed in this field to give more information that could be helpful in this zone.

Hereunder the most important studies done in the field of piles in partially saturated soils:

Georgiadis, et al., [9] studied the behaviour of piles embedded in partially saturated soil. They developed a model of partially saturated soil at constitutive load and used a finite element Program (ICFEP). The study showed that there is big different in predicted piles bearing capacity embedded in fully and partially saturated soils under different loads and different groundwater tables.

Vanapalli and Taylan, [10] investigated the capacity of pile embedded in a fine-grained soil in case of fully and partially saturation. They found that matric suction greatly affected the capacity of single pile. They used the parameters of shear strength in saturated soil and the soil water characteristic curve to incorporate the impact of matric suction using modified methods of λ, β and α. The results indicated that matric suction increased pile capacity significantly.

Fattah, et al., [11] performed analysis of finite element on a single pile in clayey soils in case of fully and partially saturation. They used laboratory methods to calculate the partially saturated parameters and they analysed using the programs of finite element, SEEP/W and SIGMA/W. The study showed that in partially saturated soil the pile capacity was about (3-5) times greater than the capacity of pile in saturated soil and the impact of lowering of water table was more than the impact of matric suction on pile capacity.

Al-Omari, et al., [12] evaluated the pile groups capacity inserted in unsaturated soil and saturated soil at different dry densities. They used clayey soil and compared the results with theoretical methods (modified and conventional) methods λ, α and β. The tests indicated that using method of β gave pile capacity near the results obtained from experimental work for both unsaturated and saturated conditions, unlike the other two methods.

Cheng and Vanapalli, [4] developed a numerical method to evaluate the behaviour of piles in unsaturated and saturated soils for both lateral and vertical loads. They used a subroutine user in ABAQUS (USDFLD) to evaluate the modulus of elasticity and shear strength of soils at unsaturated condition. The numerical results indicate that there is very big increase in pile capacity s by lowering the GWT (ground water table) from surface.

Heni, [13] performed compression tests on piles that were driven in sandy clay prepared with three different water contents. The results showed that the resistance of single piles under compressive loads affect by the increase of matric suction and slenderness ratio (L/D). The soil shear strength and pile-soil friction resistance also increased.

The study aims to investigate the behaviour of single pile in different degrees of saturation through investigate compression bearing capacity of pile and it's relative to the degree of saturation, effect of matric suction on bearing capacity of piles, the effect of variation of slenderness ratio in different degrees of saturation on pile capacity.

2. Methodology

2.1Materials used

2.1.1 Soil used

Soil used in the tests was natural soil brought from north of Baquba city, Diyala government, Iraq. Classification of soil used in this work is clay (CL). Several tests were performed to determine mechanical and physical characteristics, as illustrated in Table 1, Table 2 and Figure1.

Table 1: Engineering characteristics of soil used

Soil Property	Unit	Value	Standard
Specific Gravity (Gs)		2.7	ASTM -D- 854
Liquid limit LL	%	31	
Plastic limit PL	%	18	ASTM -D- 4318
Plasticity index I.P	%	13	
Sand	%	4	ASTM -D -422
Silt	%	43	
Clay	%	53	
Maximum dry unit weight	kN/m^3	16.75	ASTM -D -698
Optimum moisture content	%	16.7	
(USCS)classification		CL	ASTM -D- 2487

Table 2: Unconfined compression strength (qu) for different degrees of saturation

Degree of saturation Sr.	unconfined compression strength (qu) kN/m^2	Standard
60 %	480	
80%	370	ASTM-D-2166-00
90 %	130	
100 %	60	

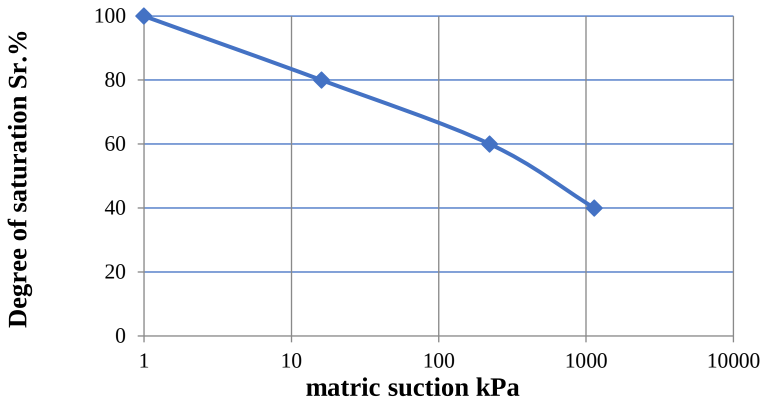


Figure 1. Relationship between degree of saturation and matric suction (soil water characteristic curve)

2.1.2 The piles used

Three piles of different slenderness ratios were employed in this work, as shown in (Figure 2. All pile models are made of hollow closed end rectangular Aluminum with a 14x14 mm cross section dimension. piles come in three lengths: (600, 500,400) mm with embedded lengths of L/D (24,30,36).

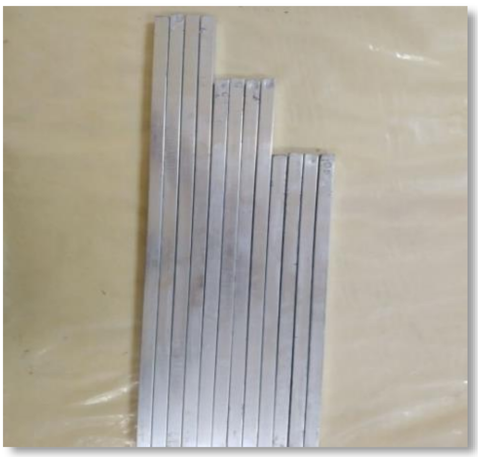


Figure 2. The piles used in the study.

2.1.3 Steel frame

The frame is locally designed and manufactured. From steel channels of (100 x 50 x 8 mm), it has 2 m height and 1 m width.

A hydraulic jack piston of (4 ton) is attached to the frame. The hydraulic jack is used to push and insert the piles into the soil. During the test the hydraulic jack attached to (30 kN) load cell S shape which linked to data logger as shown in Figure 3.

Figure 3. Steel Frame

2.1.4 Laboratory model box steel container

The test container was locally made from a steel box with (600 x 400 x 600) mm of thickness (4mm) to provide sufficient stiffness against the stresses from soil compaction and pile driving as shown in Figure 4.

Figure 4. The steel box used in the study

2.2 Soil preparation

a) Soil was air dried and crunched to pass through sieve #10, the initial water content of crunched soil was measured by taking samples from the soil according to ASTM (D 2216), [14].
b) To obtain soil with required degree of saturation Sr.%, a large electric mixer was used to mix 30 kg of soil with a predetermined amount of water for enough time to make it uniform as shown in Figure 5. The determination of water content to achieve required Sr. based on determining specific gravity of soil and dry unit weight then determining void ratio of this dry unit weight to calculate the required water content for the specific degree of saturation.This process was repeated until getting enough amount of soil to fill the model container.

Figure 5. Soil mixing

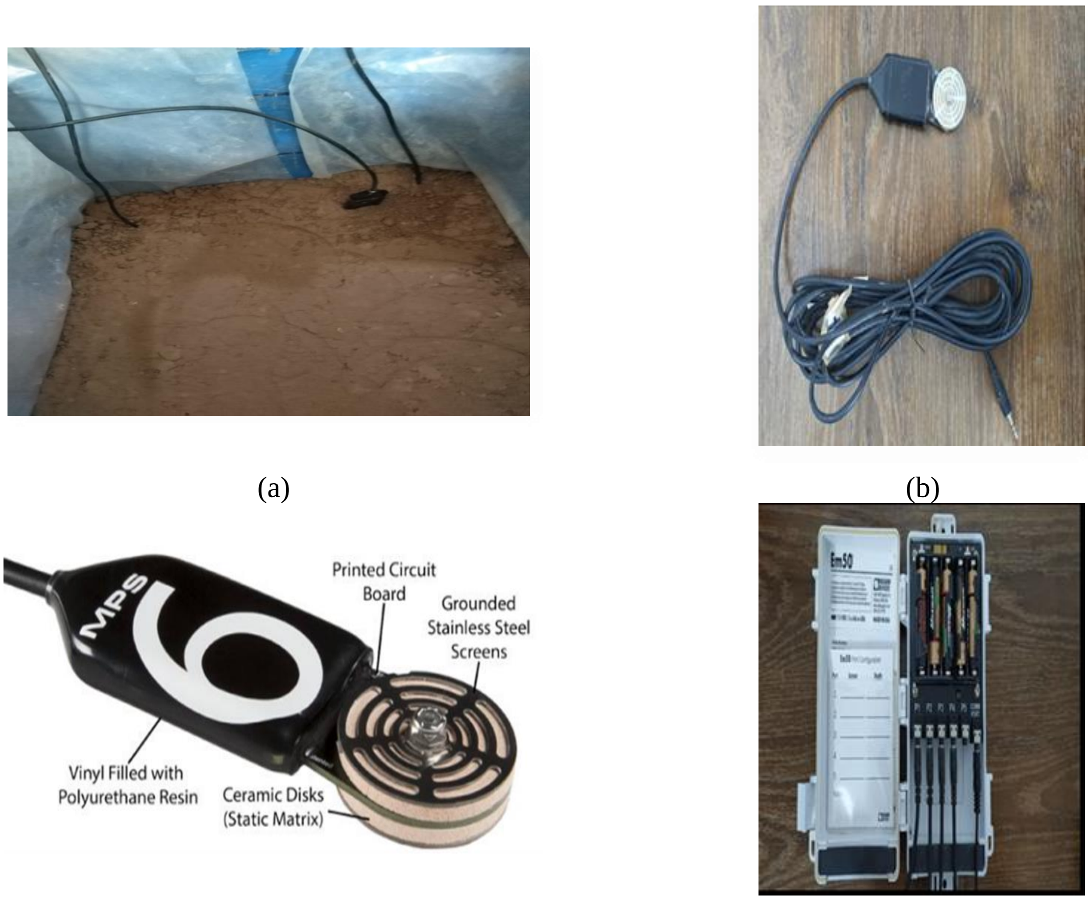
c) After sufficient mixing of soil, it was kept in sealed polythene bags of 15 kg capacity, water content checked by taking samples from each bag then the bags kept sealed for a period of at least 72 hours to achieve a regular water distribution and get a uniform moisture content.

d) To reach soil density of (16 kN/m^3), Pre calculated of soil amount was spread to occupy soil layer of 100 mm depth in the model box (water content was checked again by taking samples from each bag before spreading in the container),then soil was compacted using special compaction device to the required dry unit weight. The soil layers were constructed until fill the model box.

2.3 Soil suction measurement

There are two methods to measure the soil suction: Indirect and direct. In this research indirect method adopted through using matric potential sensors (Mp6 sensor and the Em50 Data logger) that measures the negative pore water pressure. This allows measuring the matric suction of soil. Four sensors were placed at different depths under the surface of soil in cases of unsaturation to measure the suction in the unsaturated clay. The equilibrium conditions were reached after 24 hours, as shown in Figure 6.

Table 3 Illustrates the specifications of manufacturer of (Mp6) matric potential sensors specifications (Decagon Devices, Inc.).



(a) (b) (c) (d)

Figure 6. (a) Fixing Mp 6 sensor in soil layers (b) and (c) (Mp6) electrical matric potential sensor (d) Em50 Data logger

Table 3: Mp 6 matric potential sensors specifications (Decagon Devices, Inc.)

Parameter	Value
Range	-9kPa to 100000 kPa (pf 2.00 to pf 9.01)
Resolution	0.1 kPa
Duration of measurement	150 ms
Range of operating temperature	-40 to 60 C^0

2.4 Installation of model piles

After preparing the soil, the test box brought inside the steel frame. The pile is vertically aligned using the bubble scale Then inserted in the soil using the hydraulic jack till reach the required embedded depth, three piles inserted in each container with different L/D (24, 30, 36) The embedded lengths were (335, 420,500 mm) respectively to study the effect of L/D at each degree of saturation, as shown in Figure 7. The limitation of lateral direction is (8-12) of pile section's width between pile side and steel box wall, [15]. In addition, the clear distance the tip of pile and the base of model box is (3-8) of pile width, [16].

Figure 7. Installation of model piles

2.5 Testing piles under compression

After three days minimum of instillation the piles in order to let the soil to regain its thixotropic effect. the vertical (compression) test is done by applying load on the pile using 30 kN load cell (S-shape). The inserting rate was 1 mm/min based on ASTM D1143(2018), [17]. The criteria of failure adopted in this study to evaluate the ultimate pile resistance was the Double tangent method suggested by Mansur and Hunter, [18].

3. Results and discussion

3.1 Effect of saturation degree

Figure 8 Illustrates that ultimate pile capacity for single pile of L/D (24) when soil is fully saturated (Sr.=100 %) is (400N) and increased when Sr. becomes 80 %. to be (1920N) then increased when Sr. becomes 60 % to be (2450N) then decreased when Sr. becomes 40 % to be 655N. It can be noticed that saturation degree has a strong contribution and impact on pile capacity and increased when decreasing degree of saturation from fully saturation (100 %) to partially saturation (80 %) and further increasing in pile capacity can be achieved by further decreasing in degree of saturation to (60 %) then decreased by further decreasing in Sr. to (40 %), but still more than pile capacity at saturated condition, although matric suction increased in Sr.40% to be 1130 kPa but pile capacity decreased due to decreasing the adhesion force between pile surface and soil due to decreasing in water content of soil which leads to split the pile from the soil .Since pile shaft resistance depends on adhesion factor (α) and undrained shear strength (Cu), the pile capacity decreased at Sr.40% due to extreme decrease in water content. The same thing happened in compression test for piles of L/D = (30, 36), which can be noticed in Figures 9and10, pile capacity increased to reach the maximum value by decreasing Sr. to 60% then decrease by decreasing Sr. to 40%.

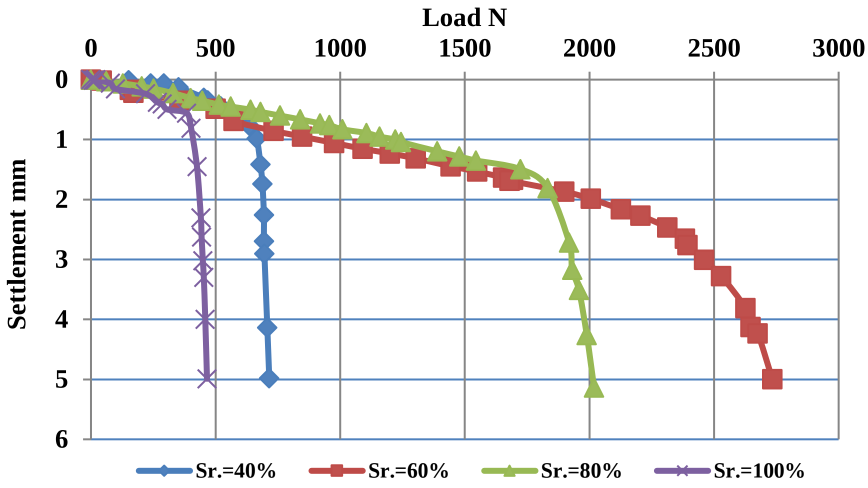


Figure 8. Load settlement curve for compression for pile of L/D=24 in different Sr.%

Figure 9 explicates the capacity for single pile of L/D=30 when soil is fully saturated (Sr.=100%) is (530N) and increased when Sr. becomes 80% to be (2400N) then increased to be (2700N) at Sr. 60% then decreased to be (730N) when Sr.=40%.That mean bearing capacity increased considerably by decreasing saturation degree of soil from saturation condition to 80% saturation due to the physical bonds generated between soil particles due to the surface tension of water particles surrounding soil particles and these bonds between soil particles results increase the shear strength of soil which leads to increase in pile capacity, further more by decreasing Sr. to 60 % maximum pile resistance occurred, that means maximum shear strength of this soil appeared at this degree of saturation.

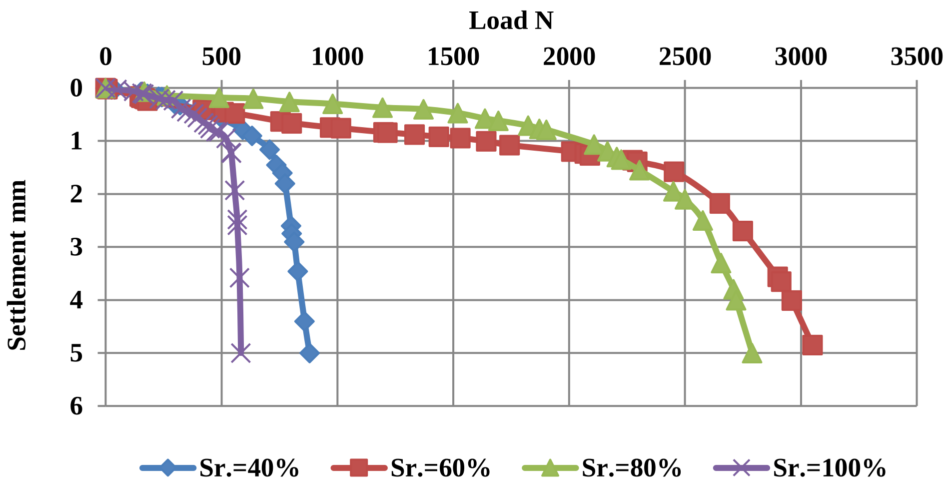


Figure 9. Load settlement curve for compression for pile with L/D=30 in different Sr.%

Figure 10 shows that capacity of single pile of L/D=36 when soil is saturated (Sr.=100 %) is (725N) and increased when Sr. becomes 80 % to be (3800N) then increased to be (4200N) when Sr.=60% then decreased to be (975N)when Sr.=40%.It can be noticed that the same trend happened in the third Figure (10),large increase in pile capacity by decreasing Sr. from 100% to 80 % , more increase in pile capacity by decreasing Sr. to 60% and little increase in pile capacity by decreasing Sr. to 40 % due to the same reasons mentioned on pile with L/D 30.

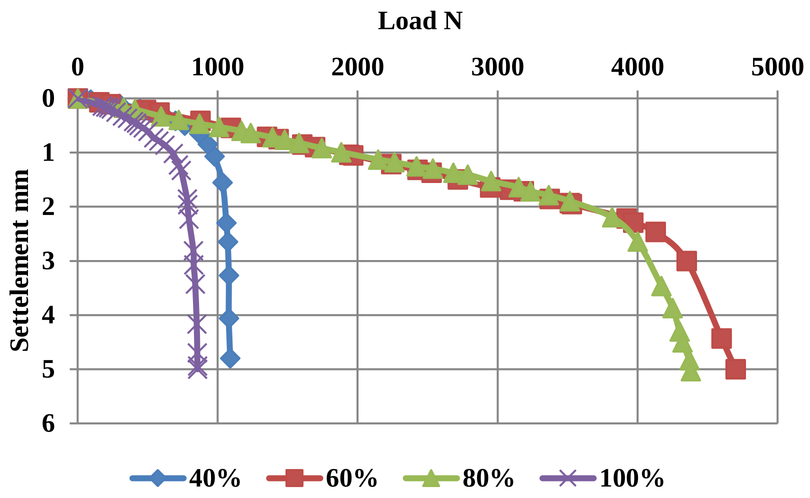


Figure 10. Load settlement curve for compression for pile of L/D=36 in different Sr.%

Figure 11 shows clearly the impact of saturation degree in increasing the pile ultimate capacity. It can be noticed that the maximum value lays at 60 % and minimum value lays at fully saturated condition further more when Sr. reduced to 40 % the pile capacity reduced too but remains more than pile capacity at saturated condition.

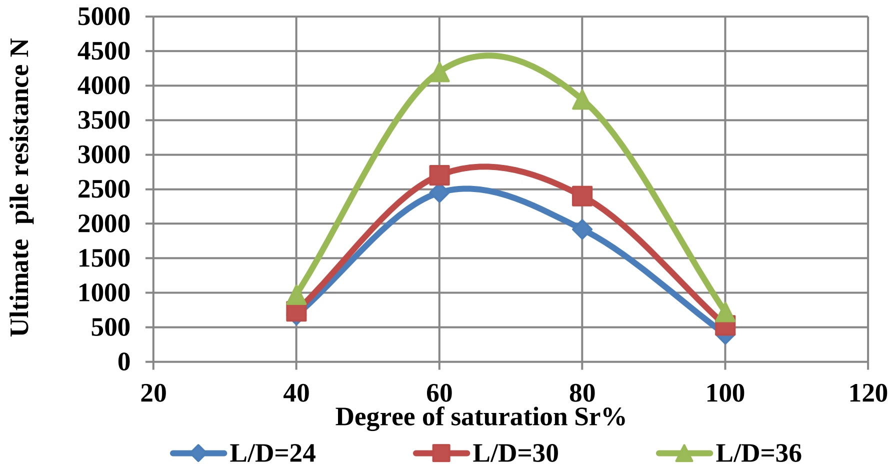


Figure 11. Ultimate pile resistance versus degree of saturation Sr.% curve in different L/D

3.2 Effect of slenderness ratio

Figure 12 shows that at Sr. 40%, pile capacity increased by increasing L/D. When L/D increased from 24 to 30 ultimate pile capacity increased from 655 N to 730 N and when L/D =36 pile capacity became 975N.

Figure 13 shows that at Sr. 60%, the pile capacity increased by increasing L/D. When L/D increased from 24 to 30 ultimate pile capacity increased from 2450 N to 2700 N and when L/D = 36 pile capacity became 4200N.

Figure 14 shows that at Sr. 80%, pile capacity increased by increasing L/D. When L/D increased from 24 to 30 ultimate pile capacity increased from 1920 N to 2400 N and when L/D = 36 pile capacity became 3800 N.

Figure 15 shows that at Sr. 100%, pile capacity increased by increasing L/D. when L/D increased from 24 to 30 ultimate pile capacity increased from 400 N to 530 N and when L/D =36 pile capacity became 725 N.

Figure 16 shows clearly the effect of L/D on increasing the pile ultimate capacity. It can be noticed that the when Sr.is 40 % and 100% the effect of L/D is not large as when Sr. 60% and 80%. That is mean there is a contribution between Sr. and L/D on pile capacity.

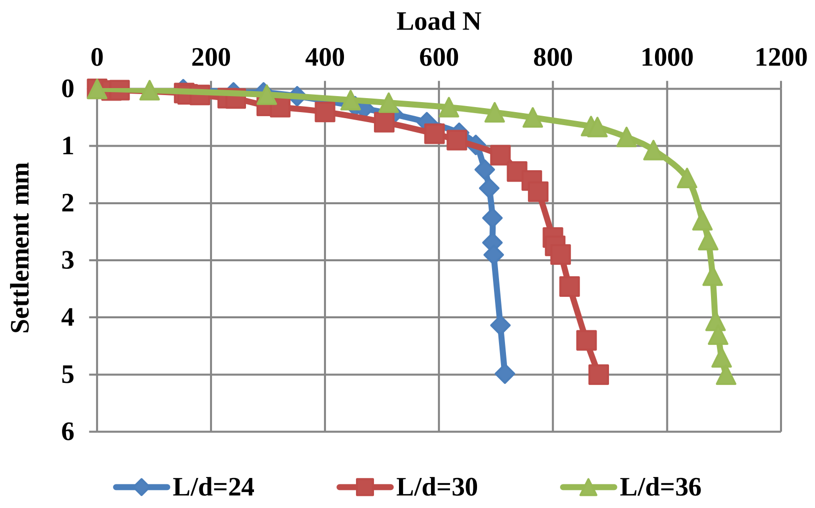


Figure 12. Load settlement curve under compression with Sr.=40% for different L/D

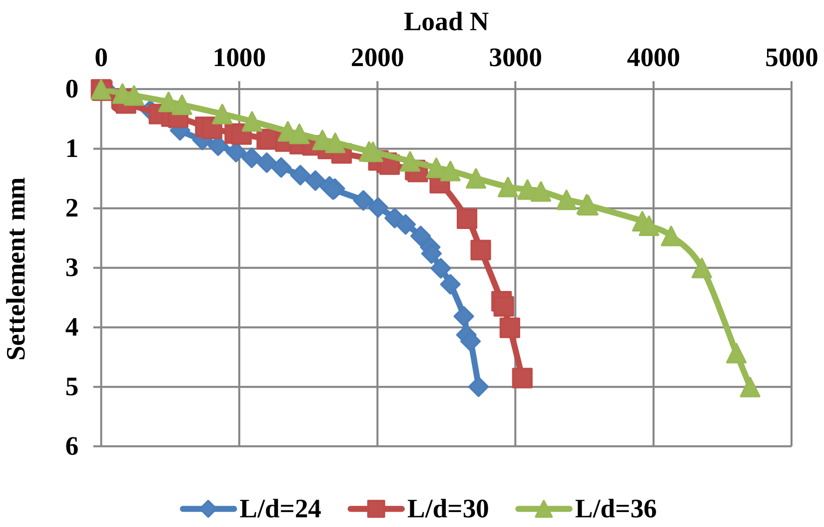


Figure 13. Load settlement curve under compression with Sr.=60 % for different L/D

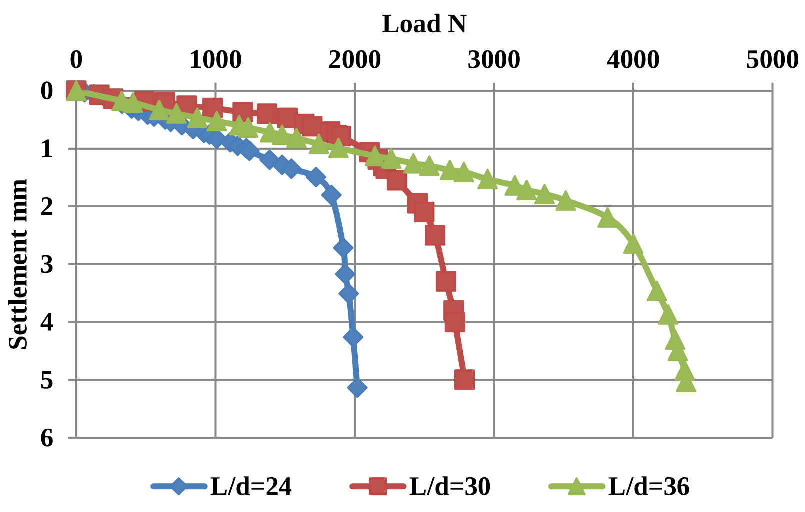


Figure 14. Load settlement curve under compression with Sr.=80% for different L/D

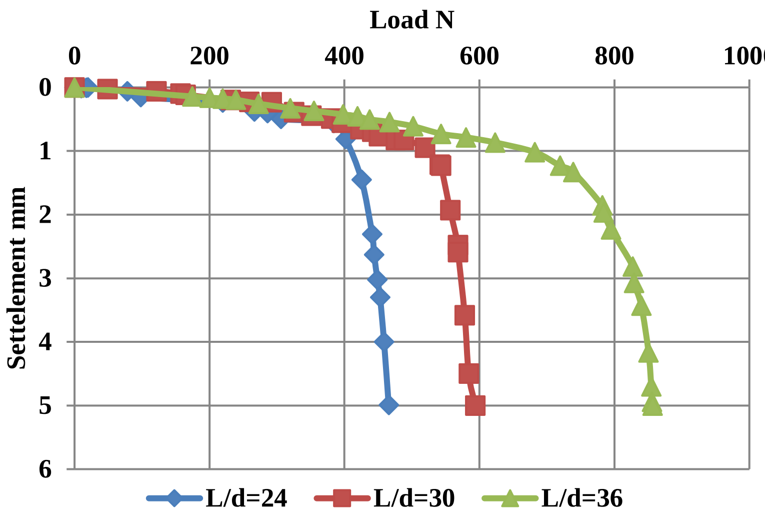


Figure 15 Load settlement curve under compression with Sr.=100% for different L/D

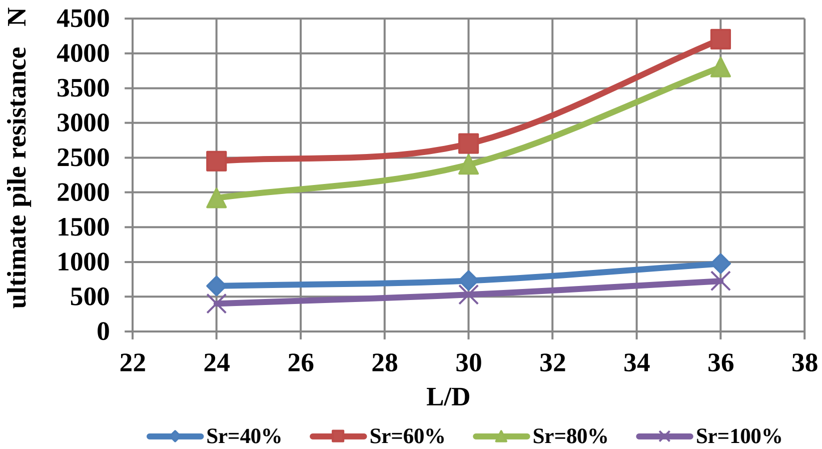


Figure 16. Ultimate pile resistance versus L/D for different degrees of saturation Sr.%

The results obtained of pile capacity of single pile inserted in clay soil at different degrees of saturation for different slenderness ratios can be summarize in Table 4.

Table 4: Pile capacity N at different degrees of saturation and different slenderness ratio

Sr. %	**L/D**		
	24	**30**	**36**
100	400	530	725
80	1920	2400	3800
60	2450	2700	4200
40	655	730	975

4. Conclusions

The most important conclusions has been obtained from the study can be summarized as follows.

1. The degree of saturation has a strong effect on pile capacity for all L/D ratios (24, 30, 36). Pile capacity increased by decreasing Sr. from100 % to 80 % then increased again by decreasing Sr. from 80 % to 60 % due to the effect of matric suction and the effect of surface tension of water particles surrounding soil particles which give the physical bond between soil particles that increase the soil shear resistance, that leads to increase pile capacity in partially saturated soil, while in saturated soils surface tension

of water disappear that make the soil lose the bonds between its particles, that leads to lose its shear strength which leads to decrease in pile capacity in saturated soils. When Sr. reduced to 40 % the pile capacity reduced too but remains more than pile capacity at saturated condition. The maximum value of pile capacity at Sr.60 % and minimum value lays at fully saturated condition for all L/D ratios.

2. When Sr. decreased from 100 % to (80 ,60 ,40%) the pile capacity increased (380, 512, 63%) respectively in pile with L/D (24), the increase was (353, 410, 38%) respectively in pile with L/D (30) and (424, 480, 34%) respectively In pile with L/D (36).
3. There is a large impact of slenderness ratio (L/D) on pile load capacity in clay soil but the effect of saturation degree on load capacity much more the effect of slenderness ratio.
4. When L/D increased from 24 to 30, the ultimate load capacity increased (11.45, 10.2, 25, 32.5%) at Sr. (100 ,80 ,60 ,40%) respectively, the increase was (33.56, 55.5, 58.3, 37%) respectively when L/D increased from 30 to 36.

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