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Distribution of axial force and shear stress along a compression pile embedded in saturated and unsaturated swelling soil

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ABSTRACT: This study consists of a series of compression load tests performed on a single model pile embedded in an expansive soil mixture prepared at different initial saturation degrees, namely; 70, 80, 90 and 100%. The soil mixture is consisted of 70% bentonite and 30% sand which reflects a very high expansive soil. The initial soil suctions were measured. The distribution of the axial force along the pile shaft during the load–settlement tests is calculated by measuring the mobilized strain on the surface of the pile shaft using strain gauges. The axial force distribution in unsaturated condition is complicated and changing from tension in the upper third of the shaft to be compression in the middle and lower thirds of the shaft. Consequently, the skin resistance would be as a result positive at the upper third of the shaft and negative at the middle and lower thirds of the shaft. For a single pile embedded in a fully saturated expansive soil mixture, the axial force is compressive and decreases with the pile depth while the average skin resistance is positive along the shaft indicating that most of the load applied at the pile head is transferred through the mobilized positive skin resistance along the shaft. The load and pile head settlement in unsaturated expansive soil is higher than that in the fully saturated soil.

RÉSUMÉ : Cette étude présente une série de tests de compression effectués sur un seul modèle de pile embarqué dans un sol expansif avec différents degrés de saturation initiale, à savoir 70, 80, 90 et 100%. Le mélange du sol est composé de 70 % de bentonite et de 30 % de sable, ce qui représente un sol très étendu. Les succions initiales du sol ont été mesurées. Pendant les essais de tassement, la répartition de la force axiale le long de l'arbre du pieu est calculée en mesurant la contrainte mobilisée au niveau de la surface de l'arbre du pieu à l'aide de jauges de contrainte collées sur le pieu considéré. Dans le cas de non saturation, la répartition des forces axiales est complexe et varie de la tension dans le tiers supérieur de l'arbre du pieu à la compression dans les tiers moyen et inférieur de l'arbre du pieu. Par conséquent, la résistance de la peau sera positive dans le tiers supérieur de l'arbre de la pile et négative au milieu et aux tiers inférieurs de l'arbre de la pile. Dans le cas d'une seule pile encastrée au sol expansif complètement saturé, la force axiale est compressive et diminue avec la profondeur de la pile tandis que la résistance moyenne de la peau est positive le long de l'arbre de la pile, indiquant que la majeure partie de la charge appliquée est transférée par la résistance à la peau positive mobilisée le long de l'arbre du pieu. La charge et le tassement de la tête du pieu dans le sol expansif non saturé sont plus élevés que dans le sol complètement saturé

KEYWORDS: expansive soil, soil suction, active zone, neutral plane, strain gauge.

1 INTRODUCTION

In swelling and shrinking soils, it is usually using piles as foundations, so that the bearing capacity of these foundations in this case develops in safer soil conditions which is under the active zone. In expansive soils, uplifting forces exist in the zone of moisture content changes in which the swelling process occurs. This zone is defined as the active zone and it is in charge of swelling and shrinking phenomenon of expansive soil. The active zone is influenced by the presence of structures like works of excavations nearby structures and/or heat transfer from buildings to the beneath soil and these may modify the active zone depth. This depth can be recognized through local experience and soil investigation works (Prakash and Sharma, 1990). It is commonly advisable to design deep foundations in highly expansive soils since deep foundations transmit the pressure under the active zone (Peck et al. 1974) and (Das 1990). The piles in expansive soils are exhibited uplift force on the shaft because of the swelling of the soils. The magnitude of interface shear stress (uplift force) on pile depends on the interface friction between the pile material and the soil, normal stress acting on the pile surface and the magnitude of swelling, which in turn creates the relative movement at the interface between the soil and the pile material (Soundara and Robinson 2016). Xioa et al (2011) stated that the increase in the pile length effectively leads to decrease the upward movement of the pile and increase the tensile stresses along the shaft. Al-Omari et al. (2017) stated that changing the degree of saturation has a great influence on the adhesion factor of a pile that installed in expansive soil. The adhesion factor increases as the saturation degree increases and vise versa. Fadhil et al (2020) concluded that the sharing ratio of the ultimate tip capacity to the ultimate pile capacity of a single pile increases when the degree of saturation decreases and matric suction increases.

The scope of this work is to calculate the axial forces and shear stresses along the pile shaft. To achieve this purpose, series of experimental compression load tests were conducted on a single pile installed in very high expansive soil in saturated and unsaturated conditions. The induced strain along the pile shaft during loading is recorded using strain gauges bonded along the shaft.

2 EXPERIMENTAL WORK

The experimental work conducted in this research was consisted of preparing the soil, the model piles and performing series of compression load-settlement tests on a single pile model. The used soil was a mixture of 70% Ca-base bentonite and 30% silica sand, this soil can be classified as a very high expansive soil mixture. Both soil mixture components were brought from a site west of Iraq. Table 1 shows the physical properties of the soil mixture. The soil mixture was prepared separately in initially saturated (S_r= 100%) and unsaturated (S_r= 90,80 and 70%) soil conditions where S_r is the initial degree of saturation. The bed of soil for saturation conditions was prepared at a dry unit weight of 12.75 kN/m^3. The model pile was made up of a hollow square aluminum bar of thickness 2 mm and of cross sectional side of 20 mm. The model pile was closed at its tips using a square aluminum plate of 2 mm thickness. The model pile had a length of 200 mm, so the length to width ratio (L/D) =10. The container or box that contained the compacted soil and the model pile had dimensions of (220×220×350) mm and made of 4 mm thickness steel plate. The dimensions of the container had been chosen carefully to prevent the stress bulb which is usually generated around the pile during the loading process not being in contact with the container's sides.

The axial-loading system used in this work was a compression machine having a strain controlling system to be in control of the rate of loading on the pile head. A load cell of a capacity 50 kN connected to a digital load indicator was attached to the compression machine to measure the applied load on the pile head. Three strain gauges were glued along the shaft of pile at different three locations; at the top, the mid-depth, and lower (near the tip) parts of the shaft to measure the generated strain during the load test. Then the mobilized axial forces and shear stresses along the pile shaft were calculated. Figure 1 shows the load-settlement test setup and soil container filled with the soil mixture and the embedded pile and placed in the loading machine. The preparation of the bed of soil was conducted according to the details outlined by Al-Omari et al. (2017), Fattah et al. (2018) and Fadhil et al. (2020).

To measure the values of suction (total and matric) at different initial moisture content and hence different initial saturation degree, filter paper method was used according to ASTM D5298-03. Samples were compacted at a dry unit weight of 12.75 kN/m^3 but at different initial moisture contents. Figure 2 shows the suction values (total and matric) at different initial saturation degrees.

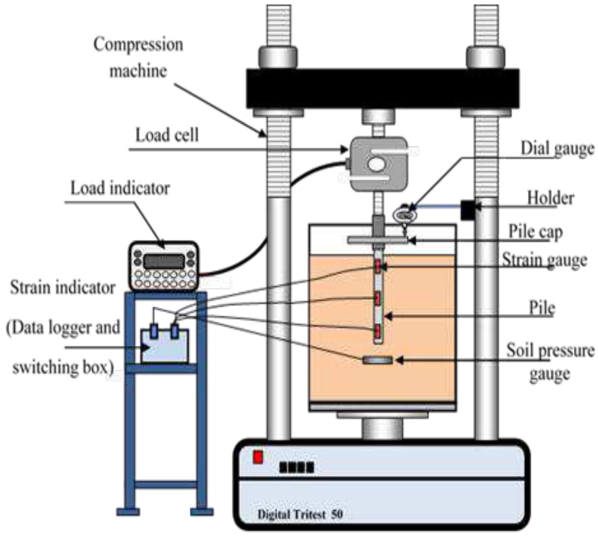
3 COMPRESSION LOAD TEST

Four constant rate compression tests of 1 mm/ min were performed on a single pile installed in a very high expansive soil mixture prepared separately at saturated and unsaturated conditions, the results are shown in Figure 3. It is obvious from this figure that the type of failure occurred is general shear failure in which failure point is simply identified from the load vs. settlement relationship. The ultimate pile capacity of pile, P_u is defined as the largest carried out load applied at the pile which is correlated with apparent settlement. In this case, the ultimate pile capacity occurred at the peak point on the load vs. settlement relationship which represents continues settlement under constant load. Figures 4 and 5 show the relation of ultimate pile capacity with the initial saturation degrees S_r and initial matric suctions, respectively. It is clear that when the decreasing occurred in the initial saturation degree and hence the increasing in the initial matric suction, the ultimate pile capacity increases remarkably. This behavior is due to the increase happened in soil cohesion due to the increase in soil matric suction and this has the effect of increasing the pile tip capacity and the shear stress of soil surrounds the pile. Georgiadis (2003) and Mohsin (2012) noticed the same behavior when using the finite element technique to evaluate the pile capacity when testing it in soil under different saturation degrees.

The ultimate pile capacity was increased by approximately 85% when the initial saturation degree decreased from 100 to 70%.

Table 1. Physical properties of the soil mixture.

Property	Value	Standards
Liquid limit	110	B.S.1377 (1990)
Plastic limit	40	ASTM D4318
Plasticity index	70	
Specific gravity	2.8	ASTM D854
Maximum dry unit weight, γ_{dmax}kN/m^3	13.6	ASTM D1557
Optimum moisture content, OMC %	28.3	



(a)

(b)

Figure 1. (a) Setup and details of the load–settlement test.
(b) Soil container in the compression machine.

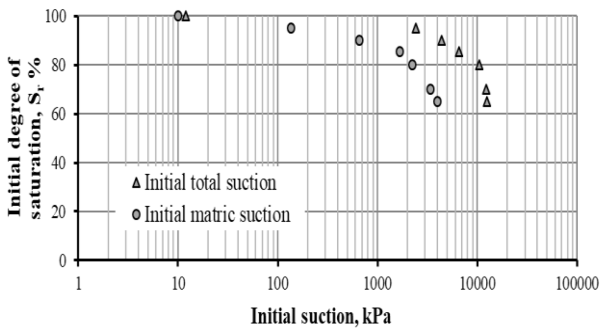


Figure 2 The initial saturation degree vs. the initial suction values measured by the filter paper method.

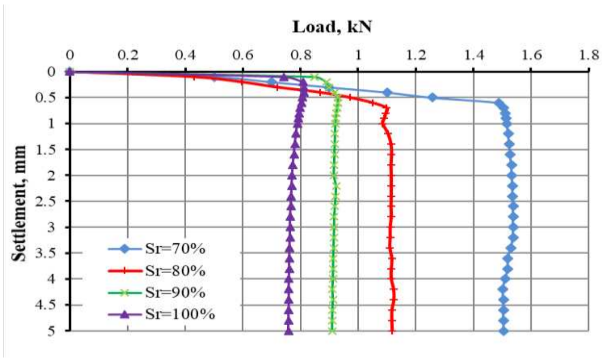


Figure 3. Load-settlement relationship of a single pile installed in expansive soil mixture.

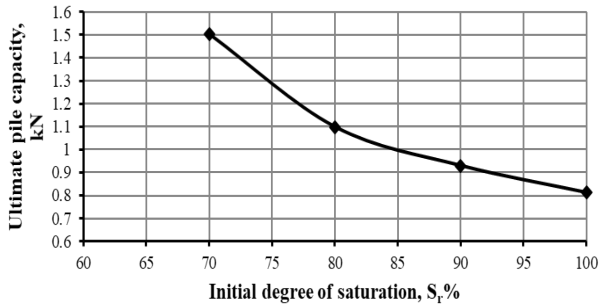


Figure 4. The ultimate capacity of a single pile vs. the initial saturation degrees S_r.

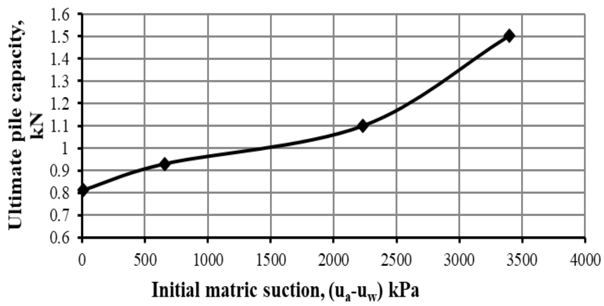


Figure 5. The ultimate capacity of a single pile vs. the values of the initial matric suction.

4 AXIAL FORCES ALONG THE SHAFT OF A SINGLE PILE

The axial forces in the shaft of a pile are generated because of applying a compressive load at its head and they are computed by taking the measurements of the mobilized strains in the shaft by means of bonding strain gauges at three different locations on the shaft; the upper, middle and lower thirds of the shaft. These axial forces were computed according to Equation 1, (Zhang et al. 2011)

$$P_{axial} = \varepsilon E_P A_c \quad (1)$$

Where P_{axial} is the axial force generated in the pile shaft, ε is the recorded strain, E_P is the elasticity modulus of the material of the pile and A_c is the cross-sectional area of pile shaft.

In this work, the negative sign points out to the compression forces and the positive sign points out to the tension forces.

The distribution of the axial forces along the shaft of pile is shown in Figure 6. It is clear from Figure 6-(a), where the initial saturation degree S_r equals 100%, the maximum value of the axial compressive force is at the top of the shaft and it decreases gradually over the shaft depth due to the shear stress mobilized over the pile length. It is also shown that when increasing the applied load, the axial force also increases. The dashed lines shown in Figure 6-(a) show the axial force distribution at the ultimate applied loads. The same behavior is recognized as well by (Zhang and Zhang 2012) who recorded the axial forces that generated in the shaft of piles embedded in soft soil.

Figures 6-(b) (c) and (d) display the axial force distributions along a single pile shaft that was installed in unsaturated expansive soil mixture. The mixture was compacted separately at different initial saturation degrees S_r of 90, 80 and 70%. The maximum axial compressive force takes place at the top of the pile and it changes along the pile shaft. The dashed lines refer to the axial force distributions at the ultimate applied loads. The axial force distributions refer that the behavior of piles in unsaturated expansive soil is very complicated and changes according to the saturation degree and the ambient condition of the test. The axial force distributions changes along the shaft from positive (tensile force) at the shaft's top third to negative (compressive force) at the mid-depth and bottom third of the shaft. This means the top portion above the active zone has the tendency to swelling whereas that portion of soil under the active zone has the tendency to shrink.

Fattah and Salman (2006) defined the active zone of the expansive soil as; the minimum depth of soil over it the varying in moisture content and expansion of soil can be happened due to the changing in the environmental circumstances after construction.

From these figures and for each load test; over and under the active zone, the developed axial forces over the shaft increase when the applied load increases. Accordingly, the active zone depth is approximately about 2.0 to 2.5 D (D is defined as the pile cross-sectional width).

When a pile is installed in the expansive soil, the generated axial forces in the shaft have to be in equilibrium. Therefore, along the pile length there is a depth in which the tensile positive forces are in equilibrium with the compressive negative forces. This depth id is known as the " Neutral plane" (Fellenius et al. 2014).

Accordingly, the neutral plane in this study is set approximately at a depth of 4.5 to 5 D (D is defined as the pile cross-sectional width).

Lu et al. (2010) reported that the strength as well as the deformation properties of the unsaturated soil may change according to the variation of its saturation degree and suction. Suction generates a tensile stress within unsaturated soils. Sahzin (1968) reported that for piles installed in expansive soil, friction forces that are developed in the upper part of the shaft try to rise the pile and the carried out load while friction forces that generated in the bottom part try to withstand that uplifting. Nelson and Millar (1992) pointed out the main problem in the swelling soil is the uplifting forces generated by such soil over the shaft of the pile.

Even the conditions of all tests were kept under control in the soil humidity and moisture content. The top portion of the bed of soil within approximately 2.0 to 2.5 D within the active zone was slightly affected by the surrounding condition; it underwent swelling or shrinking. Depending on the obtained results, the soil bed in this study might behave as the model described by Fellenius et al. (2014); "expansive soil sitting on unexpansive soil model". Soil above the neutral plane i.e. within the active zone intends to swell because of the upward tensile positive forces within it. It tries to move upward with respect to the pile which intends to move downward with respect to the surrounding soil because of the applied compressive force at its head. Therefore, when conducting the superposition of the illustrated two forces and the occurred relative movement of the pile and the surrounding soil, the dominate stresses in the active zone are tensile forces. Johnson and Stroman (1984) pointed out that during the swelling process of expansive soil the overburden stress horizontal component increases remarkably by 3 times or more than the vertical overburden stress. That is why the axial forces at the top portion increases with the increase in the saturation degree.

Under the active zone, the soil in somehow is stable although it is of expansive type. Thus, when the compressive forces are applied at the pile head, the pile moves downward regarding to the surrounding soil and this leads to the compressive forces are being dominated in this zone.

Figure 7 illustrates the axial force distributions along the pile shaft under the ultimate load which was applied at the pile head for piles installed in expansive soil mixture compacted separately at different initial saturation degrees S_r. For the soil having an initial saturation degree S_r equals 100%, the ultimate axial load distribution over the pile depth is compressive which leads then to positive skin resistance along the shaft as it is going to be shown in the next item. This is pointing to explain that the most of the applied loads at the pile head are going to be transferred through the mobilization of the shaft skin resistance. Otherwise, the ultimate axial forces generated in the upper portion of the soil above the neutral plane of the shaft of piles embedded in unsaturated expansive soil are tensile forces and they decrease as the initial saturation degree decreases. While the ultimate axial forces that generated in the shaft of the piles installed in unsaturated expansive soil below the neutral plane are compressive forces and they decrease as the initial saturation degree increases. It is clear from these results that the capacity of the tip of pile increases with the decrease in the initial saturation degree and hence the increase in the initial matric suction.

Xiao et al (2011) conducted a numerical simulation of a single pile installed in expansive soil and was subjected to load applied at the head. They found that the axial force distribution over the length of the shaft is varying progressively from tension to compression.

5 SHEAR STRESS ALONG THE PILE SHAFT

Zhang et al. (2011) and Zhang and Zhang (2012) stated that the shear stress along the shaft of the pile is determined as the quotient of subtracting two successive axial forces by the surface area between that two successive strain gauges. Moreover, at any gauge; the slop of the load-distribution curve refers to the friction over the pile depth.

Shear stress is generated gradually over the shaft after applying the load at the top of pile and it varies according to the carried out load. Figure 8 shows the shear stress (skin resistance) distribution over the shaft of pile installed in expansive soil mixture prepared separately at different initial saturation degrees as shown in the figure and at different loads applied at the top of the pile. It is observed from Figure 8-(a) that the mobilized skin resistance over the shaft which is installed in expansive soil having an initial saturation degree of 100% is positive (upward direction). It is known that it is a usual behavior of a pile installed in fully saturated clayey soil. It is clear from this figure that the maximum value of the shear stress lays in the top part of the pile shaft and decreases gradually over the shaft whereas it increases as the applied load increases. It is obvious that almost all the increments of the load which are carried out at the top of the pile are resisted by the mobilization of shear stress along the shaft. The dashed lines drawn in the same figure refer to the skin resistance distribution under the ultimate loads.

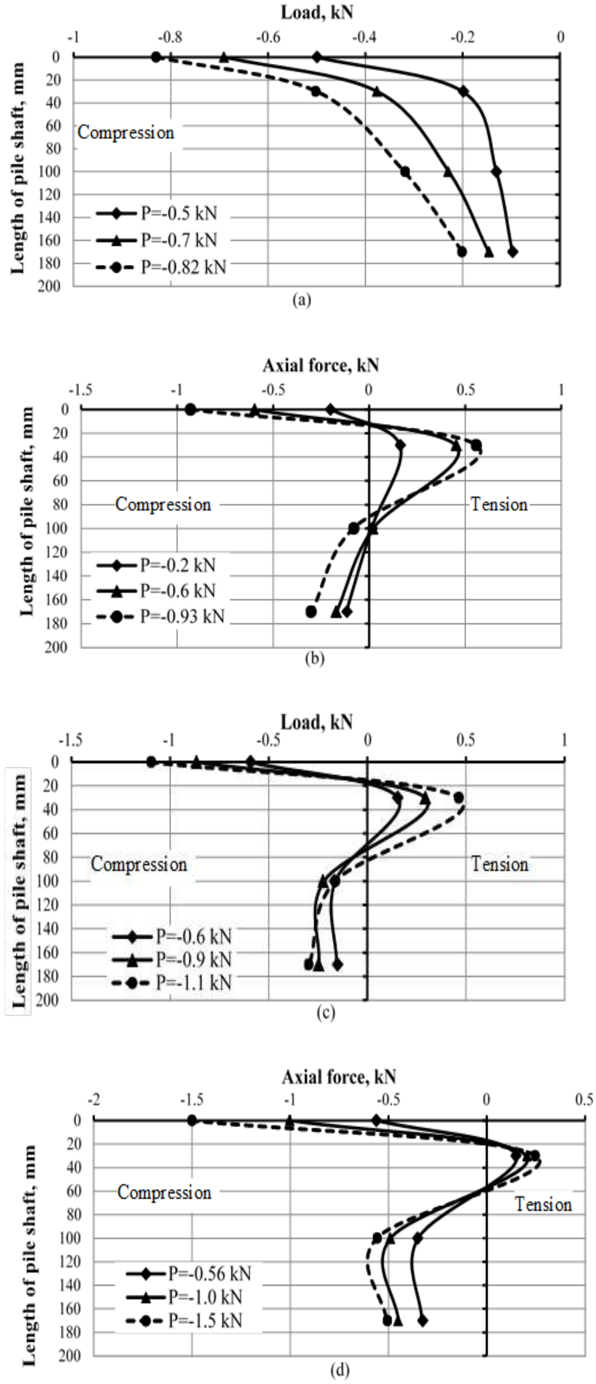


Figure 6. The distribution of axial forces over the shaft that installed in expansive soil under different applied loads P; (a) S_r=100%, (b) S_r=90%, (c) S_r= 80% and (d) S_r= 70%.

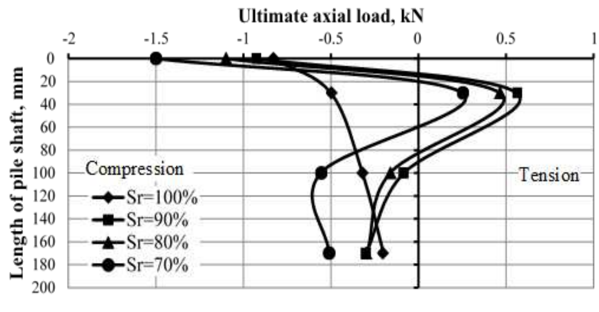


Figure 7. The distribution of the axial loads over the shaft installed in expansive soil mixture under the ultimate applied loads.

Figure 8-(b), (c) and (d) show the shear stress variation over the pile depth which is installed in unsaturated expansive soil mixture prepared separately at various initial saturation degrees of (90), (80) and (70) %, respectively. It is seen a positive upward shear stress at the top part of the shaft which is bounded by the active zone and it increases as the applied load increases. On the other hand, within the anchorage zone the shear stress turns to be negative. Fellenius et al. (2014) stated that, this transformation from +ve to –ve directions does not happen unexpectedly, it occurs through a zone of transition. The amount of proportional movement of pile relative to the soil decides if this zone is short or long.

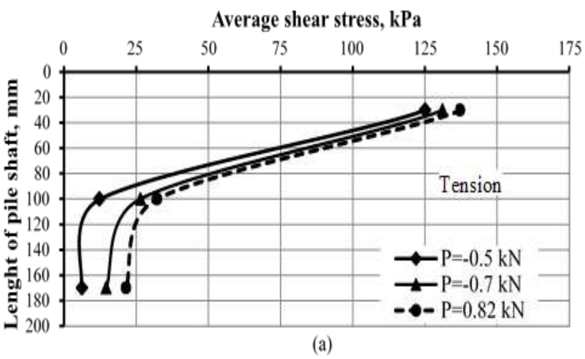
Therefore, the transition zone in this work is approximately about 4.0 to 5.5 D (D is defined as the pile cross-sectional width).

Within the active zone, uplifting skin resistance is usually generated (Nelson and Miller 1992). Chen (1975) pointed out that these stresses are unchanging through the active zone, whereas O'Neill (1988) clarified that there is a short distance known as the transition zone lays at the bottom of the active zone in which the uplifting skin resistance will increases from zero at the lower part of the active zone to a constant value which is extant at the top portion of the active zone. This zone is short and not accurate as the active zone since the active zone can be measured. As a result, it can be presumed the uplifting forces are unchanged value within the active zone.

The uplifting forces have to be countered by base uplifting resistance, carried out load and the skin resistance which is existed in the anchorage zone below the active zone (Nelson and Miller 1992).

Nelson et al. (2012) reported that the fundament of the design of piles in expansive soil is the downward or negative skin friction which is usually under the depth of the potential heave plus the dead load must be equal to the uplift pressures that are exerted by the swelling soil on the pile. Mendoza (2013) stated that the saturation degree and suction of soil are what the skin friction stresses are depending on.

Figure 9 shows the skin resistance distribution along the pile shaft under the ultimate loads applied at the head of piles installed in expansive soil mixture prepared separately at different initial saturation degrees. It is obvious that for fully saturated soil, the skin resistance is +ve. This means most the carried out loads at the pile head are transferred through the mobilization of the skin resistance along the shaft. Whereas for unsaturated condition at the soil top portion above the neutral plane, the average skin resistance is +ve and it gets larger with the decreasing of the initial saturation degree because of initial matric suctions are of large values. On the other hand, there is negative mobilized average skin resistance below the neutral plane and it is getting larger as the initial saturation degree become larger.



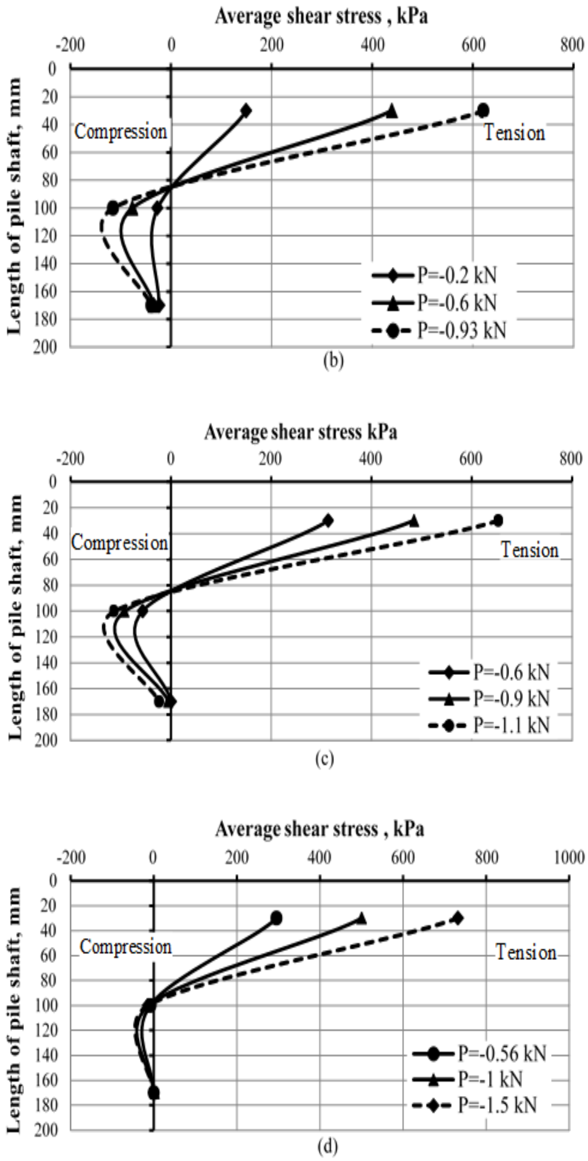


Figure 8. The average shear stress distribution over the shaft installed in expansive soil mixture under different loads P applied at the pile head (a) S_r=100, (b)S_r= 90%, (c) S_r=80% and (d) S_r=70%.

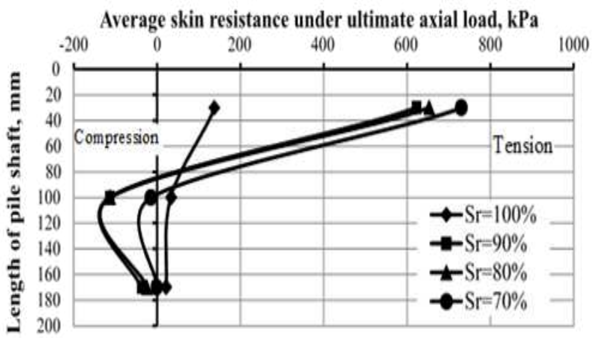


Figure 9. The average skin resistance distribution over the shaft installed in expansive soil mixture under ultimate applied loads.

6 CONCLUSIONS

Depending on the results discussed previously, the following points can be concluded:

1. There are compressive axial forces developed over the shaft installed in fully saturated expansive soil mixture when the pile was subjected to a compressive load at its head and they increase as the applied load increases. The maximum value of the axial force is at the pile head and decreases gradually over its length because of the mobilized skin resistance over the shaft.
2. For the unsaturated conditions of expansive soil mixture, the axial force distribution over the pile shaft changes from tensile force at the top part of the shaft to compressive force at the mid depth and bottom parts of the shaft. This means the top portion within the active zone intends to swell trying to lift the pile and the load applied at its head while the lower part below the active zone intends to shrink and works as an anchorage zone to resist the uplift pressure exerted by the expansive soil.
3. For the fully saturated expansive soil mixture, the generated skin resistance over the depth of the shaft is positive, referring to the fact that most of the load applied at the pile head is carried out by the positive skin resistance mobilized over the shaft.
4. For unsaturated conditions, there is a positive skin resistance at the upper part of the shaft and negative at the mid depth and bottom parts of the shaft. At the ultimate load applied at the pile head; when the initial saturation degree decreases the positive skin resistance at the top part of the shaft increases and the negative skin resistance in the mid-depth and bottom parts of the shaft decreases.
5. From this experimental work the plane of the largest axial force (neutral pane) was detected to be at approximately 4.5 to 5.5.
6. The zone in which the skin resistance conflicted from tensile force to compressive force (transition zone) was found to be approximately about 4.0 to 5.5D (where D is defined as the pile cross-sectional width).

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