Exp. Theo. NANOTECHNOLOGY 10 (2026) 1611-1624 https://doi.org/10.56053/10.3.1611

Performance of under-reamed piles in saturated clay examining effects of bulb configuration on compression and uplift behaviour

Ali F. Al-Baidhani[*], *Abdul Aziz A. Al-kifae*

Department of Civil Engineering, College of Engineering, Al-Nahrain University, Baghdad, Iraq
[*]) Email: ali.farhan999@yahoo.com

Received 27/2/2026, *Received in revised form* 23/4/2026, *Accepted* 18/6/2026, *Published* 15/7/2026

Recent advancements in nanotechnology have enhanced the understanding of cohesive soils and supported more efficient foundation solutions. This study experimentally examines the compression and uplift behavior of straight and under-reamed piles with varying bulb numbers to clarify their role in soil–pile interaction. Four small-scale aluminum pile models, a straight pile, and under-reamed piles with one, two, and three bulbs are tested in reconstituted saturated clay (CL) using a 450 mm embedment depth inside a rigid 600 × 600 × 600 mm steel container. Axial compression and uplift tests are conducted to assess load–load-displacement response, ultimate capacity, and changes in load-transfer mechanisms. Results show that under-reaming significantly improves pile performance. Compressive capacity relative to the straight pile increased by 42%, 108%, and 149% for the one, two, and three bulb piles, respectively. Load-transfer analysis revealed a shift from friction-dominated resistance toward end-bearing dominance. For the straight pile, shaft friction contributed 55% of total resistance, decreasing to 35%, 22%, and 18% for the one, two, and three bulb piles, respectively, indicating reduced frictional mobilization with increasing bulb number. Correspondingly, soil pressure beneath the pile tip decreased by 20–25% for single bulbs and up to 40% for double bulbs, confirming stress redistribution toward enlarged bases. Under uplift loading, performance also improved, with ultimate capacity increasing by 89%, 120%, and 186% for the one, two, and three bulb piles, respectively. These results show the strong influence of bulb geometry in modifying stress paths, enhancing end-bearing engagement, and reducing frictional reliance. Overall, the findings provide a quantitative basis for optimizing under-reamed pile configurations in saturated cohesive soils and improving foundation design efficiency.

Keywords: Under-reamed Piles; Bulb Geometry; Ultimate bearing capacity; Compressive load; Tension load.

1. INTRODUCTION

Recent advances in nanotechnology have significantly enhanced the understanding of cohesive soil behaviour and informed modern ground-improvement strategies, offering valuable insight into micro- and nano-scale mechanisms that strengthen fine-grained deposits. Within this broader context, under-reamed piles represent a complementary foundation system capable of mobilizing improved soil characteristics and enhancing compression and uplift performance in cohesive environments. Although nanotechnology has introduced transformative capabilities in soil modification, material enhancement, and subsurface monitoring, its conceptual integration with optimized under-reamed pile geometry remains largely unexplored from a mechanistic and performance-based perspective.

Under-reamed piles are widely used in machine foundations, transmission towers, bridges, and water-retaining structures, with their configuration primarily governed by Indian Standard IS 2911 (Part III) [1]. The bulbs, typically two to three times the shaft diameter and spaced 1.0–1.5 times the bulb diameter, are known to enhance both bearing and uplift resistance by increasing end-bearing area and modifying shaft friction [2,3]. Extensive experimental and numerical investigations have demonstrated that increasing bulb diameter or incorporating multiple bulbs leads to significant gains in uplift and compressive capacity, with reported improvements exceeding 119%–200% for enlarged configurations [4], while numerical simulations show pullout capacity increases reaching 396% and 547% for single- and double-bulb piles under variable cohesion conditions [5]. Additional studies have confirmed that geometric parameters—including pile length, diameter, bulb number, internal friction angle, and cohesion—can raise bearing capacity by more than 100% in various soil environments [6–8]. Improvements in relative density, embedment depth, and bulb spacing have also been shown to enhance tensile and compressive performance in sandy and stiff clay soils [9–11]. Research in expansive and collapsible soils indicates that under-reamed piles can reduce upward soil movement and uplift pressures by 20–30%, especially in multi-bulb configurations [12–16]. Comparative analyses in soft clay similarly report compressive-capacity gains of 73.75% for single-bulb piles, with further enhancements for double-bulb designs [17]. Despite these documented advancements, a clear research gap remains in experimentally quantifying how bulb number and configuration influence the transition between shaft-friction and end-bearing mechanisms in saturated cohesive soils, particularly under both compression and uplift loading. Existing studies provide valuable parametric insights but often lack direct comparative assessment of frictional contribution, stress redistribution, and load-sharing behavior across systematically varied bulb configurations. The present study addresses this gap by experimentally evaluating straight and under-reamed piles with one, two, and three bulbs in saturated cohesive soil, focusing on quantifying changes in compressive and uplift capacities, load-transfer mechanisms, and soil pressure distribution. This contribution establishes a mechanistic basis for optimizing under-reamed pile geometry in cohesive soil environments and provides new experimental evidence to support performance-driven geotechnical design.

This study aims to systematically investigate the influence of under-reamed bulbs on the compressive and uplift performance of piles embedded in cohesive soil. The research seeks to evaluate how variations in bulb number, spacing, and geometric configuration alter the load-transfer mechanism, stress distribution, and soil–pile interaction. By quantifying improvements in capacity and identifying shifts between shaft-friction and end-bearing behavior, the study aims to establish the governing design parameters that enhance structural efficiency. Ultimately, this work provides a scientific basis for optimizing under-reamed pile design in saturated clay conditions for improved geotechnical performance.

2. EXPERIMENTAL

All experiments are performed entirely under controlled laboratory conditions, without employing any field-scale models. Although full-scale testing would offer a closer representation of in-situ behaviour, the laboratory setup is considered sufficient for the objectives of this study.

2.1 Soil Used

A brown, clayey soil is brought up from the Al-Ekhwa residential complex project, located north of Baghdad city. Utilizing a mechanical shovel, A trial pit is excavated to a depth of 2-3 meters below N.G.L., and disturbed samples are collected. Air-tight plastic bags are placed in the pit and transported to a soil laboratory for standard experiments to determine the soil's physical properties, as shown in Figure 1. Table 1 provides details. In this particular experiment, the soil classification used is clay (CL). The state of the clay soil used in this parametric study is saturated.

Figure 1 Sequential Protocol for Soil Sampling, Air-Drying, Mechanical Grinding, and Sample Homogenization.

2.2 Experimental Setup for Pile Models and the Soil Testing Container

This study utilized three small-scale aluminum pile models, each measuring 450 mm in length, with a bulb diameter of 50 mm and an overall pile diameter of 20 mm. The ratio of pile length to diameter (L/D) is 22.5. This study employed three pile configurations: straight piles and multi-under-reamed piles (single-bulb and double-bulb) with varying vertical distances between the bulbs. The design of the under-reamed pile and under-reams is carefully selected in accordance with the Indian Code (IS 2911) specifications [18]. Figure 2 represents the configuration of pile model utilized in the study. Based on previous studies, a steel box is constructed, measuring 600 mm in height, width, and depth, with a uniform plate thickness of 6 mm. The container consists of five single pieces: four for the sides and the fifth for the base. Bolts of 10 mm diameter connect these pieces along the edges of one piece, and with a distance of 10 cm between one bolt and another. One of the container faces contains a glass with dimensions 60 mm×40 mm to monitor the process of saturation in the soil, as shown in Figure 3. To prevent the sides and bottom of the box from falling outside the influence zone of the stress bulb caused by the loading of the piles during the tests, the box is designed to be sufficiently large.

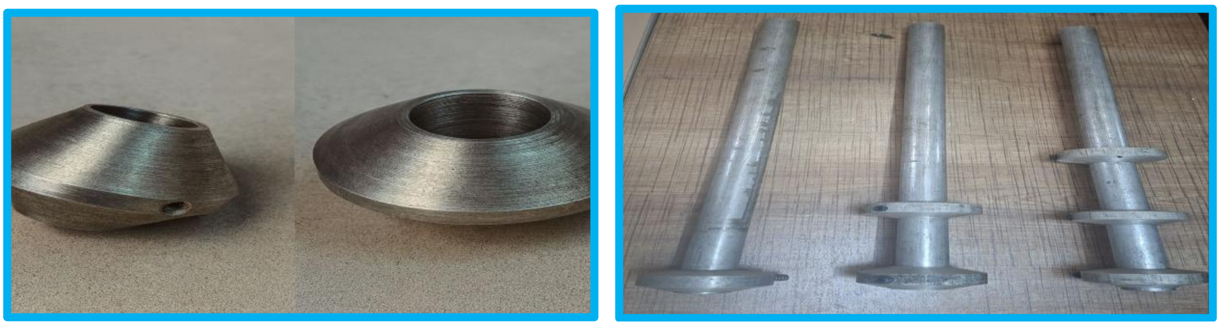

Figure 2 Under-reams piles used in the study.

Figure 3 Steel box used in the study.

Table 1 Physical properties of soil.

Test Name	Standard	Soil Property	Value
Specific Gravity	ASTM D-854 [19]	Specific Gravity (Gs)	Clay 2.76
Atterberg Limits	ASTM D-4318 [20]	Liquid limit (L.L),	45
		Plastic Limit (P.L), %	26
		Plasticity Index (P.I), %	19
Grain size	ASTM D-422[21]	Clay	68.3
		Silt	31.7
		Gravel	0
		Unified Soil Classification System (USCS)	CL
Standard Compaction	ASTM D-1557 [22]	Maximum Dry Unit Weight, (kN/m3)	16.25
		Optimum Moisture Content (O.M.C), %	19
		Initial void ratio(e0)	0.666

2.3 Vertical Loading System

The vertical loading system comprises integrated mechanical and electrical components designed to apply controlled compression and tension loads. The system utilizes a 2-ton mechanical piston mounted on the upper steel frame of the model and connected to a transmission unit governed by an electronic control panel, enabling precise regulation of piston movement in both upward and downward directions. An S-type load cell (2-ton capacity) is attached to the lower end of the piston, followed by a steel loading rod measuring 300 mm in length and 38 mm in diameter, which transfers the load directly to the pile. A digital displacement recorder is employed to measure vertical movements during testing. A ½-HP electric motor provides a constant loading rate of 1mm/min, and the system can operate in both compression and tension modes by switching the motor's operating direction through the electrical control panel.

2.4 Piled Cap Models and Ancillary Equipment

1. The pile cap for a single pile is constructed from rigid steel plates, measuring (100 × 100 × 20) mm to ensure structural rigidity.
2. Attached with a pressure sensor that measures the pressure of the soil below the pile tip, as shown in Figure 4.
3. Force sensors are placed on the reamed position and end bearing pile with the total settlement of under reamed pile.
4. Linear Variable Differential Transducer (LVDT) used for measuring vertical displacements for static movement, as shown in Figure 5.
5. A universal power supply (UPS) is employed to ensure a continuous supply of electrical energy and to maintain a stable electric current throughout the testing process.

6. A strain gauge is placed in a different position of the pile shaft shown in Figure 5.
7. A data logger that is compatible with Italian is used to record force and displacement equipment data. The LABVIEW 2019 software is used to illustrate load variation through a settlement-over-time graph. This is done in accordance with the manufacturer's recommendations.

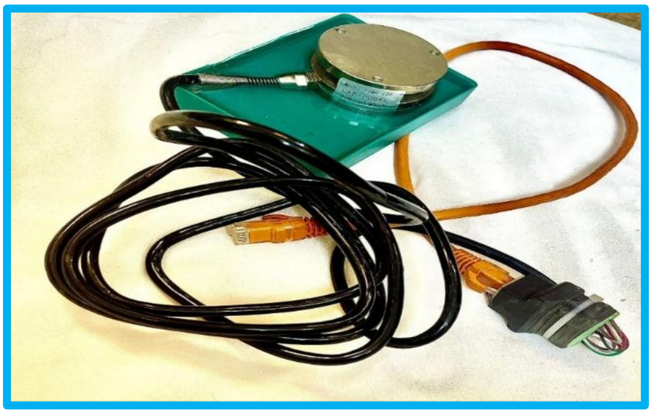

Figure 4 Soil pressure sensor under the pile tip.

Figure 5 LVDT calibration process.

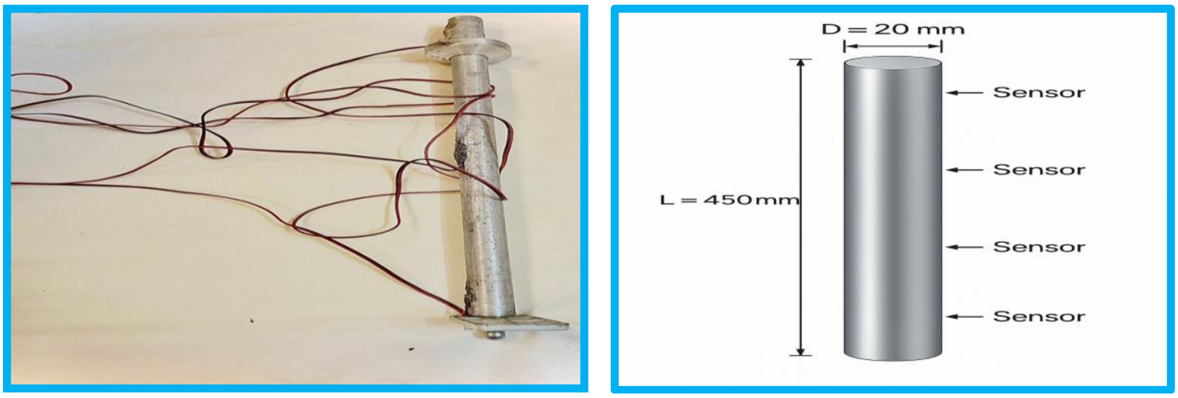

Figure 6 Attachment of strain gauges.

2.5 Soil Preparation

The effectiveness of the method for preparing the soil bed is evaluated by a series of trial tests, focusing on the main points of homogeneous soil preparation, shear strength, dry unit weight, and initial water contents before the preparation stage. The process involves drying soil to 105 °C, pulverizing it to a fine consistency, and measuring the initial water content. Experiments are conducted with a dry unit weight of 16.25 kN/m3 and a range of initial degrees of saturation to investigate the load-settling behavior of a pile. To achieve the required consistency and saturation level, the soil is mixed with additional water. Utilizing the specific gravity of the soil, the dry unit weight, and the void ratio, the water content is calculated. This process is repeated until the model container is filled with an adequate amount of soil. To ensure consistent moisture content and water distribution, the soil is stored in sealed polythene sacks for at least 72 hours after the mixing process. Samples are obtained from each container to determine the water content. The pre-calculated quantity is distributed to achieve a soil depth of 100 mm in the modelled box, resulting in a soil density of 16.25 kN/m^3. Subsequently, it is compacted to the required dry unit weight using a specialized compaction device.

2.6 Installation of model piles

The installation methodology employed in this study is referred to as the undisturbed or no-displacement method, wherein under-reamed piles are excavated and cast in situ as concrete piles. This approach is appropriate for simulating field conditions within the experimental framework. The model pile is set up vertically at the center of the model box. A water-level balance is utilized to verify the verticality of the pile. The inclination of the pile cap is similarly evaluated utilizing the identical water-level balance. Clayey soil is subsequently put around the pile to achieve the required saturation levels and to form a uniform clay layer. The soil bed preparation process involves measuring the required amount of soil for each layer, compacting it until the specified height is reached, and applying it in stages with a maximum thickness of 10 cm. Once the soil bed is prepared to the specified level, a force sensor can be installed, with connecting wires extended horizontally to the soil container wall and vertically to the data logger.

2.7 Compression and tension load of model piles in clay soils

In this experimental program, the behaviour of different pile models embedded in fully saturated soil is examined under both tension and compression loading. The study focuses exclusively on the 100% saturation condition to provide a clear and consistent hydraulic environment for evaluating soil–pile interaction. As indicated in relevant literature [23], the tests are conducted using a displacement-controlled loading system, with continuous recording of applied load and pile head displacement. Tension tests are performed to determine the mobilized ultimate shaft resistance, whereas compression tests are conducted to obtain the total pile capacity, including both shaft and base components. All experimental procedures are carried out under identical preparation and boundary conditions to ensure repeatability and reliability of the measurements. In this study, the sharing ratio (S.R) is defined as the ratio of the ultimate skin resistance (ultimate shaft capacity) mobilized from pull-out tests to the ultimate total pile capacity obtained from compression tests. The evaluation is performed on different pile models, all embedded in soil prepared under fully saturated conditions (100% degree of saturation). For each pile model, the ultimate shaft resistance is determined from the pull-out test. In contrast, the corresponding ultimate total capacity is obtained from the compression test conducted under identical saturation and boundary conditions. The sharing ratio S.R is expressed as follows:

$$\text{Ultimate shaft capacity sharing ratio, (S.R)\%} = \frac{\text{ultimate shaft capacity}}{\text{ultimate pile capacity}} * 100 \qquad (1)$$

2.8 Testing procedure

Both compression and uplift tests are performed under displacement-controlled conditions. Ultimate capacity is determined based on the point of nonlinear response in the load-displacement curve. For uplift testing, the same loading rate and criteria are applied, with the direction of loading reversed. Load and displacement data are recorded continuously using a data logger system. The failure criterion used in this study, identified by the distinct breakpoint on the load–settlement curve, is a commonly adopted method in small-scale pile testing. The breakpoint represents the transition from linear to nonlinear behavior and is considered a practical indicator of ultimate resistance, especially in cohesive soils where a clear plunging failure is not always observed. Previous studies, such as [24], [25], and [26], have employed the same approach, confirming its suitability for determining the ultimate load of ordinary and under-reamed model piles.

2.9 Test Replication and Statistical Considerations

To enhance the reliability of the experimental results, each test configuration, both compression and uplift, is repeated in three independent replicates under identical boundary and preparation conditions. The soil mixing procedure, saturation process, pile installation, and loading rate are carefully controlled to minimize procedural variability. While the number of replicates provides sufficient confidence in identifying consistent load-displacement behavior and comparative trends between pile geometries, it does not allow for advanced statistical analysis such as distribution modelling or confidence interval estimation. Nonetheless, the repeated trials demonstrated close agreement in ultimate load and deformation response, supporting the robustness of the reported findings. This replication strategy ensures that the observed differences in pile performance arise from geometric and mechanical factors rather than experimental noise, while acknowledging the inherent limitations of small-sample laboratory testing.

3. RESULTS AND DISCUSSION

3.1 Test piles under axial compressive load

After four days of installation, the piles are left to allow the soil to regain its thixotropy. The vertical (compression) test is done by applying a load on the pile using a load cell (S-shape). The insertion rate is 1 mm/min based on ASTM D1143[27]. Figures 7 and 8 show that the ultimate bearing capacity of under-reamed piles also increases up to 41.84% in the under-reamed pile with one bulb compared to the ordinary pile, then the increase is 108% and 149%, respectively, in the presence of 2 bulbs and 3 bulbs. The first increase represents the bearing capacity of the bulb, the two and third represent the friction force of the soil between the bulbs.

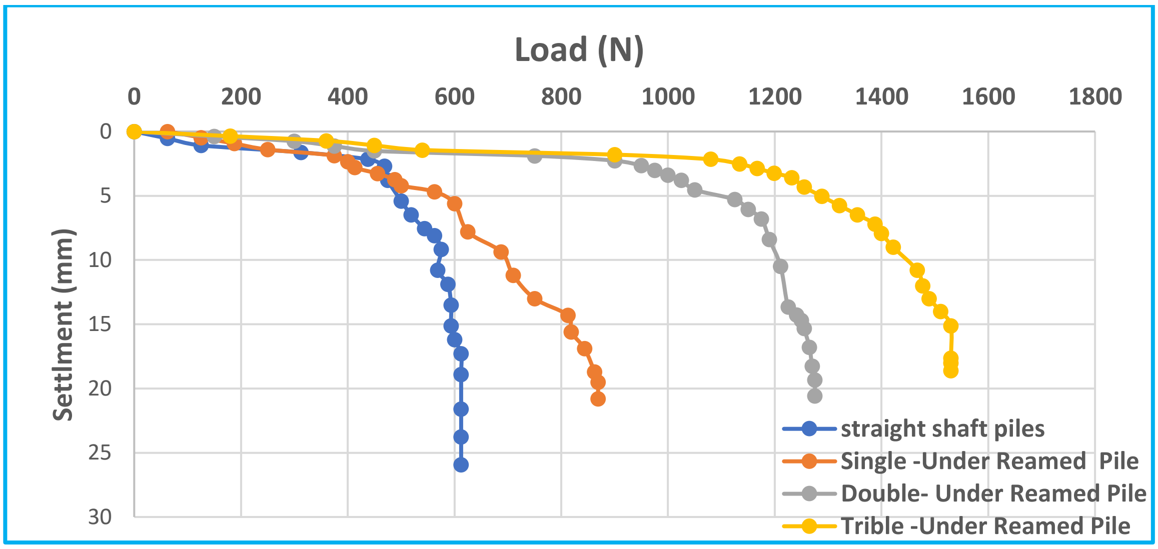

Figure 7 Load settlement relation of under-reamed and straight shaft piles, saturated condition.

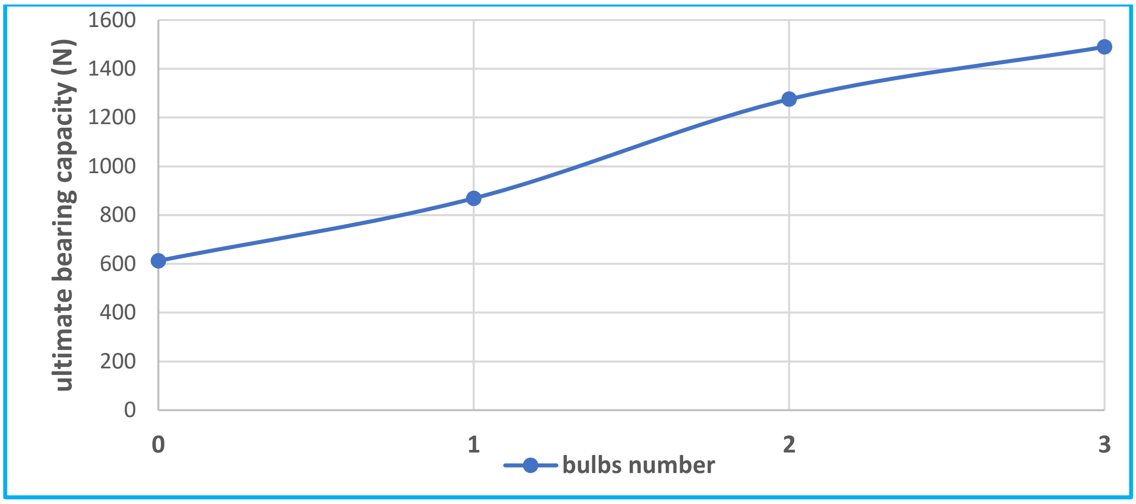

Figure 8 Relation between bulbs number and ultimate bearing capacity of piles.

The results presented in table 2 show a progressive improvement in the ultimate bearing capacity as the number of bulbs increases from the normal pile to the single, double, and triple under-reamed piles. The normal pile exhibits an ultimate capacity of 612.5 N, carried mainly by shaft friction (336.88 N) with a smaller contribution from the pile tip (275.63 N), reflecting a friction-dominated behaviour typical of fully saturated clay. Introducing a single bulb increases the capacity to 868.75 N, with the pile tip resistance rising substantially to 564.68 N while friction decreases to 304.06 N, indicating a shift toward end-bearing behaviour. With two bulbs, the capacity further increases to 1275 N as tip resistance and bulb resistance (624.75 N and 369.75 N, respectively) become the dominant components, while friction is reduced to 280.5 N. The triple under-reamed pile achieves the highest capacity of 1530 N, where most of the load is resisted by the tip and bulbs (approximately 612 N, 336.6 N, and 306 N), and friction becomes the least significant contributor at 275.4 N. This redistribution is clearly illustrated in table 3, where the friction share decreases from 55% in the normal pile to 35%, 22%, and finally 18% as bulbs are added, while the combined end-bearing contributions progressively increase to 65%, 78%, and 82% for the single, double, and triple under-reamed piles. Overall, the trend demonstrates that adding bulbs effectively transforms the load-transfer mechanism from friction-controlled to end-bearing-dominated, resulting in substantial improvements in load capacity within saturated clay.

Table 2 Ultimate pile bearing capacity with the values of total friction and end bearing for the types of model pile.

Types of model pile	Ultimate Load Capacity(N)	Pile tip force(N)	Bulb1 force(N)	Bulb2 force(N)	Bulb3 force(N)	Total Friction (N)
Normal Pile	**612.5**	**275.625**	**0**	**0**	**0**	**336.875**
Single Under-Reamed Pile	**868.75**	**564.68**		**0**	**0**	**304.0625**
Double Under-Reamed Pile	**1275**	**624.75**		**369.75**	**0**	**280.5**
Trible Under-Reamed Pile	**1530**	**612**		**336.6**	**306**	**275.4**

Table 3 Ratios of sharing of pile capacity components for the different model pile types.

Types of model pile	percentage of sharing ratios for pile capacity components				
	Total Friction (%)	**Pile tip force%**	**Bulb 1 force%**	**Bulb 2 force%**	**Bulb 3 force%**
Normal Pile	**55.7**	**44.3**	**0**	**0**	**0**
Single Under-Reamed Pile	**35.2**	**64.8**		**0**	**0**
Double Under-Reamed Pile	**22.4**	**49.3**		**28.3**	**0**
Trible Under-Reamed Pile	**18.9**	**37.2**		**22.4**	**21.5**

3.2 Soil pressure response below the pile tip

Soil pressure is measured at a distance of 2D (40 mm) under the pile tip during the compression load test conducted on a single pile using a soil pressure gauge embedded in the soil bed at the specified depth. Figure 9 shows the generated soil pressure under the pile tip due to the load applied on the pile head. The results indicate that the normal pile exhibited the highest soil pressure, reaching approximately 305 kPa. When a single under reamed bulb is added, the pressure decreased to 244 kPa, and with two bulbs it further reduced to 195.2 kPa, while the three-bulb pile recorded the lowest pressure at 153 kPa. These values correspond to reductions of about 20%, 36%, and nearly 50%, respectively, compared to the normal pile. This progressive decrease in soil pressure is attributed to the increased contact area provided by the bulbs, which allows the applied load to be distributed over a larger soil volume, thereby reducing stress beneath the pile tip. Overall, the findings demonstrate that under-reamed piles particularly those with two or three bulbs, enhance load distribution, reduce stress concentration, and improve performance in clay soils. However, practical design considerations should balance these benefits against construction complexity and cost when selecting the appropriate number of bulbs.

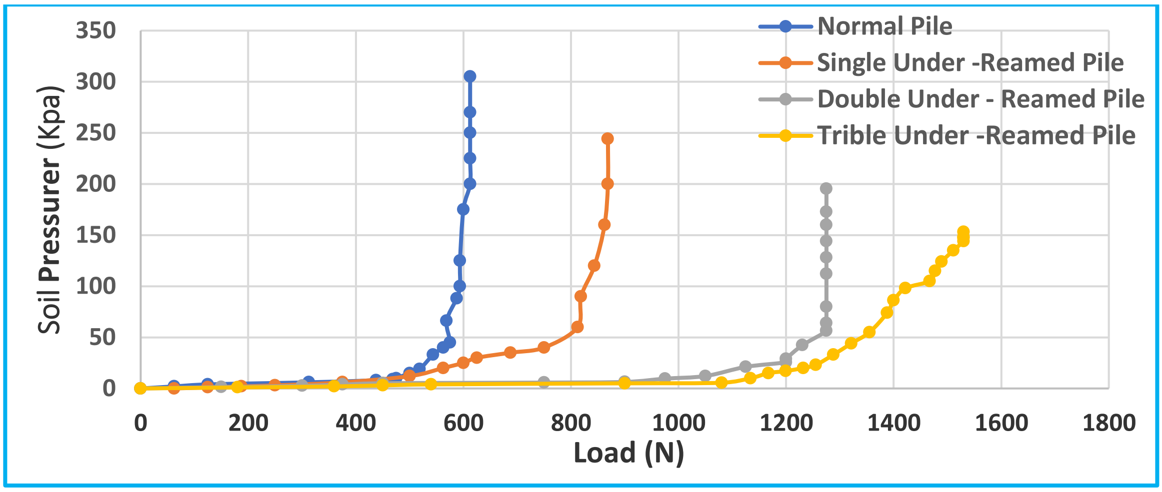

Figure 9 Soil pressure measured below the pile tip for the different model pile types.

3.3 Effect on the bulb spacing (D.U.P) in saturated condition (S=100%)

For testing program in this case, double under-reamed pile (D.U.P) or (double bulbs) is used and compared with uniform pile uniform pile as shown in Figure (10), where (5) tests to study the effect of (double bulbs) spacing on under reamed pile, the spacing between bulbs is L/4, L/2, and 3L/4.

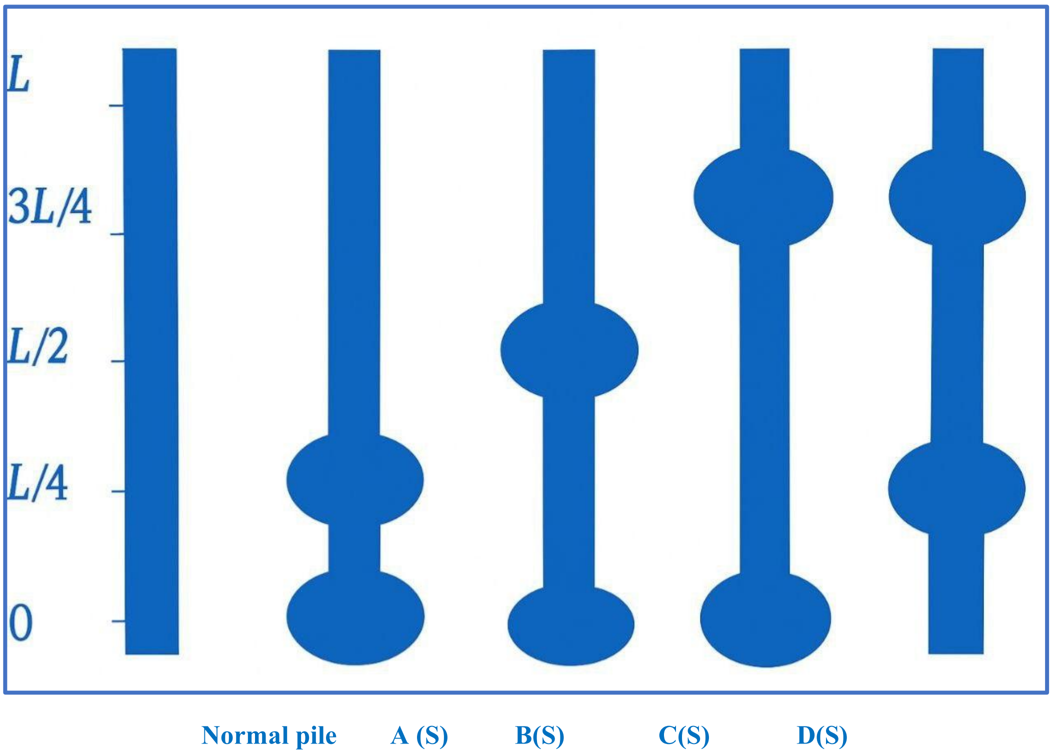

Figure 10 Different spacing of bulb in (D.U.P).

According to Figure 11, the addition of double bulbs increases the capacity of a uniform pile more than 108% in A(S), 83% in B(S), 62% in C(S) and 45% in D(S).

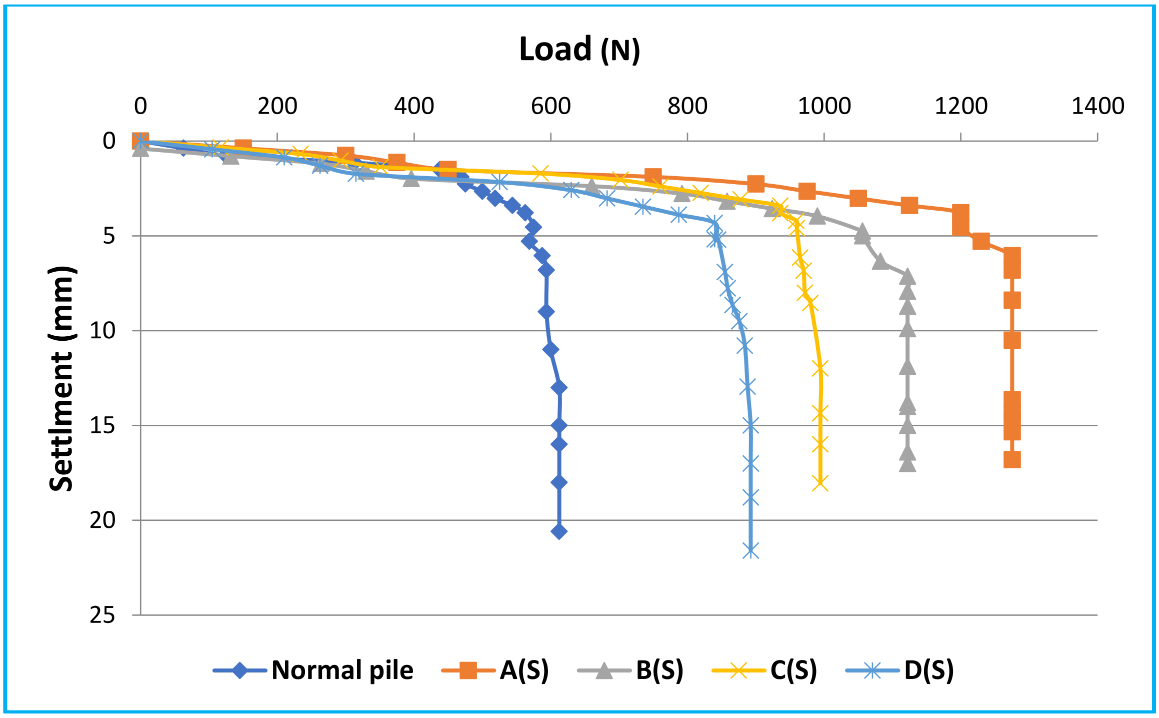

Figure11 Load-Settlement Curve of (D.U.P) with saturated Condition(S=100%) with different bulb positions.

3.4 Under-reamed pile under tension load on ultimate up-lift resistance

On the basis of the experimental data,4 Uplift tests are carried out on four types of piles embedded in soil compacted individually at the same dry unit weight of 16.5 kN/m3 but at fully saturation. A pile of length 450 mm with a shaft diameter of 20 mm and bulb diameters of 50 mm embedded in cohesive soil. The first pile is the conventional or the ordinary pile (reference pile). This pile has no special shape treatment, and it is used as a reference to measure how much improvement is obtained. Three piles are used with one (single) bulb, with double bulbs, and triple bulbs under full saturation to investigate the ultimate uplift resistance of pile models. For uplift models, the ultimate resistance is defined by the peak points of the load-displacement curve. The laboratory uplift tests clearly demonstrate the beneficial effect of providing under-reamed bulbs in cohesive soil compared with the normal straight pile. As shown in Figures 12 and 13, the normal pile mobilized an ultimate uplift capacity of about 465 N, whereas the single under-reamed pile reached approximately 877.5 N, corresponding to an increase of nearly 88.7%. Introducing a second bulb further raised the ultimate uplift load to about 1023.75 N (an increase of about 120.2%), and the triple under-reamed pile achieved the highest capacity of roughly 1330.875 N, giving an overall increase of about 186.2% relative to the normal pile. The load–settlement curves indicate that under-reamed piles sustain higher loads at any given displacement, and that the triple-bulb pile not only carries the greatest load but also shows a more gradual post-peak response, suggesting a more ductile uplift behaviour.

This improvement can be attributed to several mechanisms reported in previous studies: the bulbs enlarge the effective cross-section and provide “anchor” zones that significantly increase the projected area resisting uplift; they also enhance mobilization of shaft resistance in the surrounding clay by creating alternating zones of compression and confinement along the pile length, which increases adhesion and soil–pile interlock. In addition, the under-reamed bulbs alter the failure surface from a relatively shallow cylindrical shape for the normal pile to a deeper and more complex surface that engages a larger volume of soil, thereby increasing the work required to pull the pile out. Consequently, the results confirm that increasing the number of under-reamed bulbs is an efficient technique for enhancing the uplift resistance of piles in cohesive soils.

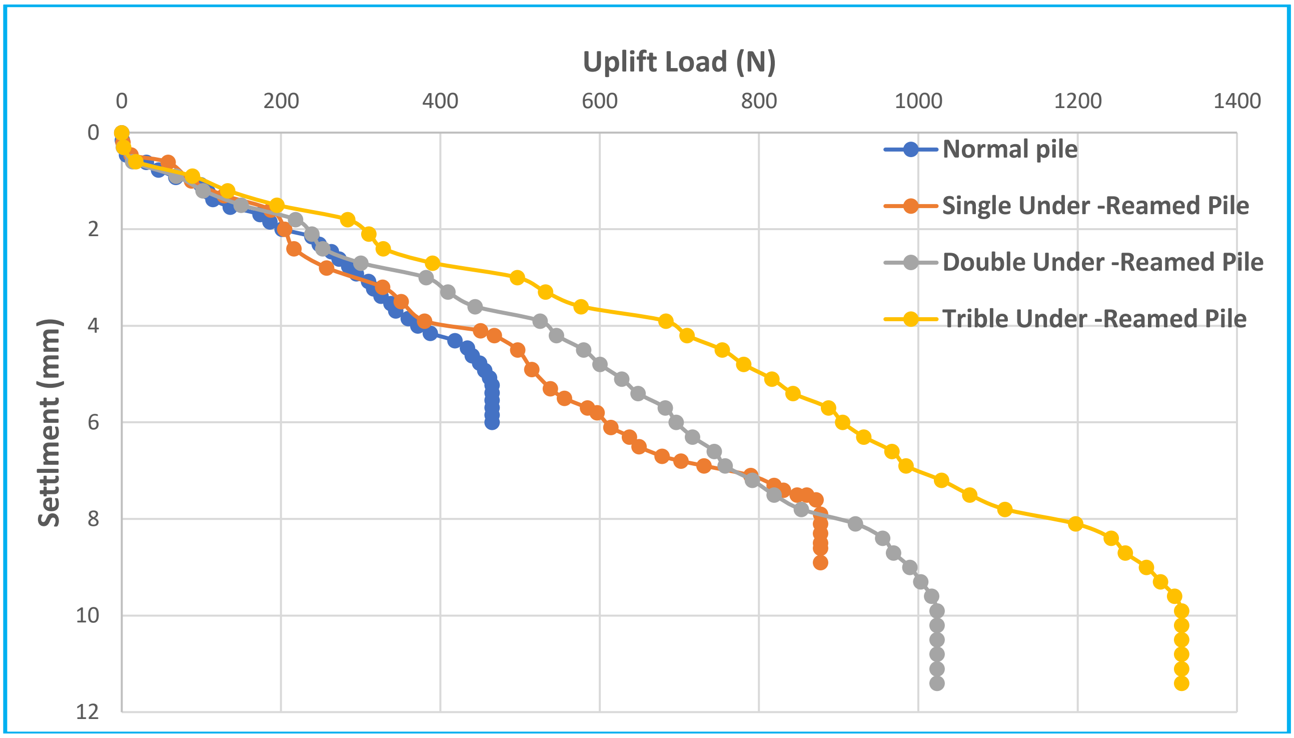

Figure 12 Ultimate pull-out capacity for the various model pile configurations.

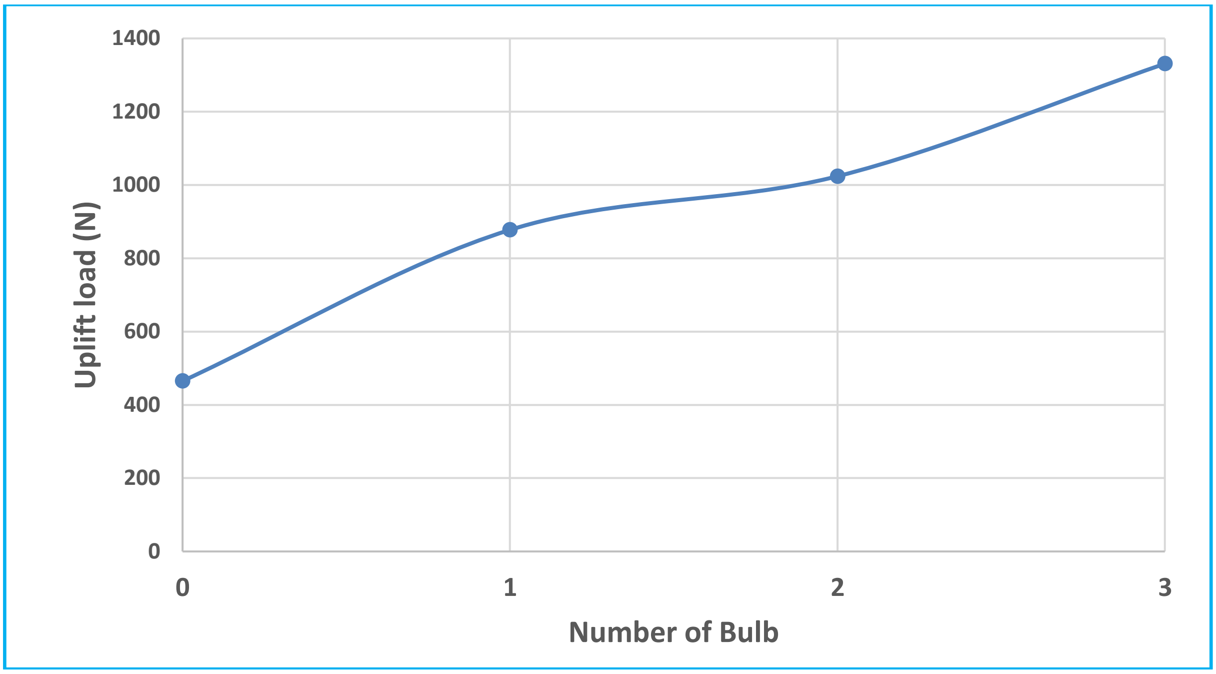

Figure 13 Influence of bulb configuration on the ultimate pullout resistance.

3.5 Comparison with previous studies

The results of the present study show several points of agreement with previous investigations on under-reamed piles. Similar to the findings of [4], who reported increases of 119% and 204% in capacity for single and double-bulb piles in clay, the current study also demonstrated significant improvements, with increases of 41.84%, 108%, and 149% for one, two, and three bulbs, respectively. Likewise, [5] observed substantial gains in uplift capacity (396% for one bulb and 547% for two bulbs), which corresponds with the general trend identified in this study that bulb enlargements effectively enhance load resistance through increased tip resistance and shaft friction. These similarities confirm that the mechanisms reported in earlier research are consistent with the behavior observed in the present experiments. The study successfully met its objectives by evaluating how different bulb configurations affect the axial behavior of piles in fully saturated clay. Tests conducted on straight piles and those with single-, double-, and triple-bulb configurations demonstrated that increasing the number of bulbs leads to higher ultimate load capacity and reduced displacement. Analysis of the load–settlement response further clarified how under-reaming modifies the balance between shaft friction and end-bearing resistance, contributing to a more comprehensive understanding of pile–soil interaction.

Although the previous study is numerical rather than experimental, the findings of the present work exhibit similar overall trends, particularly the improved load capacity and reduced settlement associated with under-reamed piles. However, several key distinctions set this investigation apart. Earlier numerical studies seldom examined under-reamed piles in fully saturated clay, whereas the current experiments are conducted under controlled 100% saturation, providing a more realistic representation of soft cohesive soils. Moreover, while most prior research focused on one- or two-bulb configurations, this study expands the scope by incorporating a three-bulb model, which has not been systematically explored under saturated conditions. In addition to evaluating ultimate capacity, the present work offers a detailed separation of shaft friction and end-bearing resistance for each pile type. These contributions advance the existing literature by addressing soil conditions and geometric configurations that previous studies have not fully captured.

3.6 Load response of various under-reamed pile configurations under tension and compression in fully saturated soil

Four series of pull-out (tension) tests and four additional series of compression tests are carried out on a single pile installed in soil compacted under fully saturated conditions. In the pull-out tests, pile capacity is governed solely by shaft (skin) resistance, whereas in the compression tests, it is influenced by both shaft friction and end bearing resistance. The calculated ultimate shaft capacity ratios for each pile model are presented in Table (4). The results indicate that the contribution ratio of shaft resistance increases nonlinearly with the number of bulbs on the pile. This trend is attributed to the increase in the measured adhesion factor. These observations are consistent with the findings of [23], who noted that the major portion of the load applied to piles embedded in clayey soils is transferred through skin friction in the form of vertical shear stresses acting along the pile–soil interface.

Table 4 Ultimate shaft capacity sharing ratios for the different pile models embedded in soil compacted under fully saturated conditions

types of model pile	**Uplift shaft capacity, kN**	**Ultimate pile capacity, kN**	**Sharing ratio, S.R%**
Normal pile	465.0	612.5	75.9
Single Under - Reamed Pile	789.0	868.8	90.8
Double Under - Reamed Pile	1023.8	1275.0	80.3
Trible Under - Reamed Pile	1330.9	1530.0	87.0

4. CONCLUSIONS

The findings of this study clearly demonstrate that adding under-reamed bulbs greatly improves pile performance in saturated clay, with compressive capacity increasing by up to 149% as more bulbs are incorporated. This enhancement is linked to a shift in load-transfer behaviour, where resistance transitions from being governed mainly by shaft friction in normal piles to being dominated by end-bearing and bulb resistance in under-reamed piles. Soil pressure measurements show that bulbs effectively reduce stress concentration beneath the pile tip by as much as 40% indicating more efficient stress redistribution. Bulb spacing also plays a decisive role, with closer spacing producing capacity gains of up to 108%. Under uplift loading, under-reamed piles exhibit substantial improvements, reaching 186% greater resistance due to increased anchorage and soil–pile interlock. The nonlinear rise in shaft-capacity sharing ratios further confirms enhanced skin-friction mobilization. Overall, the results validate under-reaming as a highly effective strategy for improving both compressive and uplift behaviour in cohesive soils, guided primarily by bulb number, spacing, and geometry.

References

[1] Nadia Farid Hassan Sabri, Jassim Muhsin Nasser, Experimental and Theoretical NANOTECHNOLOGY, 10 (2026) 835 https://doi.org/10.56053/10.S.835
[2] M. Majumder, D. Chakraborty, Front. Struct. Civ. Eng. 15 (2021) 537. https://doi.org/10.1007/s11709-021-0708-x
[3] V. Chandrasekaran, K.G. Garg, C. Prakash, Soils Found. 18 (1978) 1. https://doi.org/10.3208/sandf1972.18.2_1
[4] B. George, G. Hari, Indian Geotech. J. 46 (2016) 89. https://doi.org/10.1007/s40098-015-0157-3
[5] V.N. Khatri, A. Kumar, S.K. Gupta, R.K. Dutta, T. Gnananandarao, Int. J. Geotech. Eng. 16 (2022) 438. https://doi.org/10.1080/19386362.2019.1660527
[6] R. Vali, E.M. Khotbehsara, M. Saberian, J. Li, M. Mehrinejad, S. Jahandari, Int. J. Geotech. Eng. 13 (2019) 236.https://doi.org/10.1080/19386362.2017.1336586
[7] A.M.J. Alhassani, Int. J. Eng. 34 (2021) 1940 https://doi.org/10.5829/IJE.2021.34.08B.15
[8] Haitham Mohammed Ibrahim Al-Zuhairi, Iqbal alshalal, Hind H. Abbood, M. Al Nuaimi, Experimental and Theoretical NANOTECHNOLOGY, 10 (2026) 855 https://doi.org/10.56053/10.S.855
[9] F.H. Rahil, M.A. Al-Neami, K.A.N. Al-Zaho, Eng. Technol. J. 34 (2016) 1206 https://doi.org/10.30684/etj.34.6A.15
[10] M.S. Al-Tememy, M.A. Al-Neami, M.F. Asswad, Eng. Technol. J. 40 (2022) 1 https://doi.org/10.30684/etj.2021.131818.1062
[11] R.E. Martin, R.A. DeStephen, J. Geotech. Eng. 109 (1983) 1082 https://doi.org/10.1061/(ASCE)0733-9410(1983)109:8(1082)
[12] J.A. Peter, N. Lakshmanan, P.D. Manoharan, J. Mater. Civ. Eng. 18 (2006) 408. https://doi.org/10.1061/(ASCE)0899-1561(2006)18:3(408)
[13] H.M. Ziyara, B.S. Albusoda, IOP Conf. Ser.: Earth Environ. Sci. 856 (2021) 012052. https://doi.org/10.1088/1755-1315/856/1/012052
[14] Ketam Kadom Khudair, Farouk Boudou, Abeer Mohammed, Abdelghani Sehmi, Amal Belakredar, M. S. Ibrahim, Experimental and Theoretical NANOTECHNOLOGY, 10 (2026) 869 https://doi.org/10.56053/10.S.869
[15] M. S. Ibrahim, Tarik T. Issa, Bilal Yaqoob, Etmad Naji Fayyadh, Ahmed Rashid, Ruqaya Shaker Mahmood, Experimental and Theoretical NANOTECHNOLOGY, 10 (2026) 887 https://doi.org/10.56053/10.S.887
[16] M.A. Hayder, K.M. Omar, G.J. Amer, E3S Web Conf. 318 (2021) 01015. https://doi.org/10.1051/e3sconf/202131801015
[17] H.O. Abbas, IOP Conf. Ser.: Mater. Sci. Eng. 1076 (2021) 012094. https://doi.org/10.1088/1757-899X/1076/1/012094
[18] Bureau of Indian Standards, IS 2911: Code of Practice for Design and Construction of Pile Foundations, Parts 1–4, BIS, New Delhi, 2010–2021.
[19] ASTM International, ASTM D854-14: Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer, ASTM International, West Conshohocken, PA, 2014.
[20] ASTM International, ASTM D4318-17: Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils, ASTM International, West Conshohocken, PA, 2017.
[21] ASTM International, ASTM D422-63(2007): Standard Test Method for Particle-Size Analysis of Soils, ASTM International, West Conshohocken, PA, 2007.

[22] ASTM International, ASTM D1557-12: Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort, ASTM International, West Conshohocken, PA, 2012.
[23] S. Prakash, H.D. Sharma, *Pile Foundation in Engineering Practice*, John Wiley & Sons, New York, 1990
[24] Alyaa Hussain, Ibtihal A. Mahmood, Hussein A. Hussein, Experimental and Theoretical NANOTECHNOLOGY, 10 (2026) 907 https://doi.org/10.56053/10.S.907
[25] P. Kumar, S. Raina, Int. J. Geomech. 14 (2014) 04014036 https://doi.org/10.1061/(ASCE)GM.1943-5622.0000409
[26] G.G. Meyerhof, Can. Geotech. J. 1 (1963) 16 https://doi.org/10.1139/t63-003
[27] ASTM International, ASTM D1143/D1143M-20: Standard Test Methods for Deep Foundations Under Static Axial Compressive Load, ASTM International, West Conshohocken, PA, 2020.
[28] A.T. Jaber, N.S. Rahim, Exp. Theo. NANOTECHNOLOGY 5 (2021) 57 https://doi.org/10.56053/5.1.57
[29] A.M.A. Hassan et al., Exp. Theo. NANOTECHNOLOGY 2 (2018) 91 https://doi.org/10.56053/2.2.91
[30] Ruqayah M. Jawad, Hayder S. Hussain, Experimental and Theoretical NANOTECHNOLOGY, 10 (2026) 979 https://doi.org/10.56053/10.S.979