BILINGUAL PUBLISHING GROUP
Pioneer of Global Academics Since 1984

Advances in Geological and Geotechnical Engineering Research
https://journals.bilpubgroup.com/index.php/agger

ARTICLE

Geometrical Effect of Under-reamed Pile in Clay under Compression Load Numerical-Study

Ahmed M. Nasr , Waseim R. Azzam , Ibrahim S. Harran*

Faculty of Engineering, Tanta University, Tanta, 002040, Egypt

ABSTRACT

Recently, the use of deep foundations has increased as a result of the expansion in the construction of high-rise buildings, train tracks, and port berths. As a result of this expansion, it was necessary to use deep foundations that have low cost, high bearing loads, low settlement, and construction time, and such foundations are subjected to different types of loads such as lateral, vertical compression, and tension loads. This research paper will present one of the most important types of deep foundations that are aptly used in such structures and the most important factors affecting their bearing capacity and settlement in stiff clay. This type of deep foundation is called an under-reamed pile. The factors used in this study are pile length to diameter ratio L/D = 30, bulb diameter ratio (Du/D = 1.5, 2, 2.25, and 2.5), number of bulbs (N = 1, 2, and 3), and spacing ratio (S/D = 2 to 8). To investigate the effects of these parameters and obtain optimal results, the PLAXIS 3D was used. The analysis shows that the increase in bulb diameter increases the bearing load by 43%. Bulb spacing controls the failure mechanisms, whether cylindrical shear failure or individual failure and increases the capacity by 66% and 99%, respectively, for two and three bulbs when the bulb spacing becomes S/D = 8. When the number of bulbs increases to three, the capacity increases by 90%. If each bulb works individually, the bearing capacity doubles.

Keywords: Under-reamed pile; Bulb number; Bulb diameter; Bulb spacing; Bearing capacity

1. Introduction

Under-reamed piles have been constructed in Texas since the 1930s. These piles were initially constructed in loose soil. Jenkins and Henkel also conducted the first research on under-reamed piles in South Africa in 1949. Under-reamed piles are a type of bored pile that can have one or more bulbs based

*CORRESPONDING AUTHOR:
Ibrahim S. Harran, Faculty of Engineering, Tanta University, Tanta, Egypt; Email: Ibrahim_sabryh@f-eng.tanta.edu.eg

ARTICLE INFO
Received: 24 November 2022 | Revised: 14 December 2022 | Accepted: 19 December 2022 | Published Online: 31 January 2023
DOI: https://doi.org/10.30564/agger.v5i1.5276

CITATION
Nasr, A.M., Azzam, W.R., Harran, I.S., 2023. Geometrical Effect of Under-reamed Pile in Clay under Compression Load Numerical-Study. Advances in Geological and Geotechnical Engineering Research. 5(1): 1-9. DOI: https://doi.org/10.30564/agger.v5i1.5276

on a variety of parameters such as soil type, pile length, pile diameter, bulb number, bulb spacing, and bulb diameter. When two bulbs were used to study the influence of bulb number on a bearing load, the compression load increased by about 80% [1]. The bearing load of under-reamed piles in multi-layered soil is determined by pile length. The pile lengths used in the study were 3.5 m, 4.3 m, 5 m, 5.5 m, and 6 m, with the ANSYS program. According to the study, the bearing load of an under-reamed pile increases slightly as the pile length increases from 3.5 m to 6 m. According to a study on the bearing load's relationship with bulb diameter, the bearing load increased by 228.57% as the diameter of the bulb pile increased from 0.60 m to 1.20 m [2]. As bulb diameter increases, the area of soil sliding spreads up and beneath the bulb, influencing the pile's valid length of side friction. Consequently, the load of the pile's side friction is reduced [3]. PLAXIS 3D was used to investigate the effect of adding one or more bulbs to a stem pile on the bearing load and found that the bearing compression load was raised twice. According to studies for different pile lengths (6 m, 8 m, 10 m, and 12 m), as the pile length was increased, the bearing load of tapered piles increased dramatically, but the bearing load of under-reamed piles only increased marginally [4]. To numerically analyze under-reamed piles, use ANSYS piles exposed to axial load in tension and compression with changing geometrical factors such as bulb diameter, number, spacing, and position. They discovered that geometrical parameters had a considerable impact on the bearing load of under-reamed piles under tension and compression loads [5]. Bulb piles are regarded to have the most advantages over other piles since they can work successfully with smaller diameters and lengths. Instead of long, high-diameter piles, under-reamed loads and loads with several bulbs can be used to transfer large loads. Furthermore, soil conditions have a significant impact on the performance of under-reamed piles. under-reamed piles can also be installed in clay and sand soil to increase the bearing load of the pile foundation [6,7]. For determining the ultimate capacity of under-reamed piles, two techniques based on center-to-center bulb spacing were proposed [8]. Two methods for determining the ultimate carrying load were proposed. The first method considers shear resistance mobilized along the surface of the pile shaft further than the bulbs, shear resistance mobilized on the cylindrical surface circumscribing the bulbs, and end bearing at the pile toe. The second method considers the individual bearing resistance of each base as well as the frictional resistance mobilized along the pile shaft. The shearing resistance formed on the cylindrical surface around the bulb of many under-reamed drilled shafts has been considered [9]. The load transmission begins at the pile tip with bearings and then fails to owe to cylindrical shear failure [10]. To investigate the influence of the concrete casting method on under-reamed piles subjected to stress and compression, two groups of three under-reamed piles are used. The first group used self-compacting concrete, while the second group used conventionally vibrated cement concrete. under-reamed piles made of self-compacting concrete were proven to be more uniform and durable than piles made of regular concrete. The load-deformation behaviors of conventional concrete piles and self-compacting concrete piles were remarkably equivalent under tension and compression [11]. The under-reamed piles that have been constructed in Taihang Mountain, China, the project have a stem diameter of 0.7 m, a pile length of 32 m, a bulb diameter of 1.4 m, and two numbers of bulbs. The concrete grade used in the design is C40 for all piles [12]. under-reamed piles were used in the Eastern Expressway project in Ningbo, China. And they found that under-reamed piles can save over 30% in construction materials when compared to traditional straight piles with the same compressive bearing capacity [13].

2. Goals and objectives

The primary objective of this research is to investigate the effect of changes in the geotechnical properties and geometrical features of the under-reamed pile, such as pile length, bulb diameter, bulb spacing, and the number of bulbs, particularly bulb spacing, because previous studies focused on bulb diameter and the number of bulbs, on bearing capacity and settlement in stiff clay. However, when the under-reamed pile was subjected to compression force, the bulb spacing had a significant role in defining the failure mechanism mode, whether cylindrical shear failure or individual shear failure. The finite element analysis approach (PLAXIS 3D) was utilized to determine the best parameters for high bearing capacity.

3. Numerical modeling and analyses

3.1 Numerical modeling

The finite element model of the under-reamed pile and the surrounding soil was constructed by the Plaxis 3D program. The under-reamed pile was simulated as a concrete volume element, and the linear elastic constitutive model was used to represent the pile. To describe the soil, the Mohr-Coulomb model (MC) was used. The main five input parameters for simulating clay soil by the Mohr-Coulomb model are the unit weight (γ); Young's modulus (Es); Poisson's ratio (u); Cohesion (c); and the interface ratio between the soil and the concrete surface of the pile (RInterface). To avoid any significant boundary effects, the overall dimensions of the model boundaries are a width of 40 times the pile's diameter and the model depth is equal to twice the pile length [14].

3.2 Model validation and verification

The PLAXIS 3D was used to validate the Tian et al. under-reamed pile experimental test. The experimental model was used to explore the bearing capacity and failure mechanisms around the pile, as well as to validate the use of half and whole steel pile cross-sections in future experiments. The Mohr-Column constitutive model was used to represent clay soil. For the pile, however, a linear elastic model was adopted. The following pile geometric attributes were used in the experimental model: 210 mm under-reamed pile length (L), 10 mm stem pile diameter (D), 30 mm bulb diameter (Du), and two bulbs (N). **Table 1** shows the pile and soil parameters (1). The numerical model dimensions used are equal to the tank dimensions, the width, length, and height of 400 mm × 400 mm × 400 mm [15]. The comparison of the results of the experimental model published by Tian et al. (2016) and the numerical model in the present study analyzed by PLAXIS 3D is shown in **Figure 1**.

Table 1. Properties of pile and clay soil, Tian et al. (2016).

Parameter	**Clay**	**Steel pile**	**Unit**
Model type	MC	LE	-
Drainage type	Undrained	-	-
Soil saturated unit weight (γ_{sat})	18.6	78.5	kN/m^3
Young's modulus (E)	2.5E + 05	21E + 07	kN/m^2
Poisson's ratio (υ)	0.35	0.2	-
Cohesion (c)	59	-	kN/m²
Interface reduction factor (R)	0.5	-	-

The load settlement relationships of the numerical model match well with those of the experimental model. The differences in results between experimental and numerical analysis (using PLAXIS 3D) range from 2.5% to 10%. As a result, the outcomes of the numerical models were used to match the trend of the lab data, achieving good conformity. Its results showed that the Plaxis 3D version is capable of predicting the actions of the under-reamed pile under axial load in clay led to the proposal to use the computer program for the analyses suggested in this technical article.

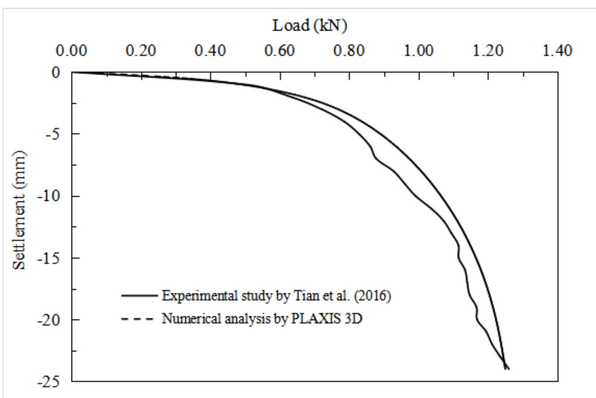

Figure 1. Comparison of the model test result by Tian et al. (2016) and the numerical analysis by PLAXIS 3D.

3.3 Characteristics and meshes of the numerical model

PLAXIS 3D uses a full-scale numerical model to investigate the effect of various geotechnical and geometrical parameters on the bearing load of an under-reamed pile. The first bulb was regarded by all groups at a bucket distance of one meter from the bottom of the under-reamed pile. The global coarseness of meshing was set to fine to provide decent results without compromising analysis time. **Figure 2** illustrates the mesh form of the under-reamed pile after meshing. The under-reamed pile was modeled in two stages. First, the gravity load was applied to the soil block to account for the initial in-situ stress states. After the specified displacement has been applied to the pile head, the pile geometry and properties are defined in the second stage. Given the geometry of the load-displacement curve, a proper point of ultimate shear failure is possibly not the best choice. They calculated the ultimate bearing load of under-reamed piles using the Indian Standards settlement criterion [5,16]. They advocated the adoption of settlement criteria in such cases [3,17].

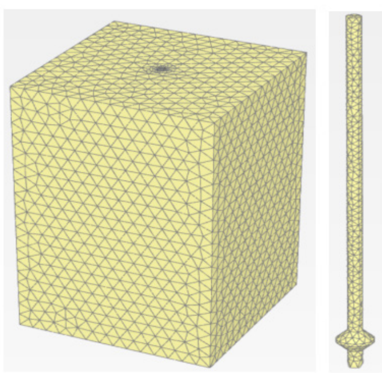

Figure 2. Meshing of under-reamed pile, (a) soil block, (b) under-reamed pile with one bulb.

3.4 Geometry and material properties

The typical under-reamed pile details are shown in **Figure 3**. The soil condition used in this study was stiff clay as shown in **Table 2**, and the groundwater table was 1 m below the ground surface. The characteristics of the under-reamed pile include the pile length (L), the stem pile diameter (D), the bulb diameter (Du), the bulb number (N), the bucket length (B) and the bulb spacing (S) as shown in **Figure 3**. **Table 3** shows the parameters used in the study.

Table 2. Properties of pile and clay soil.

Identification	**Stiff clay**	**Concrete pile**	**Units**
Model type	MC	LE	-
Drainage type	Undrained	-	-
Soil saturated unit weight (γ_{sat})	16	24	kN/m^3
Young's modulus (E)	12.8×10^3	2.6×10^7	kN/m^2
Poisson's ratio (ν)	0.35	0.2	nu
Cohesion (c_u)	75	-	kN/m^2
Interface reduction factor (R)	0.7	-	-

Table 3. Variables and ranges used in the parametric study.

Case	**Variable**	**Studied parameters**
Pile length	L/D	30
Bulb diameter ratio	Du/D	1.5, 2, 2.25 and 2.5
Number of bulbs	N	1, 2 and 3
Bulbs spacing	S/D	2, 3, 4, 5, 6, 7, and 8

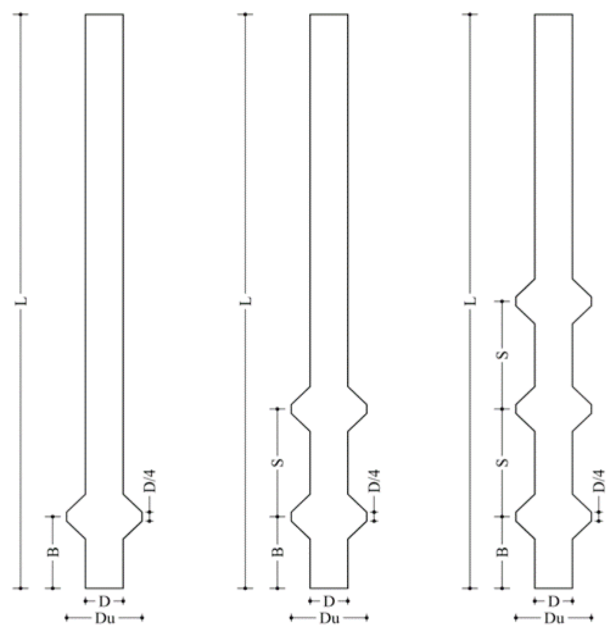

Figure 3. Typical under-reamed pile geometrical features.

3.5 Results and discussion

Figure 4 presents the load-settlement relationship for an under-reamed pile with a single bulb in stiff clay, pile length to diameter ratio L/D = 30 and bulb diameter ratios (D_u/D = 1.5, 2, 2.25, and 2.5). As the bulb diameter increases, the under-reamed pile load capacity increases significantly, resulting in reduced settlement. The corresponding capacities are (1901, 2166, 2498, and 2530) kN for single bulb under-reamed pile at (D_u/D) ratios of (1.5, 2, 2.25 and 2.5) respectively. While the bearing capacity is reduced to 1775 kN for a pile without a bulb. It is noticed that the load-settlement curve is improved and modified according to bulb diameter. For the single bulb under-reamed pile with different bulb diameter ratios (D_u/D) and (L/D = 30) at the same bearing load of 1700 kN, the settlement values are (28 mm, 21 mm, 17 mm, and 17 mm) for (Du/D) ratios (1.5, 2, 2.25, and 2.5) respectively, while the settlement of the pile without a bulb at this load is 40 mm. This indicates that the bearing capacity of an under-reamed pile with a large bulb diameter provides slight displacements and could be more acceptable for a supporting structure. It was also observed that the initial linear slope of the load-displacement curves of the under-reamed pile with different bulb diameters was almost the same with an increase in bulb diameter. It is obvious that the carrying capacity increases by (7%, 22%, 41%, and 43%) for (Du/D) ratios (1.5, 2, 2.25, and 2.5). The presence of a bulb alters and enhances the load-settling behavior of an under-reamed pile, as well as the bearing capacity in relation to pile depth of embedment and clay soil cohesiveness. The increase in bearing load occurs due to adding a bulb to the shaft which leads to an increase in the projected bearing area [12].

While, **Figure 5** presents the load-settlement relationship for an under-reamed pile with one, two, and three bulbs in stiff clay, pile length to diameter ratio (L/D) = 30, and bulb diameter ratio (Du/D = 2.5), the corresponding capacities are (2452, 3013 and 3370) kN for bulbs number (N = 1, 2, and 3) respectively. While the bearing capacity is reduced to 1775 kN for a pile without a bulb. As the bulb number increases, the under-reamed pile load capacity increases, resulting in reduced settlement. For the under-reamed pile with different bulb numbers (N) and (L/D = 30) at the same bearing load of 1700 kN, the settlement values are (16 mm, 13 mm, and 13 mm) for bulbs number (N) (1, 2, and 3) respectively, while the settlement of the pile without a bulb at this load is 40 mm. It is obvious that the carrying capacity increases by (38%, 70%, and 90%) for (N) ratios (1, 2, and 3). It can be seen that the existence of such a bulb with a sufficient number can significantly improve the pile capacity and decrease the settlement. The increase in bearing load occurs due to adding a bulb to the shaft, which leads to an increase in the projected bearing area [12].

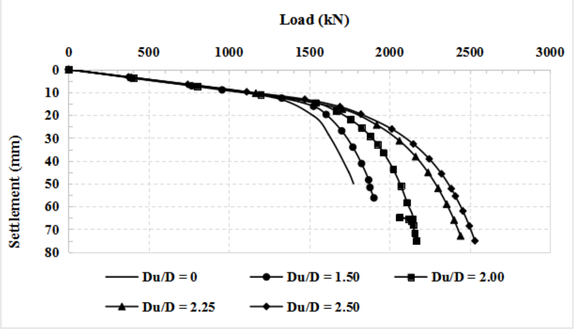

Figure 4. Load settlement relationship for under-reamed pile for (N = 1), in stiff clay, pile length to diameter ratio (L/D = 30), in different bulb diameter ratios.

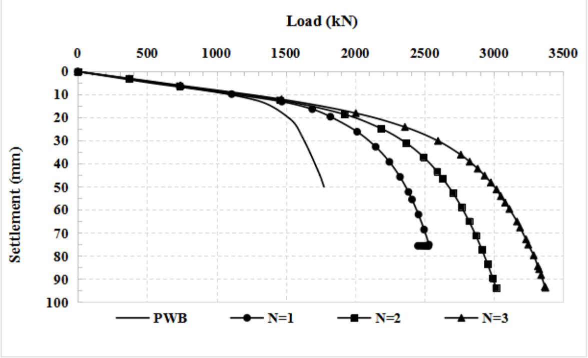

Figure 5. Load settlement relationship for under-reamed pile for (D_u/D = 2.5), in stiff clay, pile length to diameter ratio (L/D = 30), in different bulb numbers.

However, **Figure 6** presents the load-settlement relationship for an under-reamed pile with a number of bulbs (N = 2) in stiff clay, pile length to diameter ratio L/D = 30 and bulb diameter ratios (Du/D = 2). It is noticed that Increased soil cohesion leads to increased under-reamed pile-bearing capacity due to increased shaft frictional resistance and total bull-bearing load. With the increase in bulb spacing, the ultimate bearing load significantly increases and the settlement is reduced. The corresponding capacities are (2470, 2455, 2687, 2731, 2804, 2824, and 2945) kN for bulb spacing (S/D) ratios of (2, 3, 4, 5, 6, 7, and 8) respectively. While the bearing capacity is reduced to 1775 kN for a pile without a bulb. For the bulb spacings of the under-reamed pile (S/D) and (L/D = 30) at the same bearing load of 1700 kN, gives the same settlement value (18 mm) for (S/D) ratios (2, 3, 4, 5, 6, 7, and 8) respectively, while the settlement of the pile without a bulb at this load is 39 mm, it demonstrates that the settlement value is the same for under-reamed piles with various spacing ratios under compression loading. The previous analysis shows that the bulb spacing ratio of the under-reamed pile had no influence on the initial linearly elastic slope of the load-displacement curves [14]. It is obvious that the carrying capacity increases by (39%, 38%, 51%, 54%, 58%, 59%, and 66%) for (S/D) ratios (2, 3, 4, 5, 6, 7, and 8). It can be seen that the increased soil cohesion and change of bulb spacing improve the pile capacity and decrease the settlement, but failure occurs at spacing S/D = 3 before reaching the proposed settlement. When the spacing between bulbs becomes small, the confined volume of soil between the bulbs is mobilized, and the bulbs work together and act as a semi-rigid body that develops a cylindrical shear surface [15]. But when the spacing between the bulbs is large, the overall bearing load of under-reamed pile under vertical load is the combination of individual bulb capacities and the side friction resistance along the pile length [18].

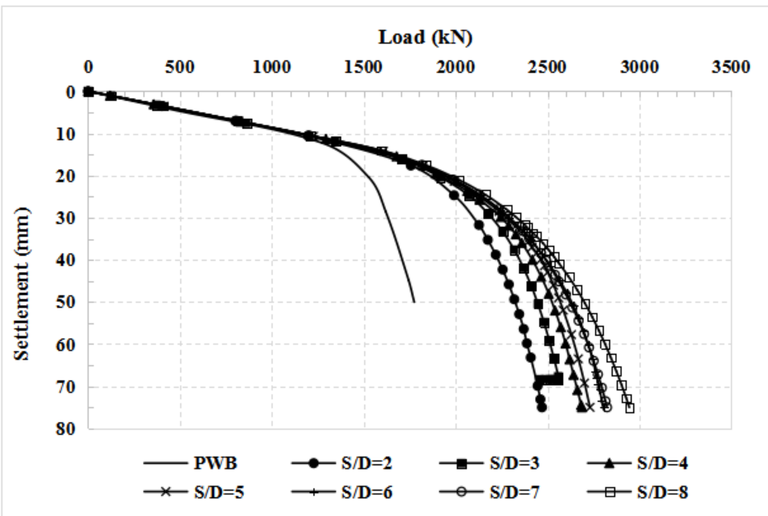

Figure 6. Load settlement relationship for under-reamed pile for (N = 2), in stiff clay, (L/D = 30) and (Du/D = 2), in different bulb spacings (S/D).

However, **Figure 7** presents the load-settlement relationship for an under-reamed pile with a number of bulbs (N = 3) in stiff clay, pile length to diameter ratio L/D = 30 and bulb diameter ratios (Du/D = 2). Increases the number of bulbs, increase soil cohesion and increases bulb spacing, the ultimate bearing load significantly increases and the settlement is reduced. The corresponding capacities are (2791, 2975, 3128, 3294, 3427, 3506, and 3535) kN for bulb spacing (S/D) ratios of (2, 3, 4, 5, 6, 7, and 8) respectively. While the bearing capacity is reduced to 1775 kN for a pile without a bulb. It is noticed that with the increase of bulb spacing, the ultimate bearing capacity improves and the settlement is reduced. For the bulb spacings of the under-reamed pile (S/D) and (L/D = 30) at the same bearing load of 1700 kN, gives the same settlement value (17 mm) for (S/D) ratios (2, 3, 4, 5, 6, 7, and 8) respectively, while the settlement of the pile without a bulb at this load is 39 mm, it demonstrates that the settlement value is the same regardless of the under-reamed pile's bearing capability at various spacing ratios under compression force. According to the earlier investigation, the under-reamed pile's bulb spacing ratio had no impact on the load-displacement curves' initial linearly elastic slope [14]. It is obvious that the carrying capacity increases by (57%, 68%, 76%, 86%, 93%, 98%, and 99%) for (S/D) ratios (2, 3, 4, 5, 6, 7, and 8). It can be seen that the change of bulb spacing with spacing can significantly improve the pile capacity and decrease the settlement but failure occurs at spacing (S/D = 3, 4, 6, and 7) before reaching the proposed settlement.

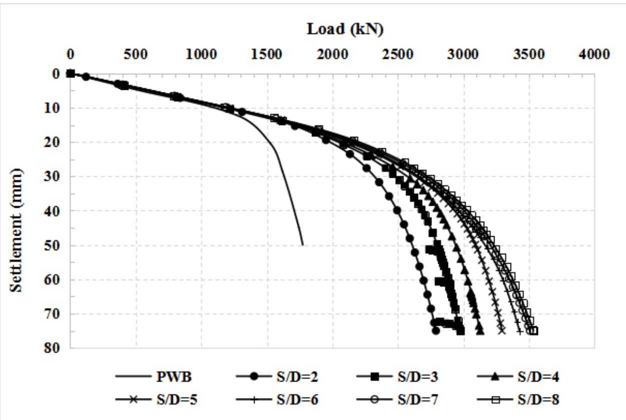

Figure 7. Load settlement relationship for under-reamed pile for (N = 3), in stiff clay, (L/D = 30) and (Du/D = 2), in different bulb spacings (S/D).

4. Conclusions

• As bulb diameter increases, the increase in bearing load occurs due to adding a bulb to the pile shaft that leads to an increase in the projected bearing area.

• As a bulb number increases, the under-reamed pile load capacity increases significantly and the settlement is reduced.

• It's important to study the effect of bulb spacing on the bearing capacity of an under-reamed pile with different bulb spacings (S/D), because the bulb spacing determines the mode of failure mechanism under compression loading.

Conflict of Interest

There is no conflict of interest.

References

[1] George, B.E., Hari, G. (editors), 2015. Numerical investigation of under-reamed piles finite element analysis was carried out using. Sixth International Geotechnical Symposium 6 IGS Chennai, India. p. 4-7.

[2] Pakrashi, S., 2017. A comparative study on safe pile capacity as shown in table 1 of IS 2911 (Part III): 1980. Journal of The Institution of Engineers (India): Series A. 98(1-2), 185-199.
DOI: https://doi.org/10.1007/s40030-017-0189-z

[3] Terzaghi, K., 1942. Discussion of the progress report of the committee on the bearing value of pile foundations. Proceedings of the American Society of Civil Engineers. 68, 311-323.

[4] Vali, R., Mehrinejad-Khotbehsara, E., Saberian, M., et al., 2019. A three-dimensional numerical comparison of bearing capacity and settlement of tapered and under-reamed piles. International Journal of Geotechnical Engineering. 13(3), 236-248.
DOI: https://doi.org/10.1080/19386362.2017.1336586

[5] Kurian, N.P., Srilakshmi, G. (editors), 2004. Studies on the geometrical features of under-reamed piles by the finite element method. Proceedings of International e-Conference on 'Modern Trends in Foundation engineering: Geotechnical Challenges and Solutions, Madras; 2004 Jan. p. 14.

[6] Golait, Y.S., Satyanarayana, V., Raju, S. (editors), 2009. Concept of under-reamed cemented stone columns for soft clay ground improvement. GeoTide. Guntur, Indian Geotechnical Society, IGC. New Delhi: Allied Publishers New Delhi. p. 356-360.

[7] Alielahi, H., Mardani, Z., Daneshvar, S., 2014.

Arrangement optimization of asymmetric under-reamed pile groups in order to evaluate tensile bearing capacity using numerical model. 8th National Congress on Civil Engineering; 2014 May 7-8; Babol, Iran. Babol: Babol Noshirvani University of Technology.

[8] Mohan, D., Murthy, V.N.S., Jain, G.S., 1969. Design and construction of multi-under-reamed piles. Proceedings the Seventh International Conference on Soil Mechanics and Foundation Engineering, Session 2, Mexico. Mexico: Mexico City. pp. 183.

[9] Martin, R.E., DeStephen, R.A., 2019. Large diameter double under-reamed drilled shafts. Journal of Geotechnical Engineering. 109(8), 1082-1098. DOI: https://doi.org/10.1061/(ASCE)0733-9410(1983)109:8(1082)

[10] Jain, G.S., Gupta, S.P., 1972. Deformation of soil around a multi under-reamed pile. Indian Concrete Journal. 46(6), 239-241.

[11] Peter, J.A., Lakshmanan, N., Manoharan, P.D., 2006. Investigation on static behavior of self compacting concrete under-reamed piles. Journal of Materials in Civil Engineering. 18(3), 408-414. DOI: https://doi.org/10.1061/(ASCE)0899-1561(2006)18:3(408)

[12] Majumder, M., Chakraborty, D., Kumawat, V., 2022. Model test study on single and group under-reamed piles in sand under compression and tension. Innovative Infrastructure Solutions. 7, 129. DOI: https://doi.org/10.1007/s41062-021-00725-4

[13] Yuan, L., Dai, G., Gong, W., 2014. Experimental investigation, calculation and analysis of compressive bearing capacity of squeezed branch piles. Hans Journal of Civil Engineering. 3, 103e9.

[14] Tian, W., Qian, Y., Lu, T., et al., 2016. The undisturbed soil experiment of the comparison about the failure of the half and whole cross-section piles under the resistance compression. International Forum on Energy, Environment & Sustainable Development. 75, 296-300. DOI: https://doi.org/10.2991/ifeesd-16.2016.51

[15] Zhang, M., Xu, P., Cui, W., et al., 2018. Bearing behavior and failure mechanism of squeezed branch piles. Journal of Rock Mechanics and Geotechnical Engineering. 10(5), 935-946. DOI: https://doi.org/ 10.1016/j.jrmge.2017.12.010

[16] IS:2911, 1980. Indian standard code of practice for design and construction of pile foundations. Part III: Under-reamed piles (first revision). Soil and Foundation Engineering. New Delhi: Bureau of Indian Standards.

[17] No, P., 1990. Drilled shafts: Construction procedures and design methods. Tunnelling & Underground Space Technology. 5(1-2), 156-157. DOI: https://doi.org/10.1016/0886-7798(90)90101-o

[18] Qian, Y., Yi, Y., Wang, R., 2013. Research on influence factors of the ultimate bearing capacity of the soil of push-extend multi-under-reamed pile under compression. Advances in Materials Research. 671-674, 538-541. DOI: https://doi.org/10.4028/www.scientific.net/AMR.671-674.538

[19] Xie, X., Yin, X., 2012. The finite element analysis of plate's distance on push-extend multi-under-reamed pile. Advances in Materials Research. 468-471, 2517-2520. DOI: https://doi.org/10.4028/www.scientific.net/AMR.468-471.2517

[20] Qian, Y.M., Shan, L.J., Xu, G.H., 2014. Testing research on the shape of the bearing push-extend reamed affecting the bearing capability of the pile of push-extend multi-under-reamed pile. Advances in Materials Research. 962-965, 1091-1094. DOI: https://doi.org/10.4028/www.scientific.net/AMR.962-965.1091

[21] George, B., Hari, G., Alexander, C., 2022. Investigation on multi under-reamed piles with small bulb diameter in clay. International Journal of Geotechnical Engineering. 16(4), 462-470. DOI: https://doi.org/10.1080/19386362.2021.1959010

[22] Peter, J.A., Lakshmanan, N., Devadas Manoha-

ran, P., 2006. Investigations on the Static Behavior of Self-Compacting Concrete Under-Reamed Piles. Journal of Materials in Civil Engineering. 18(3), 408-414.
DOI: https://doi.org/10.1061/(ASCE)0899-1561(2006)18:3(408)

[23] Qian, Y.M., Liu, X.L., Wang, R.Z., 2013. Research on the formula of the height of bearing push-extend under-reamed of the push-extend multi-under-reamed pile. Advances in Materials Research. 694(697), 883-886.
DOI: https://doi.org/10.4028/www.scientific.net/AMR.694-697.883

[24] Qian, Y.M., Zhai, R.Z., Liu, X.L., 2014. Testing research is about the influence of the diameter of the bearing push-extend reamed to the bearing capability of the pile of push-extend multi-under-reamed pile. Applied Mechanics and Materials. 578-579, 192-195.
DOI: https://doi.org/10.4028/www.scientific.net/AMM.578-579.192

[25] Qian, Y.M., Zhao, D.P., Xie, X.W., 2014. The research on the ultimate bearing capacity of soil around the push-extend multi-under-reamed pile at sliding failure state. Applied Mechanics and Materials. 578-579, 232-235.
DOI: https://doi.org/10.4028/www.scientific.net/AMM.578-579.232

[26] Qian, Y., Chen, X., Xie, X., 2014. Determine the stress calculating mode of sliding failure of soil mass under the push-extend multi-under-reamed pile. Engineering. 6(5), 254-259.
DOI: https://doi.org/10.4236/Eng.2014.65029

[27] Qian, Y., Xu, G., Wang, R., 2013. Experimental research on failure behavior of soil around pile under compression. Telkomnika Indonesian Journal of Electrical Engineering. 11(4), 23-77.
DOI: http://journal.esperg.com/index.php/tijee/article/view/2187

[28] Qian, Y.M., Yu, H., Wang, R.Z., 2013. Analyzing bearing capacity influence due to location of bearing push-extend reamed of the push-extend multi-under-reamed pile. Advanced Materials Research. 690(693), 1891-1894.
DOI: https://doi.org/10.4028/www.scientific.net/AMR.690-693.1891

[29] Shrivastava, N., Bhatia, N., 2008. Ultimate bearing capacity of under-reamed pile—Finite element approach. 12th International Conference on Computer Methods and Advances in Geomechanics. 5, 3490-3497.

[30] Liu, Y., Liu, H., Lin, D., 2011. Based on FEM in analysis of the performance of under-reamed pile expansion of the bottom. PACCS 2011 2011 3rd Pacific-Asia Conference Circuits, Communications & System; 2011 Jul 17-18; Wuhan,China. USA: IEEE. p. 5-8.
DOI: https://doi.org/10.1109/PACCS.2011.5990151