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Numerical Exploration and Optimisation on Pullout Capacity Behaviour for Under-Reamed Piles in Dry and Partially Saturated Sand

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Abstract:
The pullout capacity behaviour of straight and underreamed piles in two soil layers was investigated in the current work using Plaxis 3D 2020. The layered soil includes one layer of homogeneous sand, dense sand topped with stiff clay, and stiff clay topped with dense sand. The piles were selected per the Indian Code Specification (IS 2911). To depict the impact of bulb numbers and their positions on the ultimate pullout load of the pile, three types of large-scale concrete pile models were employed: uniform pile shaft (SP), pile with one bulb (SURP), and pile with two bulbs (DURP). Under-reamed piles measure 0.3 m in stem diameter by 4.5 m in height, with a bulb diameter of 0.75 m. The relative density of the soil is varied to understand its impact on pile behaviour, with the internal friction angle (ϕ) in sand varying between 30 and 39 degrees. In this regard, the soil was assumed to obey Mohr-Coulomb's failure criteria. The findings revealed that multiple under-reams led to more soil-structure interactions, resulting in increased mobilisation of soil resistance. Compared with a conventional pile under identical conditions, a single under-ream increased the ultimate pullout pile load by about 3.5 times. For the double under-ream, it was increased by about 4times. For all types of piles, the ultimate pullout load of a pile embedded in dry sand is often greater than that fixed in fully or partially moist soil. The ultimate pullout carrying capacity was the largest when the two under-reamed piles were embedded in stiff clay resting on dense sand, rather than in dense sand in the top layer or in a single layer of homogeneous dense sand.

Keywords:
Cohesionless soil; Failure patterns; Finite element; Pullout Capacity; Under-reamed pile.

Highlights:
- As the relative density of the soil rises, its compactness improves, resulting in enhanced load-bearing capability.
- Additional bulbs enhance the pile's resistance to pullout forces and its overall stability.
- In multi-layered soil, an improvement was observed in the load capacity of the pile compared with the dense state of sandy soil.

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1.INTRODUCTION

Underreamed piles are cast-in-place bored piles with one or more underreams, formed by enlarging the pile shaft from any position. Under-reamed piles provide improved resistance against lateral, compression, and uplift forces, making them suitable for tall buildings or structures located in regions prone to seismic activity or high wind loads. The enlarged bulbs enhance pullout resistance and help maintain the foundation's stability. It is the most cost-effective foundation, requiring less concrete to replace the excavated material, which makes larger base piles more affordable. However, building an extended base pile exposes the workers to the risk of the excavation collapsing. Tomlinson [1]. Xie and Yin [2] conducted a numerical investigation to study the effect of bulbs' spacing on the behaviour of the belled pile. They discovered that when the spacing ratio (the vertical distance between two bulbs, c-c) is less than twice the bulb diameter, the pile is not working effectively because the soil between the bulbs is thin and crushed. However, when the spacing is greater than five bulbs in diameter, the pile's load-bearing capacity increases gradually with increasing distance between bulbs. Harris and Madabhushi [3] experimentally investigated the influence of varying the underreamed angle. The outcomes indicated that the pullout resistance decreases as the under-ream angle of the pile increases, particularly at 75˚. Kumar et al. [4] performed a numerical and analytical study to examine the pullout load of under-reamed piles embedded in sandy soil. The embedment ratio (L/D), where (L) is the length of the pile and (D) is the pile stem diameter, was kept in the range of (7 to 17.5). The results showed that the pullout load corresponding to the indicated movement increases with increasing pile ratio, indicating an increase in bearing capacity. Also, adding more bulbs improves overall pile behaviour. Patra et al. [5] found that under-reamed piles exhibit greater ultimate uplift capacity in medium-over-dense sand than in dense-over-medium sand. Bose and Krishnan [6] tested models of vertical and batter piles embedded in the sand with 80% relative density and an angle of shearing resistance of 38°of variation (diameter, length, shapes, and surface characteristics). The test results demonstrated that as the L/d Ratio of the pile increases, the pile's resistance at any displacement increases significantly. The results also indicated that the pullout capacity increases with the pile's diameter. Also, they discovered that for piles of varying shapes but constant volume, circular piles withstand a higher pullout capacity than square or rectangular piles. Nasr [7] said that as the Ratio of embedment length to base diameter of the under-reamed pile increases, the pullout capacity improves at the same relative density of the sand. The percentage of pullout load increases with increasing relative density and embedded Ratio. Nazir [8] reported that the pullout load reduced dramatically as the base angle of the underreamed pile increased. The model pullout load was 6% lower for the single bulb pile with a base angle of 60°, and the pullout load with a base angle of 45° was 5% lower than the pullout load with a base angle of 30° in dense sand. Farokhi et al. [9] numerically evaluated under-reamed piles and found that, under tensile loads, half-bulb piles achieve higher maximum uplift capacity than full-bulb and uniform piles of the same dimensions and volume. The full-bulb pile also outperformed a uniform pile of equal length and volume, while the half-bulb pile's capacity was approximately 27% greater than the full-bulb and 75% higher than the uniform pile. Increasing the L/d Ratio of an under-reamed pile further enhances uplift capacity and reduces displacement. Al-Tememy et al. [10] reported that increasing sand density from loose to medium and extending the embedded pile length both improve load-carrying capacity. Al-Bayati et al. [11] tested the SURP and DURP under-reamed piles embedded in sandy soil with varying relative densities, numbers of bulbs, spacing ratios between bulbs, and soil layers. The test findings revealed that when the bulb spacing ratio is 1.5, the highest ultimate pile load for pullout is achieved. Alhassani [12] conducted a numerical study using ABAQUS to examine belled pile behaviour under uplift, lateral, and compression loads, finding that for all L/D ratios, both SURP and DURP have higher pullout capacity than uniform piles. Deb and Pal [13] studied the failure patterns of enlarged-base piles in sand under pullout loads. Variable parameters were employed to detect variations in the nonlinear failure pattern in the sand. The study considered L/D ratios of 3, 4, and 5, diameter ratios (Dp/Du) of 0.28, 0.33, 0.38, and 0.46, and a bulb angle of 45°. According to a survey of similar studies, little research has been conducted to clarify the pullout capacity of under-reamed piles in cohesionless soil, particularly in layered soils, a problem often encountered in the field. There may be a scarcity of literature on the behaviour of underreamed piles subjected to uplift loads. The test will be performed in dry, partially saturated, and fully saturated conditions. The piles' pullout bearing capacity and failure mechanisms can be assessed by analysing load-displacement behaviour. This study uses PLAXIS 3D (2020) to numerically investigate the load–displacement behaviour, pullout bearing capacity, and failure mechanisms of single under-reamed and double under-reamed piles embedded in a single sandy layer and in two different soil-layer configurations. The results will aid in optimising pile design and construction practices for various soil relative densities and different soil saturations, ensuring more efficient and reliable foundation systems in civil engineering projects.

2.NUMERICAL PROGRAM

PLAXIS 3D (2020) is used to assess under-reamed pile performance under pullout loads in sandy soil at three relative densities (Dr = 35%, 55%, and 75%), both dry and partially saturated. To achieve these goals, a series of tests will be carried out, subjecting under-reamed piles to varying loads and measuring the resulting displacements. The tests will be conducted in dry and partially saturated conditions to simulate realistic field scenarios. Analyse the load-displacement behaviour, the pullout bearing capacity, and the pile failure mechanisms to be determined.

3.VALIDATION OF NUMERICAL MODEL

The experimental examination conducted by Sakr et al. [14, 15] was used to validate the numerical results. The experiment utilised a steel pile with a shaft diameter (Dp = 20 mm) and an embedment depth (Lp = 500 mm). The bulbs are spherical, with diameters (D_u) equal to ($2D_p$). The sandy soil was used as an embedment material with densities of 16.3, 16.8, and 17.62 kN/m3 for loose sand (DR = 30%), medium sand (DR = 50%), and dense sand (DR = 80%), respectively. Table 1 summarises the soil properties employed for validation. The input parameters are listed in Table 2. The domain range used in the tests is 310 mm in length and width, and 1000 mm in height.

Table 1 Soil Input Properties.

Sand Properties	Unit	Loose	Medium	Dense
Relative Density, DR	%	30	50	80
Dry Unit Weight, γ_d	kN/m³	16.3	16.8	17.62
Friction Angle, φ	deg.	31.5	34	39
Modulus of Elasticity, Es*	kPa	15000	30000	60000
Poisson's Ratio, ν *	-----	0.2	0.25	0.3

* Assuming value from Mohammed [16].

The applied load and the upward movement were the primary results of the experimental research. The pullout load and normalised displacement relationship (δ/DP) %, where (δ) is the pile displacement and (D_p) the stem diameter, is illustrated in Fig. 1.

Table 2 Pile Input Properties.

Steel Pile Properties	Unit	Value
Unit Weight of Pile	kN/m3	78
Modulus of Elasticity, E	kN/m2	200×106
Poisson's Ratio, ν	----	0.3

The interface reduction strength parameter (R_{inter}) was taken manually (0.7), as reported by Waterman [17]. A fine mesh was used to gain accurate numerical outcomes. Fig. 2 demonstrates a finite element model for soil-pile meshing. The numerical model-estimated load-displacement curves were compared with the experimental results of Sakr et al. [15], as shown in Fig. 3. The analysis was in complete agreement with the experimental data.

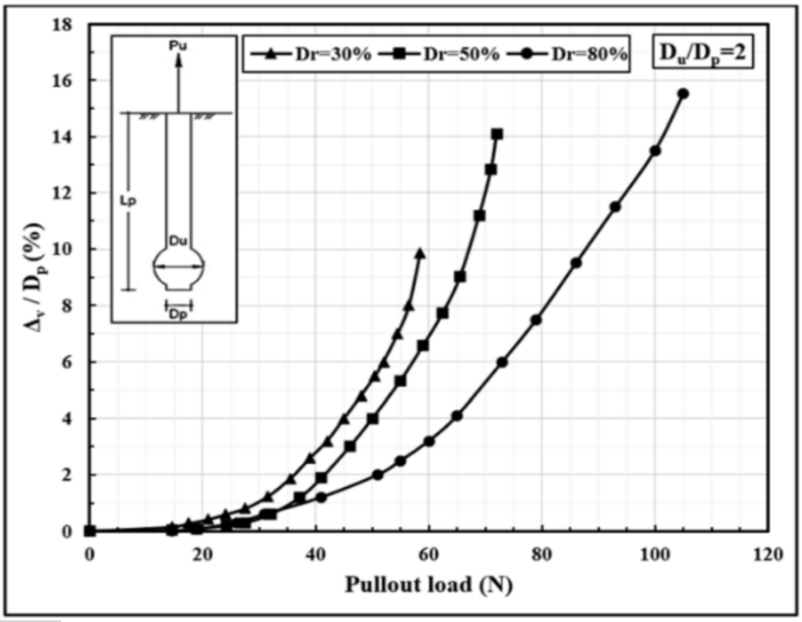


Fig. 1 Pullout Load vs. Normalised Movement Curves for Model Piles.

Fig. 2 Problem F.E Meshing.

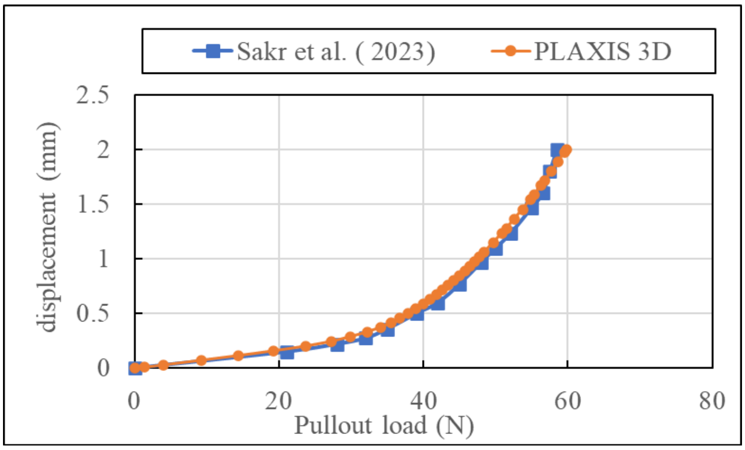


Fig. 3 Validation of the Results Obtained from PLAXIS-3D and Sakr et al. [15].

4.PARAMETRIC STUDY

4.1.Numerical Parameters and Analysis

The 10-node tetrahedral element is the basis of soil elements in three dimensions (3D finite element mesh). The constitutive model was adopted to represent the linear elastic behaviour of the under-reamed pile, whereas the Mohr–Coulomb model was employed to characterise the surrounding soil. The soil input parameters included soil cohesion (c), Young's modulus, unit weight, Poisson's Ratio (for soil elasticity), and the interface ratio between the soil and the pile–concrete surface. A fine mesh was generated, resulting in 23,866 elements and 38,006 nodes. The present study adopts the displacement criteria specified in Part 4 of the Indian Standard Code of Practice for the Design and Construction of Pile Foundations [18]. This is because the Indian Code provides comprehensive research on all variables associated with these pile types. The ultimate pullout capacity of the pile is obtained from the load–displacement curve at 10% of the pile diameter.

4.2.Soil Modelling

The sand characteristics in this study were obtained directly from laboratory experiments. Table 3 lists the sand parameters used.

Table 3 Soil Properties Used for All Models.

Soil properties	Unit	Loose Sand	Medium Sand	Dense Sand	Stiff Clay
Relative Density, DR	%	35	55	75	---
Cohesion (c)	-----	------	-----	----	80
Dry Unit Weight, γd	kN/m3	15.58	16	16.5	18
Friction Angle, φ	deg.	30	35	39	---
Modulus of Elasticity, Es*	kPa	10000	20000	35000	40000
Poisson's Ratio, ν *	-----	0.15	0.2	0.25	0.27

* Assuming value from Mohammed [16].

4.3.Pile Modelling

The pile geometry adopted in the present study, illustrated in Fig. 4, was selected in accordance with the specifications of the Indian Standard Code (IS 2911) [19], and is consistent with the configurations used by Kumar et al. [4] and Nasr [7], as summarised in Table 4.

Table 4 Under-Reamed Pile Model: Dimensions and Properties.

Parameter	Unit	Value
Material type	----	Concrete
Model	-----	Linear Elastic
Pile Length, L_P	m	4.5
Pile Diameter, D_p	m	0.3
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
Lower Under-Ream pile Angle, $Ø_2$	degree	45
Upper Under-Ream Pile Angle, $Ø_1$	degree	45
Unit Weight, $γ_p$	kN/m3	27
Young's Modulus (E)	kPa	25×106
Poisson's Ratio	-----	0.15

Following Waterman [17], the strength reduction factor (R_{inter}) was assumed to be 0.7 to account for the interaction between concrete and sand. The testing geometry box was constructed with x- and y-axis dimensions of 7 m × 7 m, whereas the sand stratum's top and bottom boundaries are at depths of z = 0 and z = 7.5 m, respectively. Fig. 5 shows the F.E. mesh for the pile-soil system.

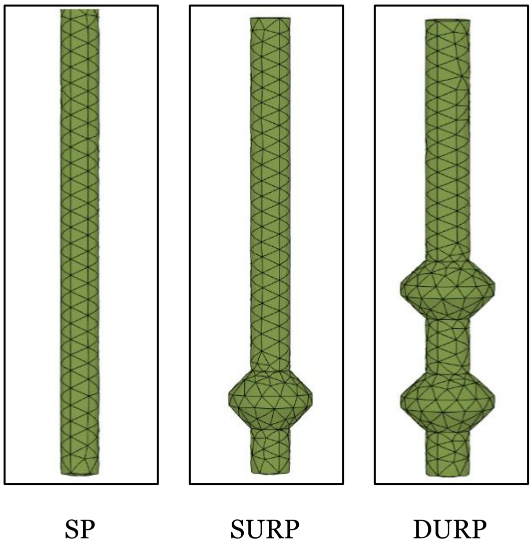
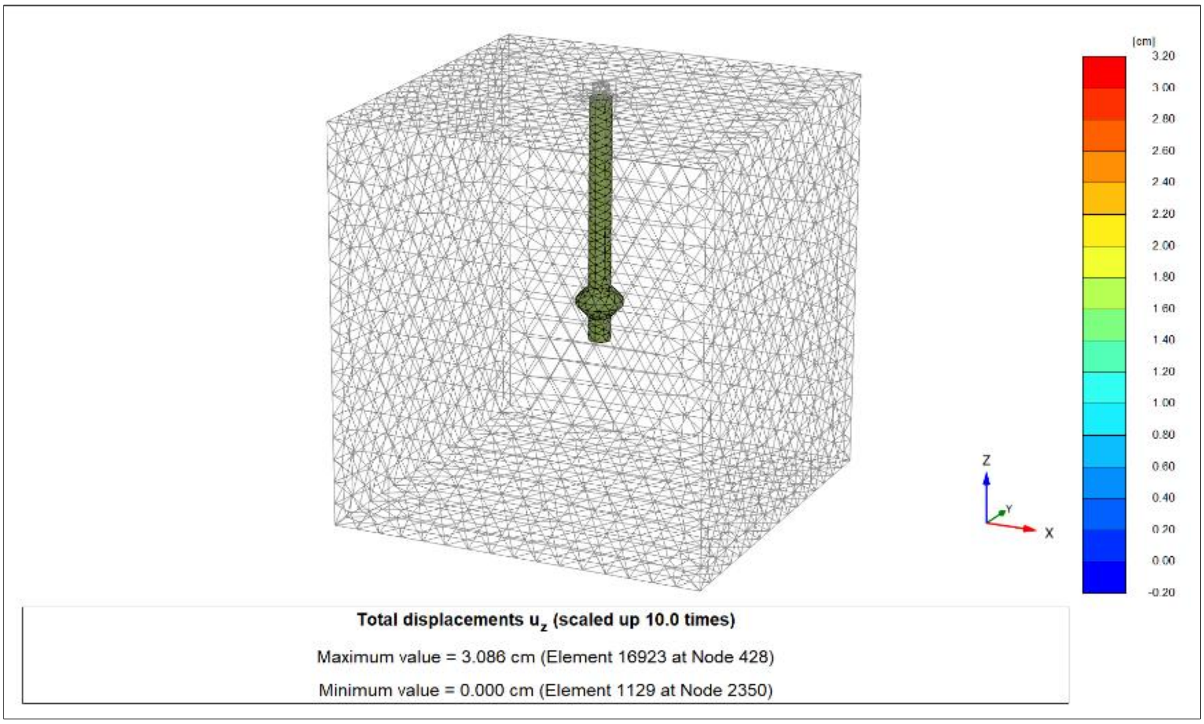


Fig. 4 Modelling Pile System (PLAXIS -3D).



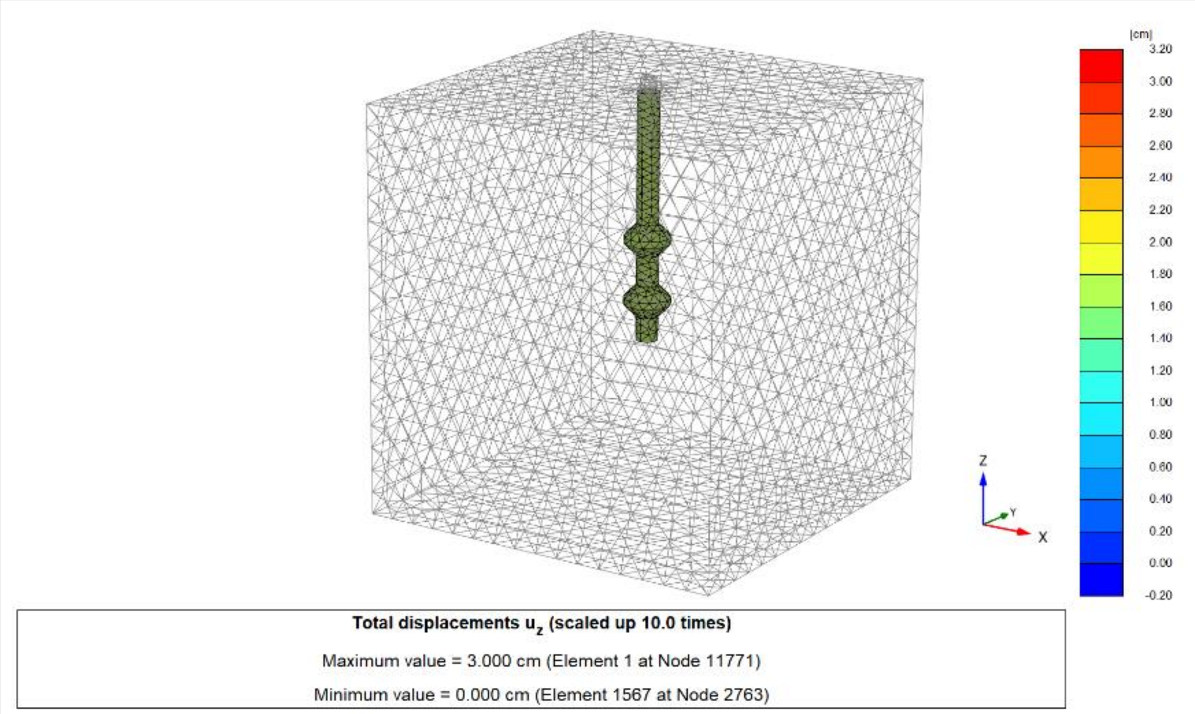


Fig. 5 Single and Double Under-Reamed Pile Meshing.

5.RESULTS AND DISCUSSION

A numerical study was conducted to evaluate the pullout capacity of all three pile types (SP, SURP, and DURP) by varying the relative density of the sandy soil (35, 55, and 75%), the number of bulbs, and the water table level. On the other hand, the study investigated the impact of soil characteristics on the load-displacement relationship in a two-layer system. The main results of the investigation are outlined in detail in the following parts:

5.1.Effect of a Single Soil Layer's Relative Density on Ultimate Pullout Capacity

The soil density plays a crucial role in determining the load-displacement curve. Figs 6-8 show load-displacement graphs of straight and belled (one and two under-reams) based on different angles of internal friction embedded in dry sand conditions.

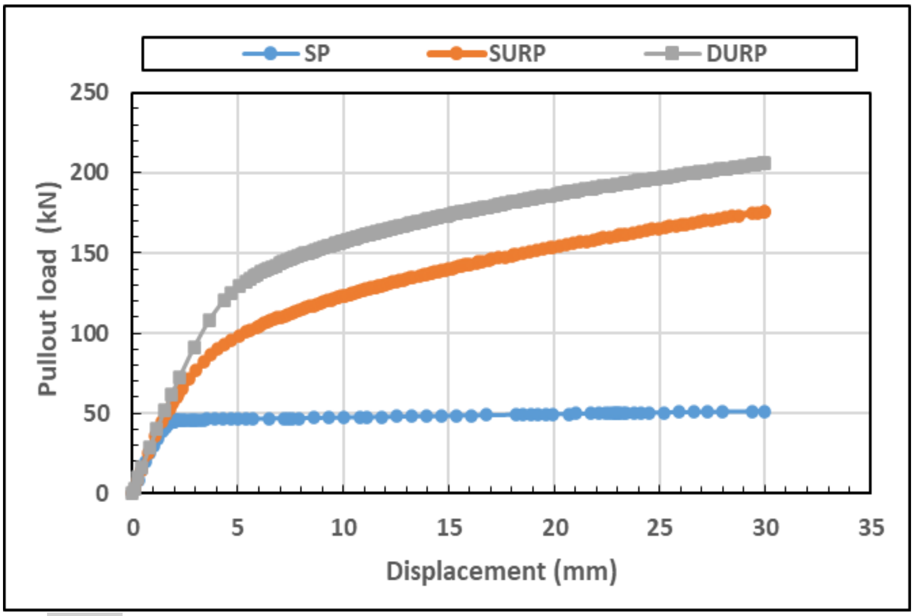


Fig. 6 Load-Displacement Curve in Sandy Soil, Relative Density 35%.

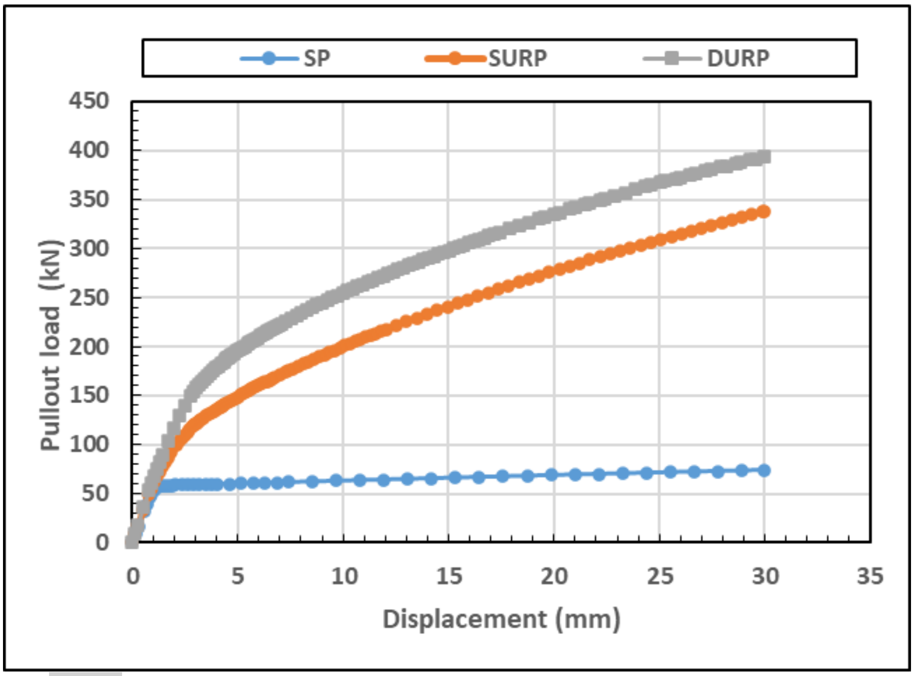


Fig. 7 Load-Displacement Curve in Sandy Soil, Relative Density 55%.

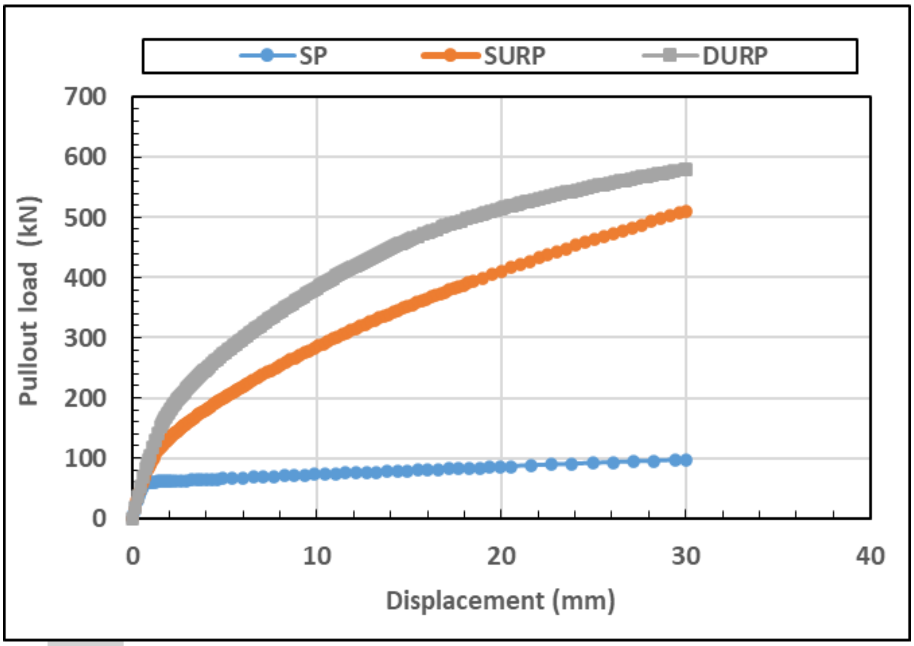


Fig. 8 Load-Displacement Curve in Sandy Soil, Relative Density 75%.

From a loose to a dense state, the sand exhibits higher initial stiffness and minimal movement. Dense soils provide greater support for the pile and enhance load-bearing capacity. This behaviour occurs because, as relative density increases, soil compactness and interlocking improve, resulting in higher stiffness and load-bearing capacity. The failure mechanism can be affected by relative density, with denser soil exhibiting more localised failures and fewer deformations. Raising the relative densities from 35% to 75% enhances the ultimate pullout capacity of the pile, as shown in Fig. 9, with improvements of 88%, 190%, and 180% for SP, SURP, and DURP, respectively. The results obtained were close to those of Kumar [4], Nasr [7], Al-Bayati et al. [11], and Dickin and Leung [20].

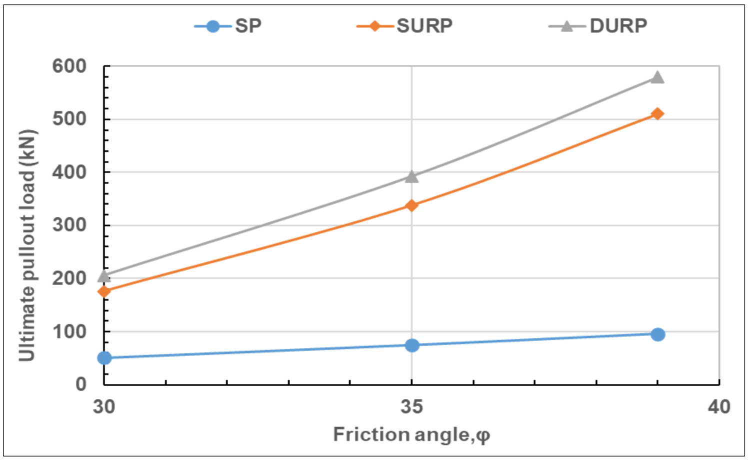


Fig. 9 Ultimate Pullout Capacity Under-Reamed Piles Based on Different Angles of Fraction.

5.2.Effect of the Number of Bulbs on Ultimate Pullout Capacity

Table 5 illustrates the improvement in the uplift carrying capacity of SURP and DURP piles in three relative densities. A good improvement was observed compared to the conventional pile. From the numerical results shown in Fig. 10, it is clear that the number of underreams had a substantial impact on the pullout load capacity of the belled pile. Adding bulbs to a straight pile increases the surface area in contact with the surrounding soil. This results in enhanced pullout load-bearing capacity as the bulbs provide additional resistance against uplift and lateral forces. The increased contact area allows for better distribution of the applied loads, reducing stress concentration and potential failure.

Table 5 Improvement of Uplift Loading of Underreamed Pile in Different Relative Densities.

Sand State	Degree of Improvement %	
	SURP	DURP
Loose	240	300
medium	350	430
dense	430	500

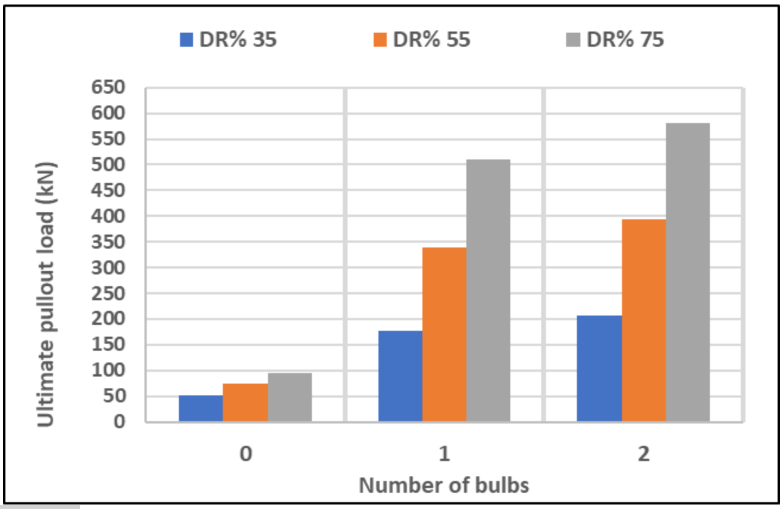


Fig. 10 Effect of the Number of Bulbs on the Ultimate Pullout Load.

By incorporating bulbs, the load distribution along the pile shaft becomes more uniform. This is particularly beneficial in soils with varying relative densities. The bulbs can help distribute the load to different soil layers, compensating for variations in soil strength and stiffness. As a result, the overall performance of the pile has improved, reducing the risk of localised failures. The bulbs facilitate improved soil-pile interaction by increasing frictional resistance and mobilising skin friction.

5.3.Under-Reamed Pile Failure Mechanisms Pattern

Fig. 11 shows the failure patterns of SP, SURP, and DURP piles under pullout loading. For a vertical uplift of 30 mm, the SP pile exhibits very limited failure along the shaft, confined to the area immediately surrounding the pile. In contrast, the SURP and DURP piles experience greater soil displacements than the straight pile, with the zones of significant movement being more extensive. Moreover, for the SURP and DURP piles, the soil movement around the projections is noticeably greater than that around the main shaft.

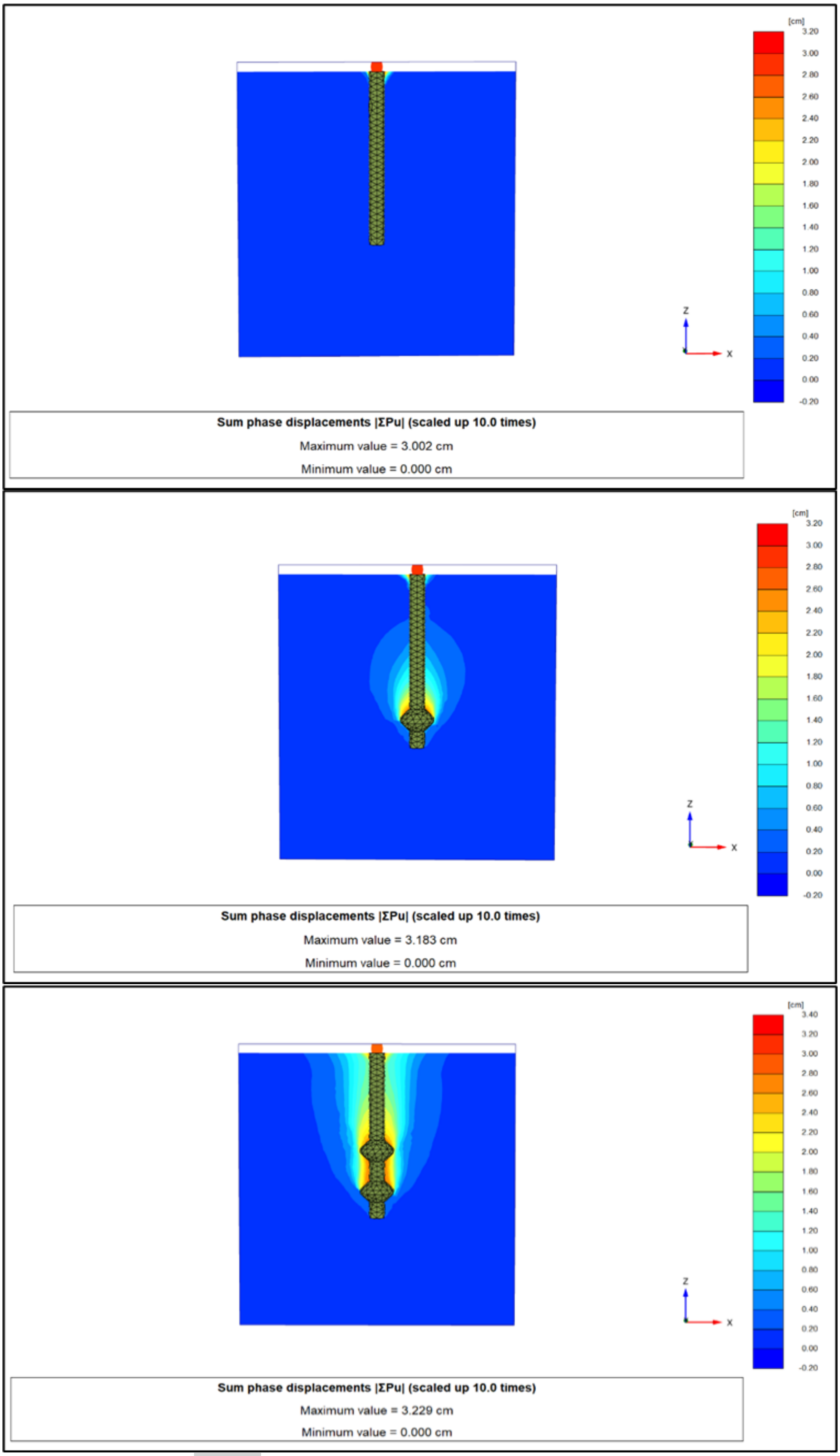


Fig. 11 Deformation Contour of Under-Reamed.

The failure mechanism during pullout loading typically involves two main components:

1- Base Failure: The under-reamed bulb, which is larger in diameter than the shaft, acts as an anchor in the soil. However, under excessive pullout loads, the sandy soil can fail around the bulb due to insufficient bearing capacity. This failure occurs along a failure surface around the bulb, resulting in the pile losing its resistance to pullout forces.

2- Shaft Failure: In sandy soils, the pullout load can induce shear failure along the pile shaft. The failure occurs due to excessive shear stresses exceeding the soil's shear strength. This failure can manifest as a shear plane developing along the pile shaft, leading to reduced frictional resistance and a potential for pile pullout. The generated failure patterns, in the form of a balloon-shaped uplift case, were along lines similar to those of Harris and Madabhushi [3], Kumar [4], and Schafer and Madabhushi [21]. It is important to note that the actual failure mechanism can vary depending on soil properties, pile dimensions, and applied loads.

5.4.Influence of Water Table Level on Piles' Ultimate Bearing Capacity

The mechanical behaviour of partially saturated soils could differ from that of fully saturated soils. The level of the groundwater table has a significant impact on the pullout carrying capacity. To clarify the influence of water table level variation on the ultimate pullout load, the water table is assumed to be 2 m below the soil surface and at ground level. The effect of water table level on dense sand conditions is explored, and the findings are drawn in Fig. 12 and Table 6.

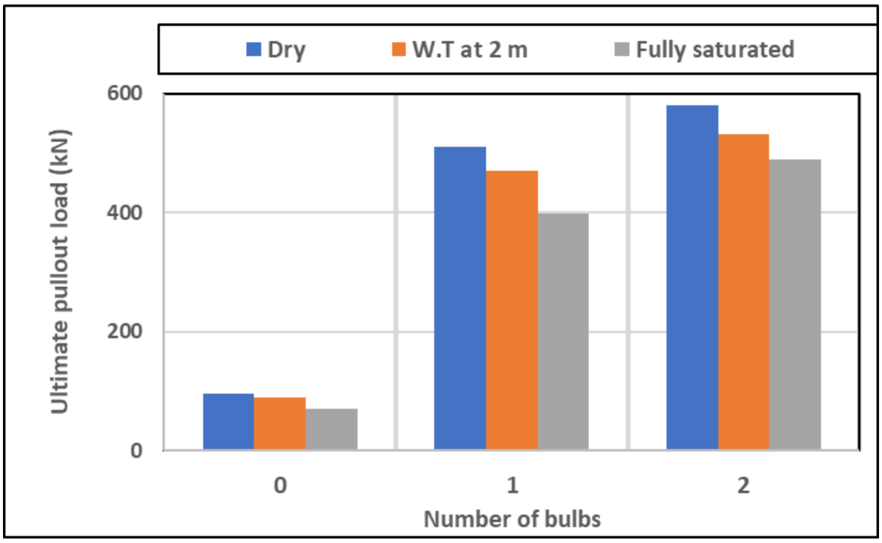


Fig. 12 Ultimate Pullout Load Variation with Number of Bulbs Under Different Sand Conditions Embedded in Dense Sand.

Table 6 Ultimate Pullout Loading of Uniform and Underreamed Piles in Different Sand Conditions.

Ultimate Pullout load (kN)			
Pile type	**Dry**	**Fully saturated**	**W.T at 2m**
SP	96	70	86
SURP	510	398	471
DURP	579.8	488.7	532

It was detected that the maximum pullout loading of SP, SURP, and DURP embedded within dry, dense sandy soil is greater than that embedded within partially and fully saturated soil. This increase occurs because the absence of pore water pressure and the higher frictional resistance in dry sand contribute to the higher ultimate capacity of piles compared to those embedded in fully or partially saturated sand. On the other hand, the presence of water in saturated sand reduces the interlocking between sand grains, resulting in decreased frictional resistance and lower pile capacity.

5.5.Load-displacement Behaviour of Under-Reamed in Layered Soils

The objective of the current study is to evaluate the uplift capability of SURP and DURP piles in two soil layers under vertical pullout force. Soils with two layers are assumed to be composed of dense sand resting on stiff clay and stiff clay resting on dense sand. Fig. 13 depicts the soil model, pile, and pile load. The water table level was set at 2 meters below the ground surface. The problem dimensions are similar to those used for a one-layer uniform soil. The pile length and the bulb location determined the thickness of each layer. It must be noted that the bulb's position always lies within the bottom layer at the beginning of loading, to examine changes in the behaviour of the load-displacement curve as it enters the upper layer. Figs 14 -15 show the pullout load versus vertical movement for SURP and DURP piles in layered soil systems, indicating that the ultimate pullout load varies with the layer configuration. Overall, the highest ultimate pullout capacity was observed when a stiff clay overlie dense sand, as both the pile shaft and bulb are embedded in strong, dense soil layers.

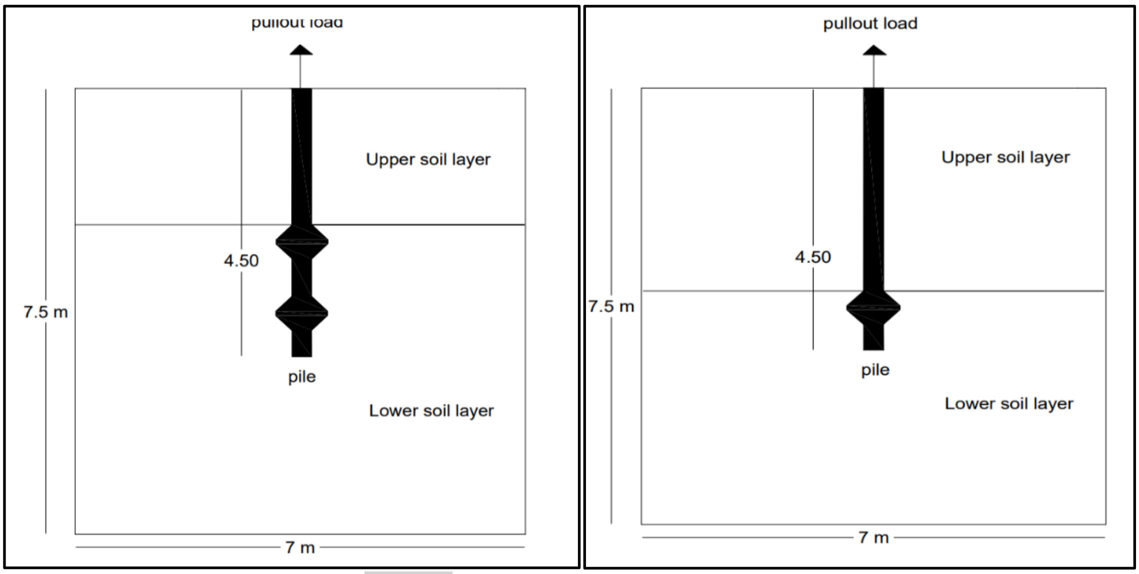


Fig. 13 Problem Statement Model.

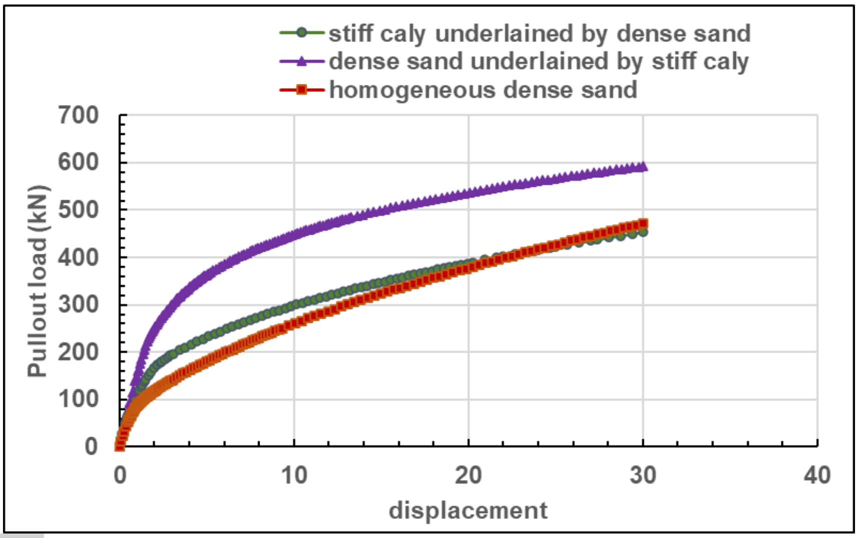


Fig. 14 Load-Displacement Curve of SURP Pile in Changed Types of Soil Layers.

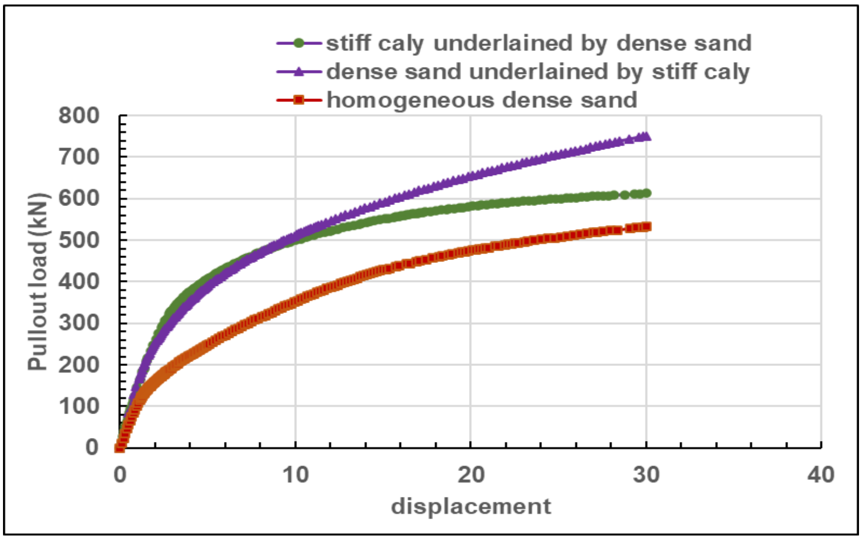


Fig. 15 Load–Displacement Response of DURP Pile under Various Soil Layer Arrangements.

The early reactions of piles exposed to uplift in stiff clay covered by dense sand are as expected for a pile in dense sand, with capacity increasing and then declining. This may be extrapolated from the load-displacement behaviour of SURP and DURP at an early stage. As the pile moves into the sand layer, capacity begins to decrease, and the behaviour observed is much closer to that of a homogeneous, dense sand stratum in two types of under-reamed piles. Owing to the additional bearing area and improved load distribution provided by the two under-reams, a twin under-reamed pile exhibits greater initial resistance to pullout loads and upward movement compared to an under-reamed pile with a single bulb. The results obtained are in line with those of Schafer and Madabhushi [21].

6.CONCLUSIONS

Adding one or two bulbs to the straight pile, resting in loose, medium, or dense sand, can yield significant benefits. The following conclusions are drawn from the study results:

- As relative density increases, soil compactness and interlocking improve, resulting in higher stiffness and load-bearing capacity.
- Additional bulbs enhance the pile's load-bearing capacity and improve its overall stability. Increasing the number of bulbs increases the pile's resistance to pullout forces. Moreover, the added bulbs increase the frictional resistance between the pile and the surrounding soil.
- The pullout load for a single underreamed pile increases by up to 350% from no bulb to one bulb. The power of adding more bulbs to the pullout load is most significant for under-reamed piles, where it surpasses 400%.
- Enhancing the pile's ability to withstand vertical pullout loads. Ultimately, incorporating two bulbs into the pile's design optimises its performance and durability, making it a reliable foundation solution for various construction projects; however, this requires more concrete for bulb formation.
- Denser soil provides better pile pullout support, reducing the likelihood of pullout failure and increasing frictional resistance along the pile shaft. This increased friction helps transfer the applied pullout load to the surrounding soil, enhancing the pile's resistance against pullout failure.
- The absence of pore water pressure and the higher frictional resistance in dry sand contribute to the higher ultimate capacity of piles compared to those embedded in fully or partially saturated sand.
- In a multi-layered soil system, an improvement in the pile's load-carrying capacity was observed, with higher initial stiffness than in the dense state of sandy soil.

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REFERENCES

[1] Tomlinson M, Woodward J. **Pile Design and Construction Practice.** *CRC Press* 2007.

[2] Xie XY, Yin XS. **The Finite Element Analysis of Plate's Distance on Push-Extend Multi-Under-Reamed Pile.** *Advanced Materials Research* 2012; **468**: 2517-2520.

[3] Harris DE, Madabhushi GSP. **Uplift Capacity of an Under-Reamed Pile Foundation.** *Proceedings of the Institution of Civil Engineers-Geotechnical Engineering* 2015; **168**(6): 526-538.

[4] Kumar A, Khatri VN, Gupta SK. **Numerical and Analytical Study on Uplift Capacity of Under-Reamed Piles in Sand.** *Marine Georesources & Geotechnology* 2022; **40**(1): 104-124.

[5] Patra NR, Deograthias M, James M. **Pullout Capacity of Anchor Piles.** *Electronic Journal of Geotechnical Engineering* 2004; **2004-0340**.

[6] Al-Neami MA, Wasmi M. **Influence of Cyclic Loading on Performance of Steel Piles in Sandy Soil.** *MATEC Web of Conferences* 2018; **162**: 01012.

[7] Nasr A, Azzam W, Abd Elgwad A. **Experimental Study of Enlarged Base Pile under Tension Load in Sand.** *Journal of Engineering Research* 2022; **6**(2): 40-44.

[8] Nazir R, Moayedi H, Pratikso A, Mosallanezhad M. **The Uplift Load Capacity of an Enlarged Base Pier Embedded in Dry Sand.** *Arabian Journal of Geosciences* 2015; **8**: 7285-7296.

[9] Farokhi AS, Alielahi H, Mardani Z. **Optimising the Performance of Under-Reamed Piles in Clay Using Numerical Method.** *Electronic Journal of Geotechnical Engineering* 2014; **19**(G): 1507-1520.

[10] Al-Tememy MS, Al-Neami MA, Aswad MF. **Finite Element Analysis on Behavior of Single Battered Pile in Sandy Soil under Pullout Loading.** *International Journal of Engineering* 2022; **35**(6): 1127-1134.

[11] Al-Bayati AW, Al-Neami MA, Rahil FH. **Experimental Work on the Effect of Under-Reamed Pile Geometry on the Pullout Capacity of Sand.**

International Journal of Engineering 2023.

[12] Alhassani AMJ. **Analysis of Under-Reamed Piles Subjected to Different Types of Loads in Clayey Soil.** *International Journal of Engineering* 2021; **34**(8): 1940-1948.

[13] Deb T, Pal SK. **Study on the Uplift Behavior and Failure Pattern of Single Belled Anchor with 3D and 2D Models in Cohesionless Soil Bed.** *Iranian Journal of Science and Technology, Transactions of Civil Engineering* 2019; **43**: 327-343.

[14] Sakr M, Nasr A, Basha A, Khaffaf M. **Comparative Study on the Behavior of Under-Reamed Piles under Vertical Uplift Loads in Sand.** *International Journal of Innovative Science, Engineering & Technology* 2022; **9**(1): 28-44.

[15] Sakrp M, Nasr A, Basha A, Khaffaf M. **Experimental and Analytical Assessment of the Pullout Capacity of Axially Loaded Under-Reamed Pile in Cohesionless Soil.** *Innovative Infrastructure Solutions* 2023; **8**(1): 73.

[16] Mohammed AA. **Investigation of Sampling Error on Soil Testing Results.** *International Journal of Civil Engineering and Technology* 2018; **9**(13): 579-589.

[17] Waterman D. **Structural Elements and Excavations.** *Presentation in CG1 Chile* 2006.

[18] Bureau of Indian Standards. **IS 2911 (Part IV): Design and Construction of Pile Foundation Code of Practice, Load Test on Piles.** *New Delhi, India* 2010.

[19] Bureau of Indian Standards. **IS 2911 (Part III): Indian Standard Code of Practice for Design and Construction of Pile Foundations, Underreamed Piles.** *New Delhi, India* 1980.

[20] Dickin EA, Leung CF. **Performance of Piles with Enlarged Bases Subject to Uplift Forces.** *Canadian Geotechnical Journal* 1990; **27**(5): 546-556.

[21] Schafer M, Madabhushi SPG. **Uplift Resistance of Enlarged Base Pile Foundations.** *Indian Geotechnical Journal* 2020; **50**: 426-441.