Engineering and Technology Journal
Journal homepage: https://etj.uotechnology.edu.iq

Enhancing Pullout Load Performance of Under-Reamed Piles in Homogeneous Layered Clay: A Numerical Comparative Study

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HIGHLIGHTS

- Increased soil cohesiveness improves the load-deformation behaviour of the under-reamed pile under pullout loads.
- The bearing pullout load rises as the number of bulbs increases.
- The maximum ultimate pullout capacity is obtained in the case of the stiff clay resting on the soft clay.
- The failure patterns of soil movement around the projections were larger than those around the shaft.

ARTICLE INFO

Handling editor: Mahmoud S. Al-Khafaji

Keywords:
Numerical study; under-reamed pile homogeneous clay; pullout load; failure mechanism.

ABSTRACT

A 3D numerical model generated using PLAXIS-3D software was used in the present research to predict the behavior of under-reamed piles under pullout loading conditions with presumed soil Mohr-Coulomb failure. The under-reamed pile was embedded in homogeneous, layered clay soil, with stiff clay overlain by soft clay and soft clay overlain by stiff clay. The piles were chosen per the Indian Code (IS 2911) specification, and two variables were studied: bulb provision and soil layering. Inhomogeneous clay with varying cohesion values (20, 40, and 80 kPa) and under the same conditions, the pullout capacity was improved compared to a straight shaft (SP). The pullout capacity of the single bulb (SURP) increased once, while that of the double bulb (DURP) increased twice. The results revealed that anchoring the pile in a stronger stratum at a greater depth is advantageous when designing under-reamed pile foundations. In the case of stiff clay on top of soft clay, additional resistance against pullout is achieved, reducing the risk of pullout failure compared to soft clay in the upper layer.

1. Introduction

Due to rapid development, the construction of facilities such as high-rise structures, transmission and communication towers, enormous industrial foundations, water containers, machine foundations, and bridges has significantly increased. As a result of the limited available land, these structures are often suggested to be established on soils with low bearing capacity, such as soft clays. The pullout capacity of pile foundations can be further increased by installing bulbs. The bulb-shaped projections of under-reamed piles provide additional resistance to vertical compression and tension (Majumder and Chakraborty) [1].

The pullout load-carrying capacity is crucial for piles supporting high-rise structures after an earthquake. Under-reamed piles have been utilized to improve foundations' pullout capacity and capability. These are cast-in-place concrete piles with one or more under-reams placed in the bearing stratum see Figure 1 (a and b), as described by Honda et al., [2].

A limited number of studies have examined the ultimate pullout capacity of under-reamed piles in clay under tension. George and Hari [3], conducted a numerical investigation to estimate the compression and tension capacities of uniformed bored cast in situ piles with two different stem diameters, single and double under-reamed piles in homogeneous clay. They reported that the pullout load improvement is approximately 119% for one under-reamed pile and 204% for an under-reamed pile with a bulb diameter 2.6 times greater than the pile shaft. In a finite element study, Khatri et al. [4], revealed that adding bulbs significantly improved the pile's load-deformation behavior, decreasing deformation corresponding to a given load with adding more bulbs. The pullout load for single and double under-reamed piles was found to be approximately 396% and 547% greater, respectively, within the specified range of L/D (embedded ratio) with linearly increasing cohesion.

http://doi.org/10.30684/etj.2023.140795.1474
Received 12 June 2023; Received in revised form 13 July 2023; Accepted 20 July 2023; Available online 18 August 2023
2412-0758/University of Technology-Iraq, Baghdad, Iraq

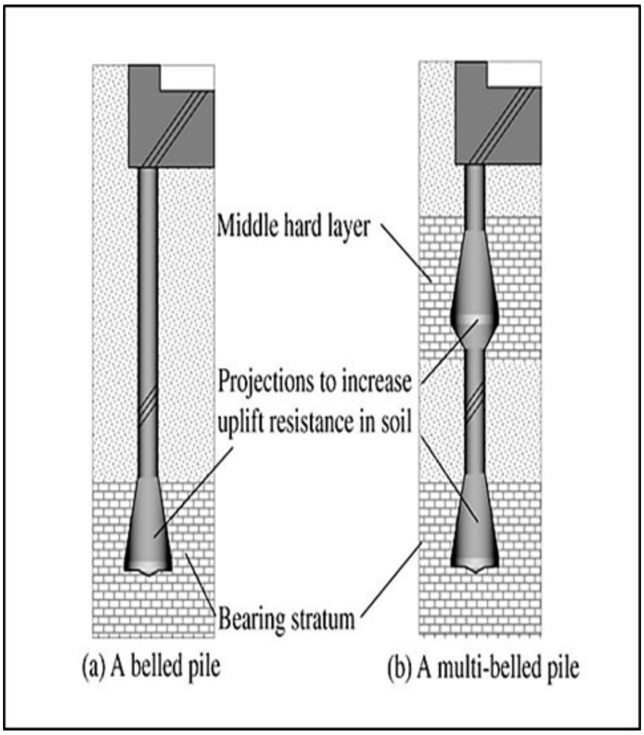


Figure 1: Schematic diagrams of the belled pile a), one- bulb, b) multi -bulbs

Martin and De Stephen [5], stated that a foundation of belled piles with double bulbs is a suitable option for over-consolidated stiff clay. They also reported that the spacing ratio between the two bulbs should be 1.5 to 2 times larger than the bulb's diameter. Vali et al. [6], examined the effect of bulb number, length, pile diameter, angle of internal friction, and cohesion on the bearing capacity of under-reamed piles. They found that increasing the pile length raises the bearing capacity by about 10% until it is fixed at 10 meters. Additionally, increasing soil cohesion leads to a 63% increase in the bearing capacity. When bulbs are increased by one or half, the under-reamed pile-bearing capacity increases by 115%. Alhassani [7], conducted a numerical study using the ABAQUS program to investigate the behavior of under-reamed piles subjected to pullout and compression loads. The test results showed that for all L/D pile ratios, the uplift pile capacity of SURP and DURP is significantly greater than that of a straight pile.

Al-Neami and Raheel [8], demonstrated that adding wings to the pile enhances lateral load resistance and decreases lateral displacement. Increasing the wing length greatly increases the pile's lateral capacity compared to a regular pile. The bending moment is significantly affected by increasing sand density from loose to medium, then dense, increasing the bending moment's magnitude. Bhattacharya and Kumar [9], used axisymmetric lower limit techniques and finite element methods to study the behavior of circular anchors subject to pullout loads in soft clay overlain by sand. They found that the pullout capacity rises with the depth of the top sand layer up to a critical value; beyond this rate, it was preferable to have the anchor base at the bottom of the sand layer rather than embedding it in the clay layer.

Farokhi et al. [10], numerically evaluated under-reamed piles in clayey soils and discovered that, when subjected to a tensile load, a half-bulb under-reamed pile has a larger maximum tensile bearing capacity than a full-bulb under-reamed pile and a uniform cross-section pile of the same dimension and volume. Moreover, the maximum pullout capacity of a full bulb was greater than that of a uniform cross-section pile of equal length and volume. A half-bulb pile's maximum pullout bearing capacity was approximately 27% greater than that of a full-bulb belled pile and 75% greater than that of a uniform pile of the same dimension and volume. Additionally, as the L/d ratio of an under-reamed pile rises, the tensile bearing capacity increases while displacement decreases. Rahil et al. [11], and Al-Tememy et al. [12], established that raising the relative density of the sand from loose to medium sand and increasing the embedded length of the same pile improves load-carrying capacity.

In this paper, a numerical investigation using a finite element program (PLAXIS 3D 2020) will be presented to estimate the efficiency of under-reamed piles under pullout capacity in a large-scale model embedded in clay with different consistencies (soft, medium, and stiff clay) and compared with straight piles under the same conditions. Performance evaluation will also assess the behavior of belled piles in two different layered soil configurations with varying clay stiffness (stiff clay over soft clay and the opposite scenario with soft clay over stiff clay).

2. Numerical Programs

The numerical analysis results obtained using PLAXIS (3D-2020) software, which works on the FE approach, will be employed to evaluate the efficiency of under-reamed piles with pullout capacity embedded in clay. Three different cohesion values and layered soil profiles listed in Table 1 will be considered when examining the form factor of the bulbs and its effect on the improvement of the pullout load capacity in a large-scale model. The numerical analysis is advantageous for investigating the effectiveness of geometrical structures on the bearing pullout load and displacement of under-reamed piles. In this research, SP, SURP, and DURP mention the conventional, single under-reamed, and double under-reamed piles, respectively.

Table 1: Schedule of study achieved

Task aim	Upper layer	Lower layer
Investigating the pullout performance of an under reamed pile in one layer	Clay Cu=20,40,80 kPa	
Investigating the pullout performance of an under reamed pile in stiff clay overlain by soft clay	Soft clay c =20 kPa	Stiff clay c =80 kPa
Investigating the pullout performance of an under reamed pile in soft clay overlain by stiff clay	Stiff clay c=80 kPa	Soft clay c=20 kPa

3. Validation of the Numerical Model

Before the examination can begin, validating the finite element model and software is preferred. An additional investigation was undertaken to compute the under-reamed pile in homogeneous clay, utilizing information from the soil and pile parameters provided by George and Hari [3], and Kumar et al., [13]. The pile geometry was chosen per the applicable Indian standard code specification (IS 2911). The investigation was carried out for single, double, and under-reamed piles to analyze the behavior of the load-displacement curve, as seen in Figure 2. Table 2 displays the data used in the analysis.

The PLAXIS-3D software analysis results demonstrate excellent agreement with the experimental data. Figure 3 (a and b) demonstrates that the similarity between the two outcomes exceeds 99%.

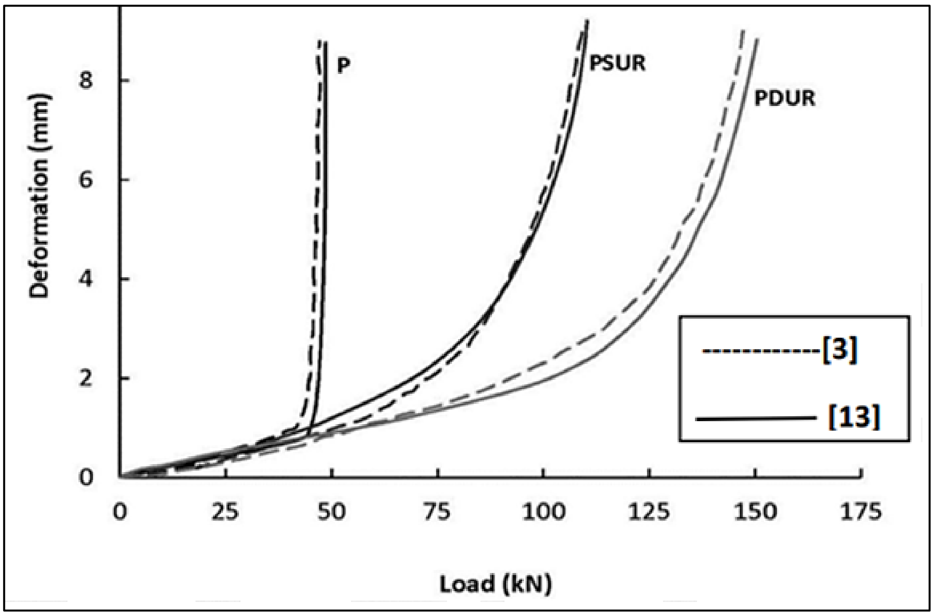
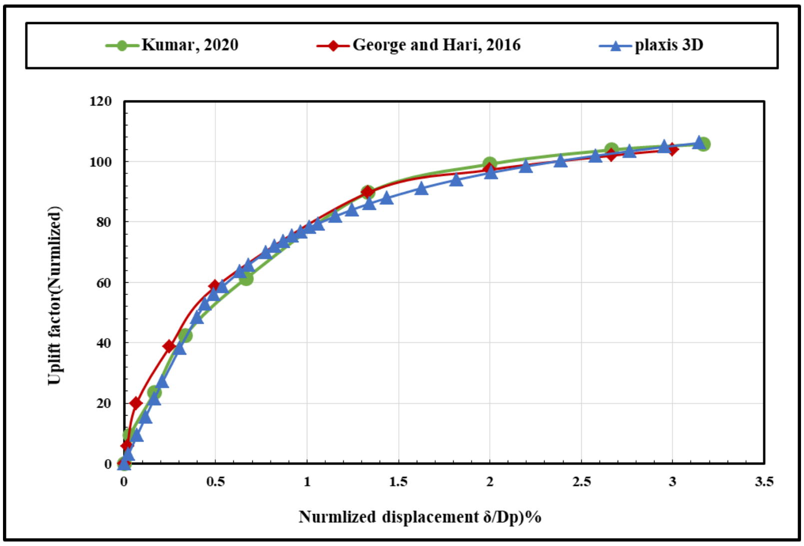


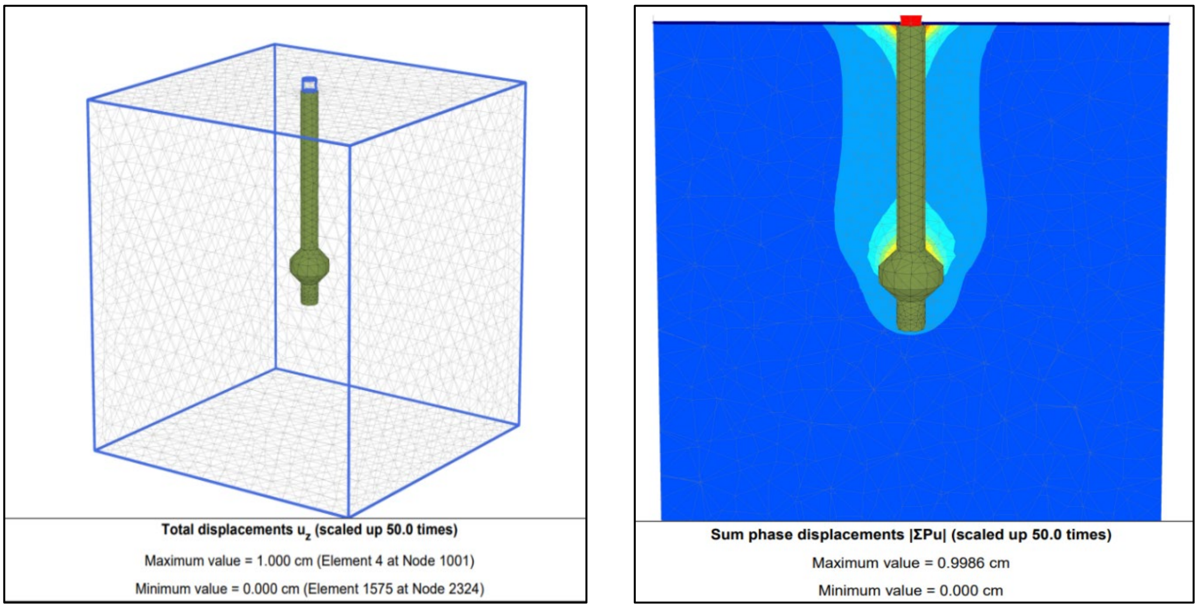
Figure 2: Load-displacement curve for SP, SURP, and DURP [3,13]

Table 2: Clayey soil and pile input properties

Properties	Soil	Pile
Model	Mohr-coulomb	Linear-Elastic
E, MPa	15	31000
Unit weight, kN/m^3	16	27
Cohesion, kPa	15	----
Poisson's ratio	0.35	0.15
The angle of friction, degree	1	----
Length, m	---	4.5
Diameter of the shift, m	---	0.3
Diameter of the bulbs, m	-----	0.8



a) Load-displacement curve for SURP



b) Finite element meshing and deformation of the problem

Figure 3: a) Load-displacement curve for SURP obtained from PLAXIS -3D compared with [3,13], b) Finite element meshing and deformation of the problem

4. Parametric Study

4.1 Numerical Parameters and Analysis

Plaxis-3D numerical modeling with ten-node elements was used to investigate the behavior of under-reamed piles in layered clayey soil. The constitutive model was used to represent the linear elastic performance of the under-reamed pile, and the Mohr-Coulomb model was used to characterize soil behavior around the pile shaft. The input parameters to model the soil are the unit weight, Young's modulus, Poisson's ratio for soil elasticity, cohesion (c), and interface ratio between the soil and concrete surface of the pile. A fine mesh has been generated, and the results of meshing the problem were 22,584 elements and 35,015 nodes. The present research uses the proposed displacement standard in Part 4 of the Indian standard code of practice for the design and construction of pile foundations [14], which reports that the ultimate pullout capacity of the pile is derived from the load-movement curve, which is equal to 10% of the pile diameter.4.2. Soil properties. The soil parameters employed in the current survey are reported in Table 3 based on the literature of George and Hari [3], and Kumar et al., [13].

4.2 Pile Geometry

The geometry of the pile design used in the current study, shown in Figure 4 (a-c), was selected according to the relevant Indian standard code specification (IS 2911) [15], which was followed by George and Hari [3], and Kumar et al. [13], as shown in Table 4. According to Waterman [16], the strength reduction factor Rinter is assumed to be 0.6 based on the interaction between concrete and clay and depending on the surface roughness of the pile.

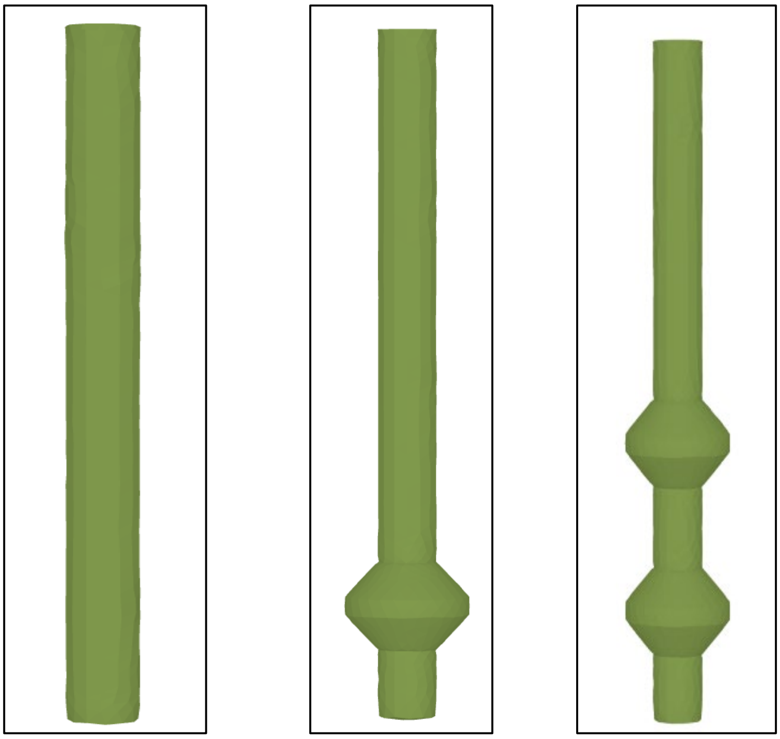
Table 3: Oil properties used for all models

Parameter	Unit	Soft- clay	Medium -clay	Stiff- clay
Material model	---		Mohr-Coulomb	
Drainage type	----		Drained	
Unit weight (γ)	kN/m^3	16	16	18
DR%	---	----	----	----
Young's modulus (E)*	kPa	16000	18000	4000
Poisson's ratio (υ)*	-	0.35	0.27	0.25
Cohesion (c)	kPa	20	50	80

*Assuming from Budhu (2020) [17].

Table 4: Dimension with properties of under-reamed pile's model

Parameter	Unit	value
material type	----	concrete
Model	-----	Linear elastic
Pile diameter, D_p	m	0.3
Pile length, L_P	m	4.5
Under-reams diameter (D_U/D_P)	m	0.75
Bulb spacing ratio c-c S/D_U =1.5(D_U/D_P)	m	1.125
Upper angle of the under-ream pile, $Ø_1$	degree	45
Lower angle of the under-ream pile, $Ø_2$	degree	45
Young's modulus (E)	kPa	25×10^6
Unit weight, $γ_p$	kN/m^3	27
Poisson's ratio	-----	0.15



a) SP **b) SURP** **c) DURP**

Figure 4: a) SP, b) SURP, and c) DURP Modeling pile system (PLAXIS -3D)

The testing box geometry was constructed with 7 m x 7 m dimensions on the x-axis- and y-axis. The soil layer's top boundary is at a depth of z equals zero, while the soil layer's bottom boundary is at a depth of z = 7.5 m. Figure 5 (a and b) shows the pile-soil F.E. meshing.

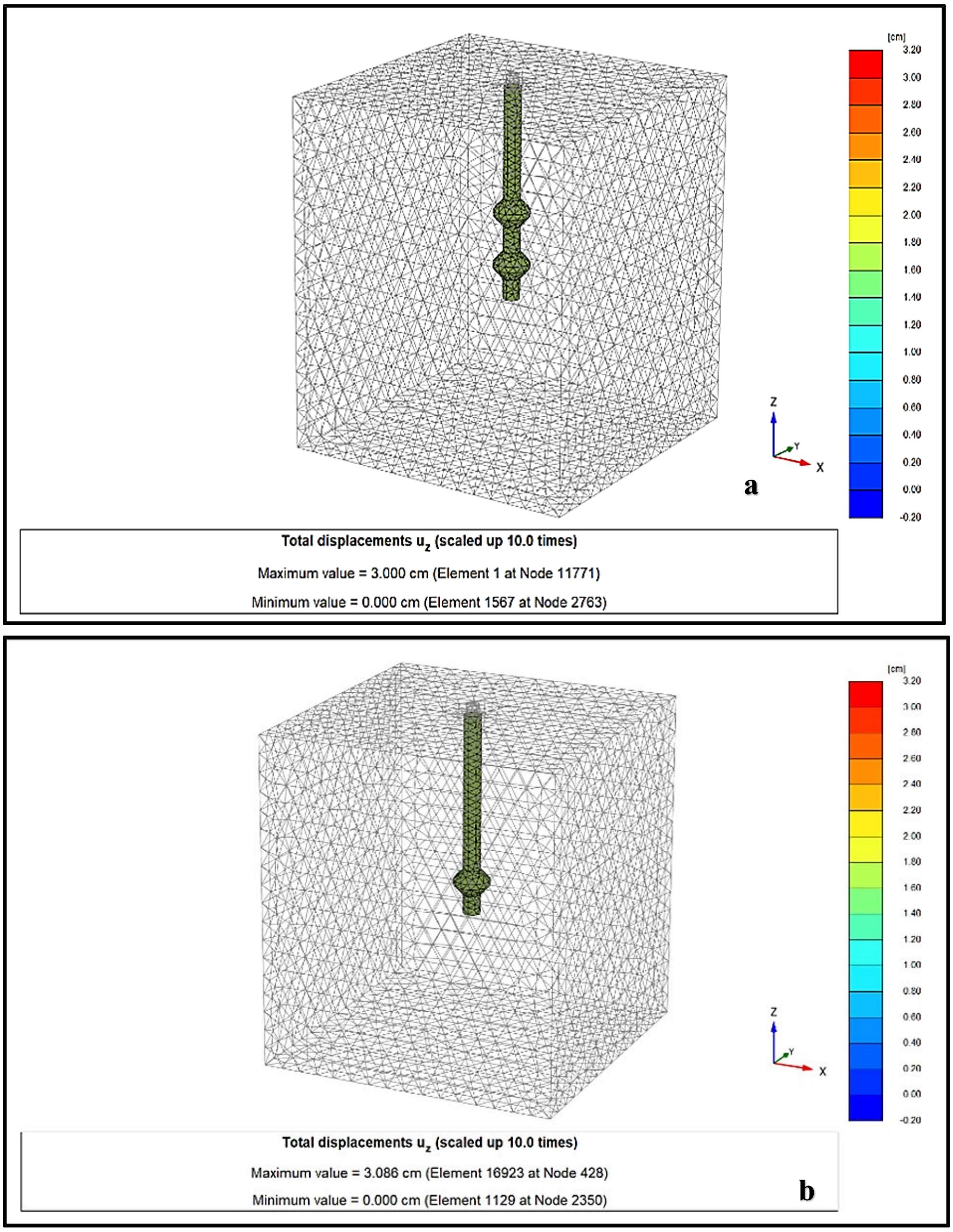


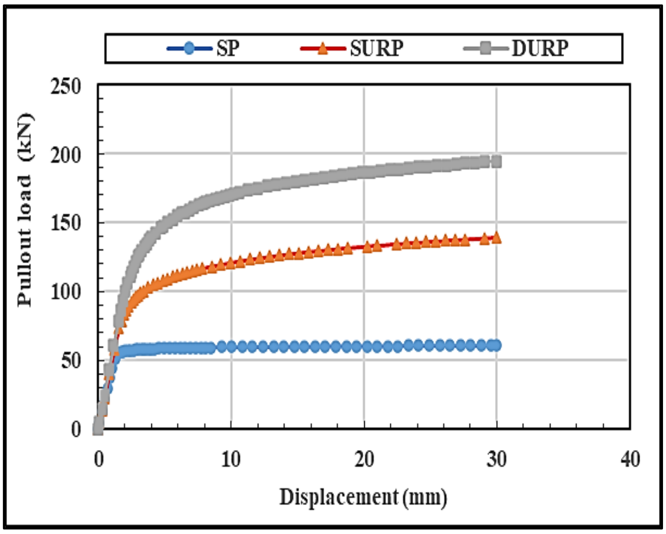
Figure 5: a) Single under-reamed pile, b) double under-reamed pile meshing

5. Results and Discussion

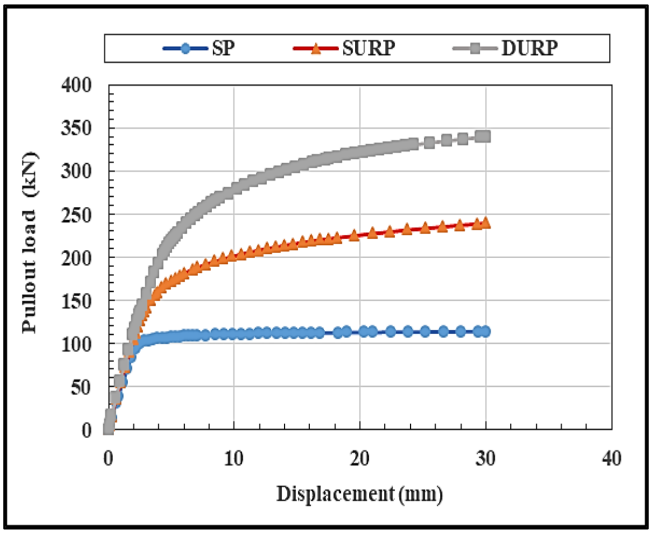
In the present research, the pullout loading of under-reamed piles was numerically observed by varying the geotechnical and geometrical properties. Moreover, the pullout capacity of piles was investigated by changing the soil strata, the provision of bulbs, and the soil cohesion (20, 40, and 80 kPa). The ultimate pullout load capacity of the pile is derived from the load-deformation curve as 10% of the pile diameter.

5.1 Under-reamed Pile in a Single Layer of Clayey Soil

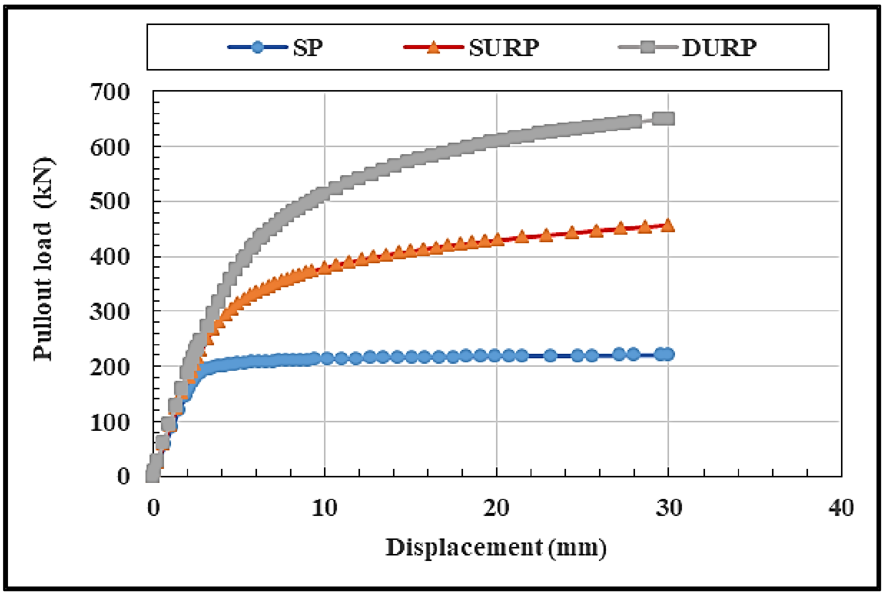
Figure 6 (a-c) shows the load-displacement relations of the straight pile and under-reamed piles based on different parameters of soil cohesion (20, 40, and 80 kPa). The water table was fixed at ground level. Figure 6 illustrates the effectiveness of the number of under-reams on the ultimate pullout loading. A significant improvement compared to the conventional pile was observed.



a) Cohesion =20 kPa



b) Cohesion =40 kPa



C) Cohesion =80 kPa

Figure 6: Load-displacement curves for different cohesion soils a) cohesion 20 kPa, b) 40 kPa, and c) 80 kPa

From the numerical output analysis, it can be observed that the bearing pullout load increases with an increasing number of bulbs. Therefore, the number of bulbs plays a significant role in enhancing the pile capacity due to adding more bearing area to the shaft see Figure 7. Additionally, increasing the soil cohesion from 20 to 80 kPa slightly improved the pullout load because of the increased adhesion between the soil and the pile. Multiple bulbs also increased the pile surface area that came into contact with the surrounding soil. The expanded bearing area helps to distribute the applied load over a larger contact area, reducing the stress on the soil and improving load-carrying capacity. However, a significant improvement is achieved when the cohesion increases from 20 to 80 kPa, especially for double under-reamed piles. Table 5 shows the degree of improvement in the pullout load of single and double under-reamed piles with three different undrained cohesions compared to the conventional pile. The outcomes obtained are in agreement with the findings reported by Alhassani [7], George and Hari [3], and Kumar et al. [13], especially for under-reamed piles installed on soft clay soil.

Table 5: Improvement of the pullout capacity of the under-reamed pile in different cohesions

Soil type	**Degree of Improvement%**	
	Single under-reamed pile	Double under-reamed pile
Soft clay	130%	194%
Medium clay	110%	200%
Stiff clay	107%	195%

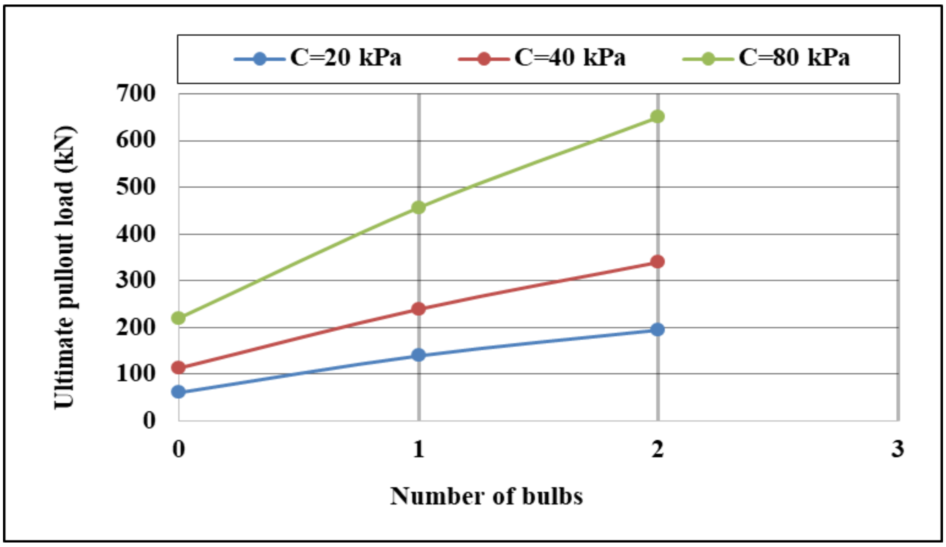


Figure 7: The ultimate pullout load for the changed number of bulbs

It can be shown that increasing the soil cohesion from 20 to 80 improves the ultimate pullout capacity for the same type of pile, and the benefits were found for SP, SURP, and DURP at 262%, 227%, and 234%, respectively see Figure 8. Cohesion in soils significantly affects shaft resistance. As soil particle cohesion increases from soft to medium and stiff, shaft resistance also rises. This increased cohesion along the pile enhances pullout loading capacity as cohesive soil resists movement and improves load transfer. Additionally, the bulbs interact with the soil through adhesion and cohesion forces in cohesive soils. As the soil strength increases, so do the adhesion and cohesion forces between the soil and the bulbs. This enhanced interaction leads to increased resistance to pullout forces and, consequently, increased pullout loading capacity.

Regarding Soil-Pile Bonding, the bond between the soil and the pile may be relatively weak in certain cases. However, as the soil strength increases to medium and stiff, the bonding between the soil and the pile surface improves. This enhanced bonding further enhances the load transfer mechanism, resulting in a higher pullout loading capacity.

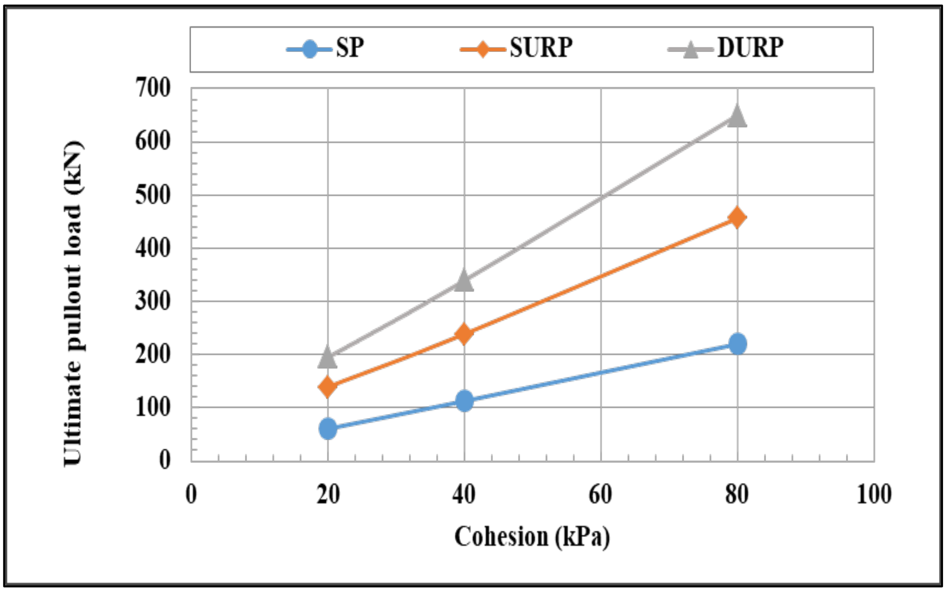


Figure 8: Ultimate pullout capacity under-reamed piles based on different soil cohesion

The failure patterns for SP, SURP, and DURP generated during the pullout load are shown in Figure 9 (a-c). Studying the results of the three types of piles with a 30 mm vertical uplift movement reveals that for the conventional pile (SP), the resistance along the pile shaft was very small and limited to the closed area around the pile. In contrast, for SURP and DURP, soil deformation was greater than that in a straight pile, and the areas where large movements occurred were wider. Observing the behavior of soil movement in the cases of SURP and DURP, it was evident that the soil movement around the projections was larger than around the shaft. The generated failure patterns for the pullout situation were similar to those reported by George and Hari [3], and Kumar et al., [13]. The results show that the under-reamed piles (SURP and DURP) exhibited better resistance to soil movement and larger deformation areas than the conventional pile (SP). These findings are consistent with previous research conducted by George and Hari [3], and Kumar et al., [13].

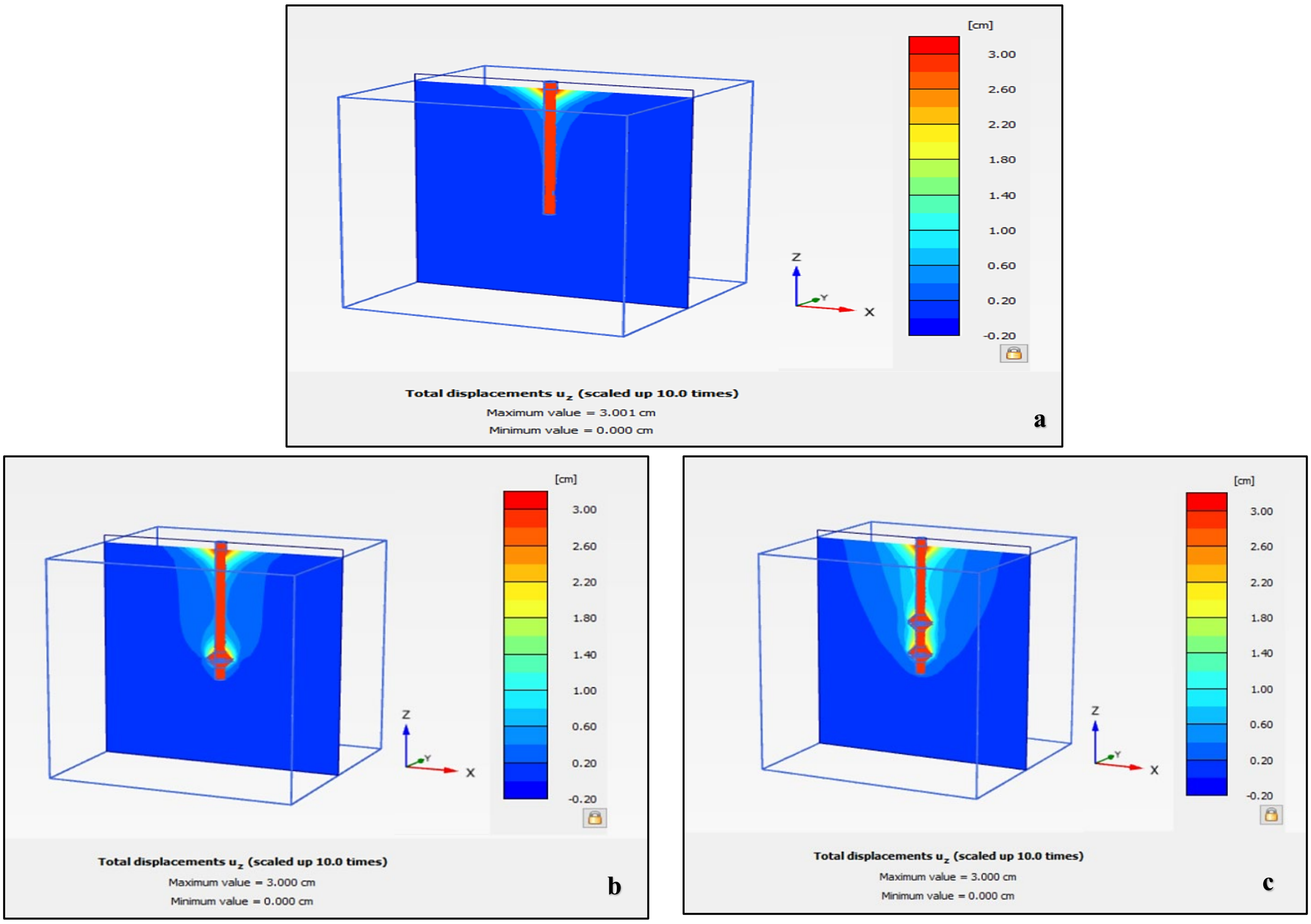


Figure 9: a) SP, b) SURP, and c) DURP Deformation contour of belled piles

5.2 Behavior of Load-Displacement Curve of The Single Under-Reamed Pile in Layered Soils

To simplify the effect of changing soil consistency on the undreamed pile's pullout load, two soil layers (soft soil on hard soil and vice versa) were studied, as shown in Figure 10, which depicts the soil layer, pile, and vertical uplift load. The water table level was kept at 2 m below the ground surface. The dimensions of the problem are the same as those used in one-layer homogeneous soil: under-reams resting within the lower layer at the beginning of the loading, the length of the pile, and the bulb's place determine the thickness of each layer.

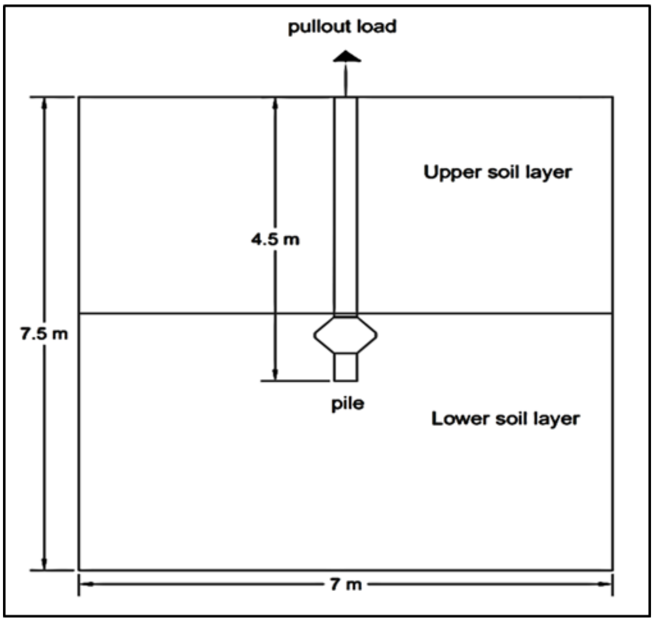


Figure 10: Problem statement model of SURP

As shown in Figure 11, the pullout versus vertical movement of the SURP pile in layered soil systems demonstrates a varied ultimate pullout load depending on the layer system. When comparing the implantation of the pile in soft soil with one of the upper or lower soils being strong, the load-displacement curve exhibits a significant increase. It should be noted that the bulb position is always within the bottom layer. In the early stage of the load-displacement curve for both cases of stiff clay over soft clay and soft over stiff clay, there is an increase in pullout capacity when the bulb is used, followed by a constant rate of capacity with large displacement. The maximum ultimate pullout capacity obtained from the case of the stiff clay resting on the soft clay is about 336 kN, followed by a reduction in value when the bulb is located in the case of stiff clay overlaid by soft clay, with a difference of approximately 246 kN.

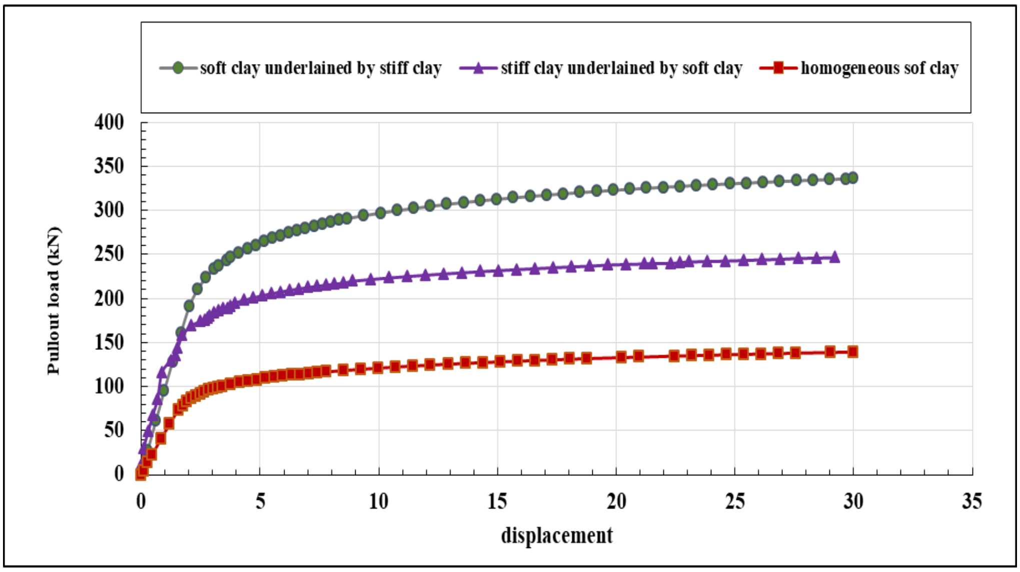


Figure 11: Load-displacement curve of one under-reamed pile in changed types of soil layers

The presence of stiff clay on top of soft clay provides additional resistance against pullout. The stiff clay layer acts as a confining medium, preventing excessive movement and reducing the risk of pullout failure. The cohesive properties of the stiff clay layer help maintain the integrity and stability of the pile. On the other hand, in the case of soft clay over stiff clay, this may result in reduced resistance against pullout loading. Soft clay has lower shear strength and cohesion than stiff clay; therefore, the soft clay layer may allow for greater displacement and increase the risk of pullout failure.

6. Conclusion

The following significant outcomes were identified from the analysis and interpretation of the results:

1) Increasing the soil cohesion from 20 to 80 kPa improves the load-deformation behavior of a pile subjected to pullout loads.
2) Adding bulbs improves the load-deformation behavior of a pile in soil with varying cohesions when exposed to uplift loads. Adding a single bulb to a pile increases pullout capacity from 107 to 130%, while using two bulbs increases the ultimate load to 200%.
3) The pullout load of the under-reamed pile in the initial movement is slightly larger than that of the straight pile.
4) An improvement in the displacement curve when comparing the pile's location in a weak, homogenous soil to soil in which one of its layers is strong soil.
5) For a single under-reamed pile, the variety of the soil layers, including the under-ream seating, is very effective in controlling the load-displacement relationship. The clayey soil placed immediately above the bulb predominantly moves along the pile material and inside the failure zone.
6) The cohesion forces within the soil matrix provide stability and resistance against movement. This reduced soil deformation results in a more efficient load transfer to the under-reamed piles, increasing pullout loading.
7) The conclusions drawn from this study are based on a limited analysis of piles of one particular length and may not be fully applicable to piles and bulbs of other dimensions.

Author contributions

Conceptualization, A. AL. Bayati, M. AL-Neami and F. Rahil; methodology, A. AL. Bayati; validation, A. AL. Bayati; resources, data curation, A. AL. Bayati; writing—original draft preparation, A. AL. Bayati and M. AL-Neami; writing—review and editing, A. AL. Bayati and M. AL-Neami; supervision, M. AL-Neami . All authors have read and agreed to the published version of the manuscript.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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