Research Article

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Experimental and numerical study of the bulb's location effect on the behavior of under-reamed pile in expansive soil

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Abstract: In this experimental and numerical analysis, three varieties of under-reamed piles comprising one bulb were used. The location of the bulb changes from pile to pile, as it is found at the bottom, center, and top of the pile, respectively. *PLAXES 3D* was used to conduct the research. In expansive soil, the under-reamed piles were 350 mm long, with the pile tip in dense sandy soil. The experiment was carried out in both saturated and unsaturated circumstances. The influence of the bulb location on the pile's bearing capacity for vertical and lateral loads, as well as the amount of swelling pressure and upward movement owing to swelling, was investigated. The results showed that in the unsaturated state, the bulb at the top of the pile gives bearing that is higher than the bulb at the bottom of the pile and near to the bulb in the center. In the case of unsaturated soil, the closer the bulb is to the top, the larger the bearing capacity, whereas in the event of swelling, the bearing capacity is highest when the bulb is in the middle of the pile. The same is true of the pile's upward movement, which is greater when the bulb is at the top than when it is at the bottom.

Keywords: under-reamed pile, expansive soil, bulb location, Plaxis software

1 Introduction

Albusoda and Al-Anbary (2017) [1] Studied the behavior of square helical piles models embedded in expansive soil bed overlaying a layer of sandy soil. Model tests are performed with helical pile lengths 350mm, 400mm and 450mm and with helix diameters 15mm and 20mm. Also, one helix and double helix were used for these piles. Water was allowed to seep from the bottom of sandy soil to reach the surface of expansive soil through four sand drains around the helical pile. This study revealed that the upward movement of helical piles decreases with increasing depth of embedment in the sandy layer, helix diameter, and the number of the helix. The increase in these parameters provides anchorage against uplifting. Helical piles embedded in the sandy soil of relative density (40%) have uplift movement more than helical piles of relative density (80%).

Under-reamed piles, also known as bored cast in situ concrete piles with one or more bulbs generated by widening the borehole, are one of the forms of deep foundations used to shift loads away from weak soil layers to strong ones.

An under-reaming tool is used for the pile stem. Under-reamed piles are utilized in both clay and sandy (weak and stiff) soils, as well as in locations where vibrations and noise are prohibited [2].

Goalait and Padade (2018) [3] and [4–6] presented numerical studies on the effect of bulb diameter, pile diameter, length, distance from the bulb to pile base, the proportion of the bulb diameter to the pile diameter, and the ratio of the pile length to the diameter on pile Q_u, as well as the impact of the previous factors on pile settlement. The findings confirmed that increasing the length and number of bulbs increases Qu and reduces pile settlement.

Albusoda and Abbase (2016) [7] investigated the effect of the length of the pile with the bulb in it on its upward movement and swelling pressure, finding that the presence of the bulb reduces the upward movement by 20% and the draw force by 20% on the usual pile.

Al-Busoda and Abbas (2017) [8] compared helical piles to regular piles and discovered that the inclusion of a helix in the pile reduces swelling pressure by 5-8 times and the length of the pile by 80%, similar to the behavior of under-reamed heaps. Karkush and Hussein (2021) [9] conducted an experimental investigation of the bearing capacity of screw piles and excess pore water pressure in soft clay under static axial loading.

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Chandra and Prakash (1983) [10] conducted a site test on an under-reamed pile of one bulb with a diameter of 300 mm, a bulb diameter of 750 mm, and a total length of 3.5 meters in sandy soil, and found that the pile behaved as a short rigid pile with the point of rotation in the middle of the pile, indicating that the presence of the bulb made the pile rigid for the same diameter and length.

Vali *et. al.* (2017) [11] investigated the effect of the number of bulbs, pile diameter, pile length, angle of internal friction of the sand, and cohesion on the bearing capacity of under-reamed piles, and discovered that increasing the pile length increases the bearing capacity of under-reamed piles by about 10%, after which it is fixed at 10 meters. The diameter of the pile shaft can be increased by up to 120%. In terms of the angle's relationship, Internal friction raises the bearing capacity by 45%, and increasing soil cohesion increases the bearing capacity by 63%. When the number of bulbs is increased by one or half, the under-reamed pile bearing capacity increases by 115%, and the increase continues by about 12% with the additional bulbs.

The impact of the bulb's position on the bearing capacity of an under-reamed pile subjected to vertical and lateral loads, as well as its upward movement in saturated and unsaturated soils, is investigated in this study. The under-reamed pile was tested and embedded in saturated (w=52%) and unsaturated (w=27.5%) soils, with the first condition involving the behavior of the soil and pile under the impact of swelling pressure.

2 Material characteristics

The soil employed in this study is made up of two parts: the first is expansive clay soil, which is made up of 80% bentonite and 20% sand. These percentages were chosen so that there was still significant swelling. To maximize permeability and obtain saturation in the quickest time, the sand was combined with bentonite. This proportion was discovered after multiple experimental attempts, resulting in a high swelling rate.

Physical tests were carried out to determine the features of the under-studied soil, prepared soil (expansive soil), and sandy soil, as well as their ASTM [12] categorization. Specific gravity, Atterberg limits, grain size analysis, and the usual Proctor compaction test were among the experiments performed. Table 1 shows the results of the physical testing for expanding soils.

Table 1: Soil and pile properties considered in finite element analysis

Model parameters	Clay soil (undrained behavior)	Sandy soil (drained behavior)	Soil properties	Clay	Sand
$\gamma_{unsat.}$ (kN/m^3)	17.6	17.65	Specific gravity (Gs)	2.78	2.67
$\gamma_{sa(swelling)t}$ (kN/m^3)	17.16	19.3	Liquid limit (L.L), %	100	
E_{50} (kPa)	7829	43200	Plastic limit (P.L), %	41	
E_{ur} (kPa)	19487	43200	Unified soil classification	CH	SP
E_{oed} (kPa)	6120	13104	Initial void ratio (e_0)	0.97	
M	1	0.5	Swelling pressure, (kPa)	220	
K^{NC}	0.5	0.4	Parameter	Pile	Cap
R_f	1	0.9	Material	concrete	steel
c_{ref} (kPa)	2	0.1	Material model	Liner-elastic	Liner-elastic
Ø°	14	39	Unit weight, γ (kN/m^3)	23	78
ν'un	0.45	0.25	Young's modulus, E (kPa)	22.5E6	200E6
ψ	0	9	Poisson's ratio, ν	0.15	0.25
R_{inter}	0.7	0.8			
K_o	Manual	Manual			
Free Swelling, (%) ε_a	10%				

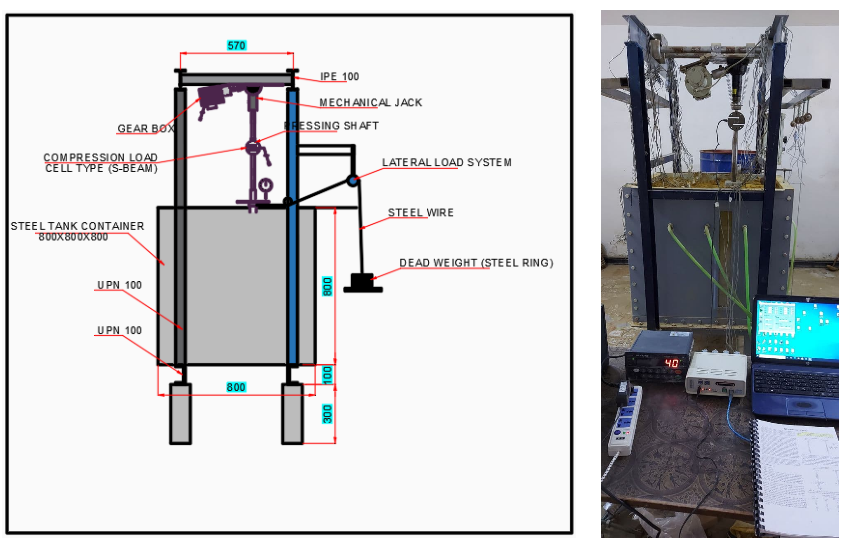
2.1 Physical model

A physical model with dimensions of 800*800*800 mm, equipped with a vertical and lateral loading mechanism, was utilized to conduct pile testing, and the pile was put into the clay layer deeper 290 mm. The pile's foundation is a dense sandy layer, and the free part of the pile was 60 mm long, as illustrated in Figures 1 and 2.

The under-reamed pile employed in this study is a cylindrical shape made of concrete with a length of 350 mm and a diameter of 20 mm. The pile tip is on sandy soil because the area immersed in the soil was 290 mm. The bulb has a diameter of 40 mm and is centered 60 meters from the pile tip.

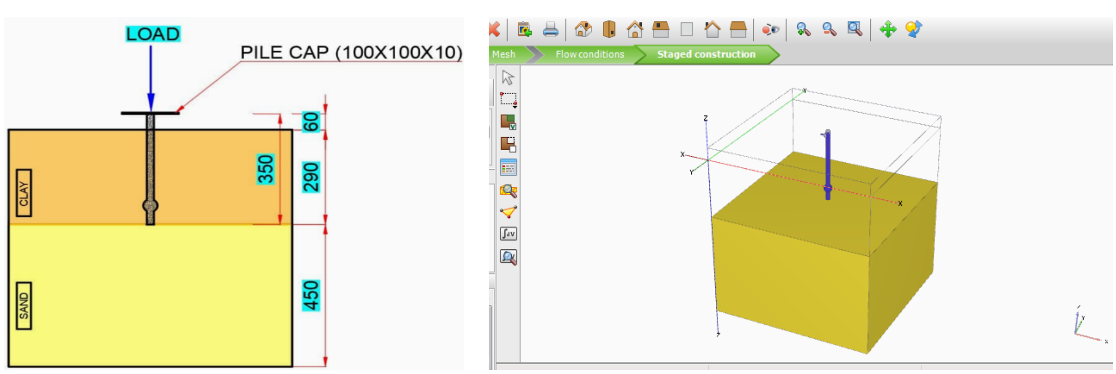
2.2 Problem modeling and numerical simulation

This study made use of a program. PLAXIS 3D. It is one of the most essential, powerful, and comprehensive programs for studying the deformation and stability of geotechnical and rock mechanics problems. The program's many uses begin with simple issues like excavations and earth fills, progressing to foundation issues like piles and big structures like tunnels and dams [13]. Under-reamed pile foundations are a three-dimensional challenge that necessitates three-dimensional modeling as well. The Mohr-Coulomb model, Drucker-Prager model, Linear Elastic model, Cam Clay model, and Hardening Soil model are all nonlinear models that simulate soil dynamics [14].



(A) (B)

Figure 1: (A) Sketch for lateral and vertical load system. (B) Under-reamed pile testing



(A) (B)

Figure 2: 3-Dimensional model of single bulb pile of the problem geometry under lateral load

Soil hardening is a sophisticated model of elastic polymers that may be used to replicate various sorts of soft and hard soils [15]. This model is more accurate than Mohr-Coulomb in representing the process of soil hardening and plasticity. The hyperbolic relationship between vertical strain and stress acquired from regular triaxial tests is the source of this type of model. For the first time, this equation was formulated by [16]. It was eventually incorporated into the hyperbolic model [17]. In contrast to the elastic-plastic model such as Mohr-Coulomb, the hardening soil model includes an unconstrained yield surface that expands as a response to plastic stress, making its explanation of plasticity more realistic. Triaxial loading secant stiffness (E_{50}), oedometer loading stiffness (E_{oed}), and loading/reloading stiffness are the three types of input stiffness that adequately describe soil (E_{ur}).

The numerically simulated problems in this work reflect a numerical simulation of the small physical model that was examined and carried out experimentally. The numerical modeling was carried out under the following circumstances:

- The problem boundary conditions are as follows: The model's base is fixed, with the boundaries acting as rollers to allow for vertical heave or movement.
- The profile of the soil: There are two layers to the soil profile. Dense sand lies beneath expansive clay soil.
- Models that were used: The pile was modeled using the linear elastic model, while the clay and sand soil was modeled using the hardening soil model. Table 1 shows the input parameters for models.
- Loading: The pile is exposed to static lateral and vertical loads.

3 Results and discussion

Three single-bulb pile models were evaluated, and the dimensions were identical to those used in the practical portion of the study. The three versions are depicted in Figure 3, with the bulbs at the bottom, center, and top of the pile, respectively. The three under-reamed piles (L/d=14.5) were tested with lateral and vertical loads for saturated (w=52%) and unsaturated soil (w=27.5%) conditions, with the results displayed in Figure 4. The pile was loaded vertically and laterally to determine its bearing capacity against the vertical load and lateral load, as shown in the Figure, and a lateral bearing capacity was tested as a percentage of allowable load (10%) [18]. The test was carried out following ASTM standards, and the Plaxis program was used to validate the results, as shown in Figure 4A.

The maximum bearing capacity of the under-reamed piles is substantially higher when the bulb is at the top or middle of the pile, as shown in Figure 5A, than when it is at the bottom of the pile, where the increase is around 27%. When the soil was saturated and swelling occurred, the findings were completely different, as the bearing capacity was larger at the bottom of the pile than in the center, and the rise was about (40-52%) from the top bulb to the lower bulb.

The reasons for the increase in unsaturated soil are that the soil column under the bulb when it is at the top or middle is made entirely of clay, with the cohesion of 80 kN/m2, and it continues until the stress generated by the imposed load decays, but the soil column in the last bulb is much less, and the stress is then transmitted to the sandy soil, overlapping with the stress generated by the pile's end, as shown in Figure 6. In the second scenario, the total saturation of the soil remains the same as in the previous description, but the cohesiveness of the clay reduced to 17 kN/m2 and the angle of friction of the sand decreased

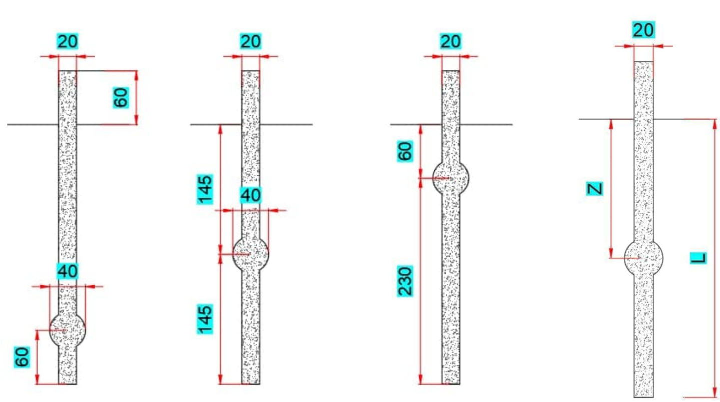


Figure 3: Sketch of single bulb under-reamed piles with different bulb position

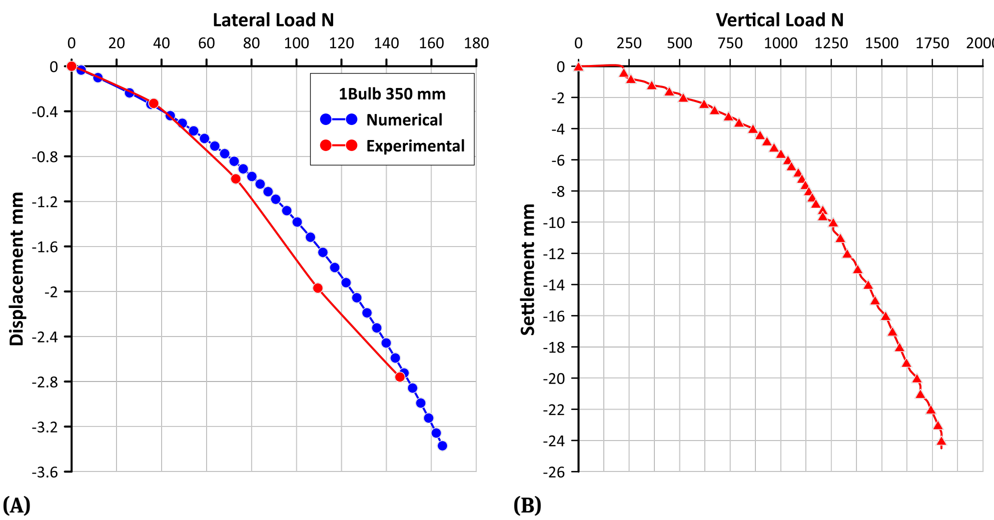


Figure 4: (A) Comparison of lateral bearing capacity for single bulb pile between numerical and experimental (B) Load settlement test (experimental)

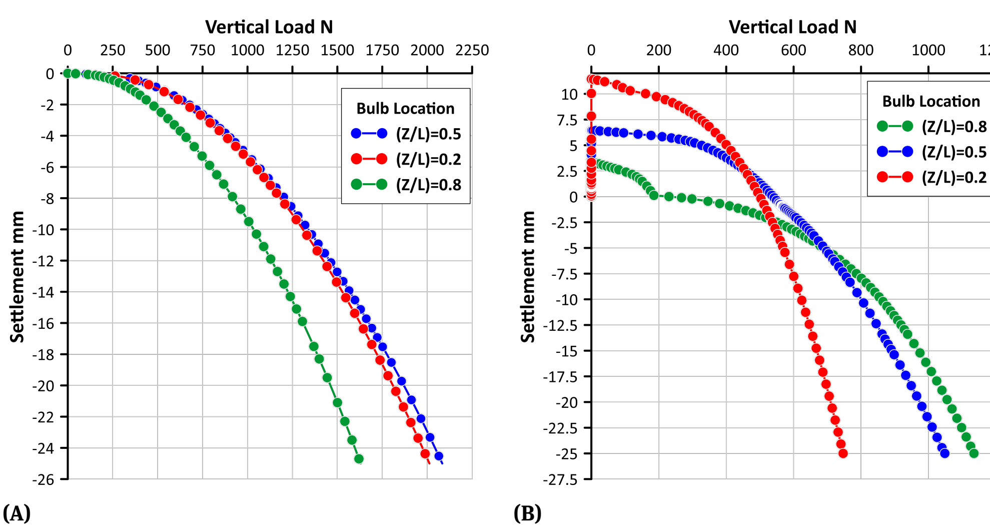


Figure 5: The relation between settlement and axial load for single bulb under-reamed piles (A) Unsaturated soil (B)Saturated soil

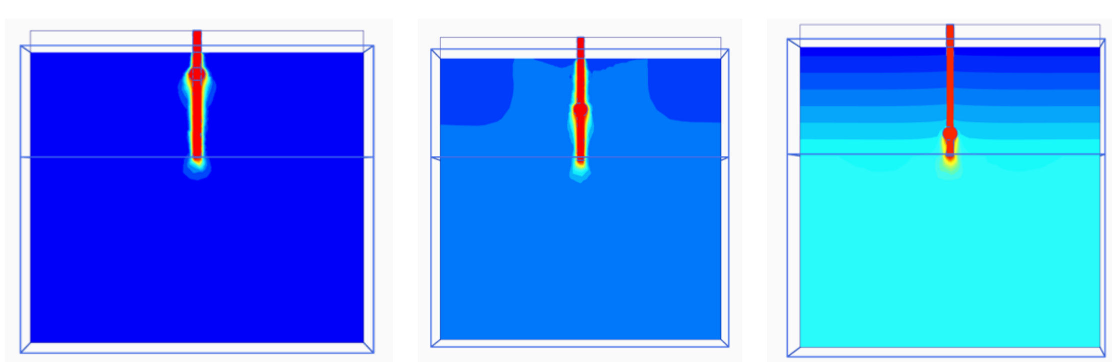


Figure 6: Deformation sketch of single bulb of under-reamed piles under axial load

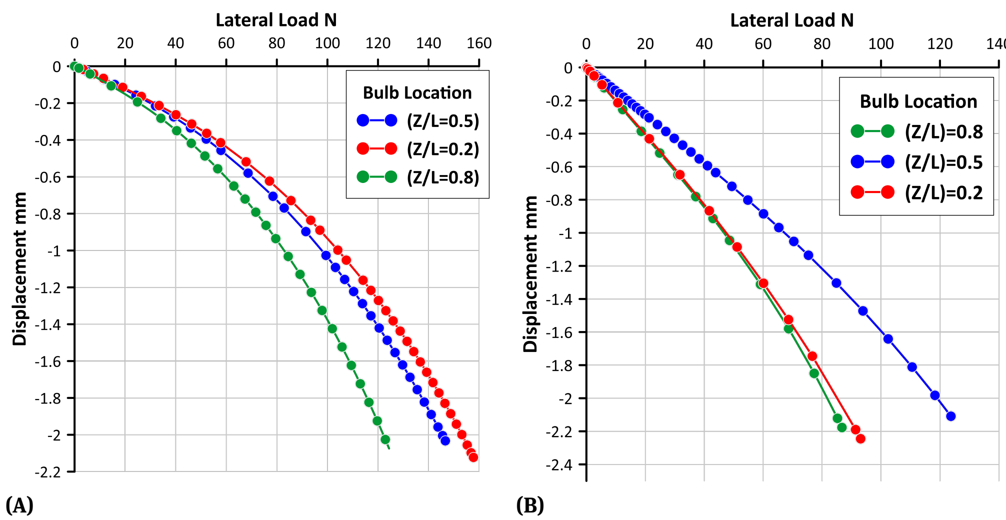


Figure 7: The relation between displacement and lateral load for single bulb under-reamed piles (A) Unsaturated soil (s=78%) (B) Saturated soil (s=100%)
Note that in the figures, the length of the pile starts at point zero, which symbolizes the pile's free head above the soil, which is 6 cm, and the depth embedded in the soil ranges from −6 cm to −35 cm.

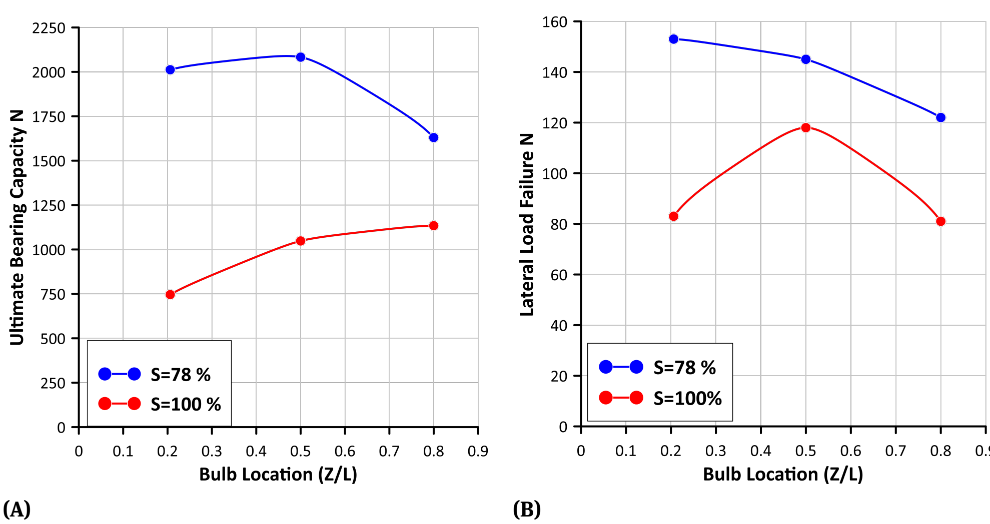


Figure 8: Relation between bulb location and (A) Vertical load (B) Lateral load

from 39° to 37°, resulting in a decrease in the soil's bearing capacity. In the case of unsaturated soil, the location of the bulb had a clear effect on the bearing capacity of the single bulb pile for the lateral load, as the bulb was at the top of the pile, giving more bearing than if it was in the middle of the pile by 8% and higher than if it was at the bottom by 30%. In saturated soil, the under-reamed pile with the middle bulb had the highest tolerance of the three piles, with a rate of around 42%, as illustrated in Figure 7.

The location of the bulb also affected the movement of the under-reamed pile up in the case of total saturation, with the upper bulb giving a substantially greater movement than the other two (middle and lower) by (78%, 237%, respectively). When it came to the required swelling uplift force, the middle bulb had the largest uplift force, which was 8% higher than the upper and 134 percent higher than the lower.

The relationship between the ultimate bearing capacity of under-reamed piles and the placement of the bulb in saturated (swelling) and unsaturated soils is shown in Figure 8A because the behavior of the substrate varies depending on the location of the bulb and the soil condition.

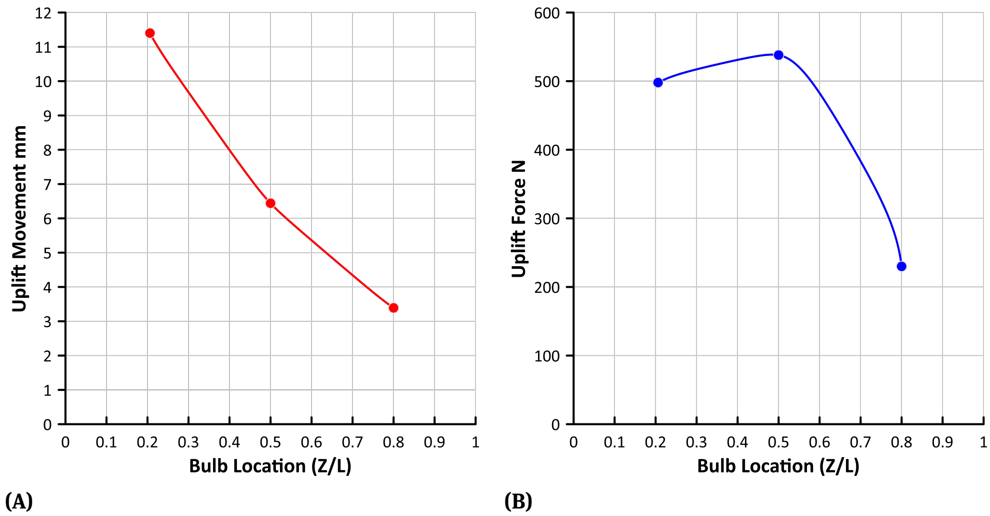


Figure 9: Relation between bulb location and (A) Uplift movement (B) Uplift force

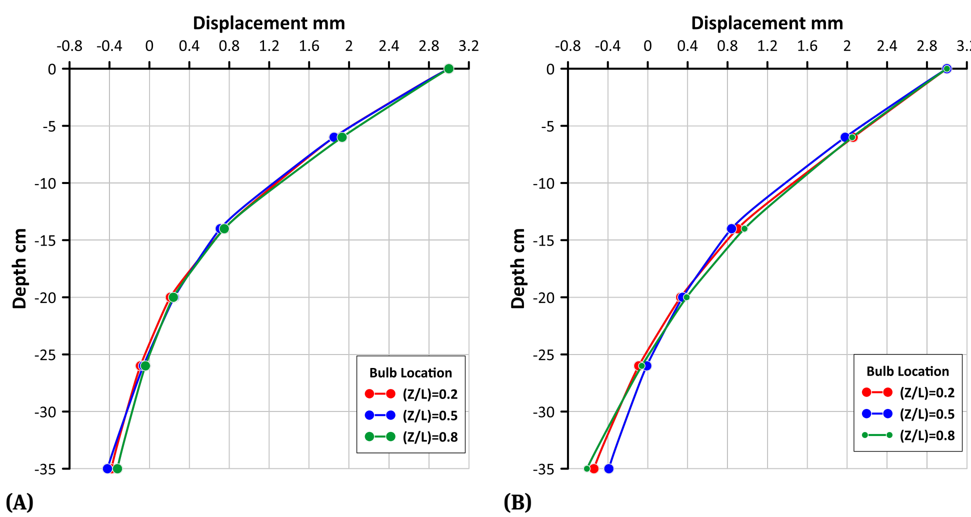


Figure 10: Lateral displacement along with the under-reamed piles under lateral (A) Unsaturated soil (B) Saturated soil

The bearing capacity of the pile is higher in the unsaturated situation (S = 78 percent) when the bulb is at z/L = 0.5, while it is lowest when the bulb is at z/L = 0.8. When the bulb is at z/L = 0.8, the bearing capacity is large, while the pile with the bulb at z/L = 0.2 has a lower ultimate bearing capacity. In the case of unsaturated soil (S = 78 percent), the pile with the upper bulb (z/L = 0.2) had the highest bearing capacity, while the pile with the lower bulb (z/L = 0.8) had the lowest bearing capacity. When it came to swelling (s = 100%), the pile with the middle bulb (z/L = 0.5) had the greatest bearing capacity. Figure 9A shows the upward movement of the pile with the highest bulb (z/L = 0.2) higher than the other two piles. In terms of uplift force, the pile with the middle bulb (z/L = 0.5) was higher than the other two heaps (see Figure 9B).

The following is how the aforementioned behavior can be explained:

The void ratio of unsaturated soil (s = 78%) is 0.97, and the cohesion is 80 kPa (stiff soil), however after saturation (s = 100%), the soil weakens, the void ratio increases owing to swelling (e =1.45), and the soil strength drops to (c = 17kPa).

It is important to note that the loading process in the numerical simulation is carried out under the strain-controlled condition and the presented results are at the displacement of 3mm at the pile head. The effect of bulb location on the bearing capacity of the pile, lateral displacement, and upward movement was observed in Figures 8 and 9. The rotation point did not change as shown in Figure 10, where the rotation point was at a distance of 20 cm along the length of the pile embedded in the soil in both unsaturated and saturated conditions.

4 Conclusions

- The bottom bulb pile has ultimate bearing capacity for both vertical and lateral loads (1629 N and 121N, respectively) in unsaturated soil. The vertical and lateral bearing capacities increase by (28%), (24%), and (20%), respectively, whether the bulb is situated in the middle or top pile.
- The bearing capacity of the lower bulb pile for the vertical load (1134 N) and the bearing capacity of the other piles decreased by 8% and 34%, respectively, in saturated soil, while the bearing capacity of the lateral load (81 N) and the bearing capacity of the other piles increased by 49% and 5%, respectively.
- In saturated swelling soil, the upward movement of the lower bulb pile was (3.39 mm), while the other piles rose by (90%, 237%). The swelling uplift force for the lower bulb pile was 230 N, and for the other piles, it was 134% and 117%, respectively.
- The rotation point was located at a distance of 10D from the ground surface and was unaffected by the difference in location of the bulb to the length of the pile, and the lateral displacement curve along the length of the pile was unaffected by the difference in location of the bulb to the length of the pile.

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