Numerical Analysis of Under-Reamed Pile Subjected to Dynamic Loading in Sandy Soil

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Abstract. Under-reamed piles are piles with enlarged bases, which may be single bulb or multi bulbs. Such piles are suitable for resisting considerable soil movement of filled up ground, soft clay, and loose sand and have the advantages of increasing the soil strength and decreasing the displacement. In the present study, the finite element method was used to analyse the performance of a single pile with under-reamed bulbs of different shapes, that is, single cone, double cone, and half and full sphere, embedded in homogeneous, poorly graded sandy soil. The model of under-reamed pile was made of reinforced concrete and the bulb located at the middle of the embedded length of the pile. The dynamic load applied on the piles is a vertical harmonic load produced from the vibration of machine fixed on the pile cap and the results analysed using PLAXIS 3D software. The Moher-Coulomb model was used to simulate the behaviour of the soil and the linear elastic model was used for simulating the behaviour of the pile material. The load-settlement curve was obtained from the analysis of different patterns of the under-reamed pile, and the results showed a reduction in the settlement by 1.670% when using a single cone. The single cone gives the best results in comparison with other shapes of under-reamed bulbs.

Key words: Under-reamed pile, dynamic load, sandy soil, PLAXIS 3D.

1. Introduction

Under-reamed piles are concrete piles cast in-situ with one or more bulbs in their stems. The bulbs help to distribute the loads in soil and lead to increases in the carrying capacity of the piles under both pull out and compressive loadings. Under-reamed piles provide better anchoring along the embedded depth of pile, and thus the main applications of such piles are in support of machines, bridges, transmission towers, and water tanks. One of the main dynamic problems of foundations is machine foundation, the design of machine foundation should produce a safe and economical foundation by satisfying the requirements of the machinery and the associated structural criteria. The vibrations of machines induce elastic waves in soil that generate low strains [1]. The design of a machine foundation requires the use of the concepts of soil dynamics, soil mechanics, and vibration theory to address such problems. These concepts can be used to control the vibration amplitude of the machine as transmitted to the foundation and to restrain it within the allowable limits. The basic goal in the design of machine foundation is to limit the motion to amplitudes that allow satisfactory operation of the machine [1].
Patra and Deogratias [2] investigated the behaviour of under-reamed piles experimentally, with piles embedded in layered and homogeneous sand being subjected to axial and oblique pulling loads. The results of these tests indicated a nonlinear load-displacement relationship and the uplift carrying capacity of pile increased with increasing the length and dimensions of base of the under-reamed pile. The ultimate carrying capacity of under-reamed piles embedded in soil can be estimated effectively based on theoretical and semi-empirical works [3, 4]. Full scale tests and small model laboratory tests have been conducted on under-reamed piles to calculate the ultimate carrying capacity of such piles [5], while Chae et al. [6] conducted a series of full-scale pull-out load test to determine the pull-out carrying capacity of under-reamed piles with bell-shape bulbs inserted into weathered sandstone soil. A comparison of results from full scale tests, theoretical methods, and 3D finite element analysis revealed that the theoretical methods overestimate the ultimate pull out capacity of such piles regardless the shape of bulb. Lin et al. [7] also conducted a series of experimental full-scale tests to determine the slip failure surface that indicated that the failure surface is initiated at some distance from the pile surface.

Bharathi and Dubey [8] implemented 2D linear finite element analyses of piles with and without underreaming subjected to sinusoidal dynamic loads in sandy soil (SM) using ABAQUS software. Based on the results of the numerical study, as the eccentricity of the oscillator (i.e. force level) increased, the vertical displacement amplitude increased. It was also found that the maximum displacement amplitude of the under-reamed pile was less than that of uniform cross-sectional area pile. Therefore, it preferable to use under-reamed piles in situations where the system is subjected to heavy vertical dynamic sinusoidal loads. Farokhi et al. [9] studied the influence of geometrical shape of bulbs on the compression carrying capacity of under-reamed piles inserted in clayey soil. The studied shapes were uniform cross-sectional area, half-bulb under-reamed pile, and full bulb under-reamed pile. The results of tests indicated that the half-bulb under-reamed pile had higher compressive carrying capacity than the full-bulb under-reamed pile or uniform cross-section pile of the same length and volume. The maximum compressive carrying capacity of the half-bulb under-reamed pile was about 13% higher than that of the full-bulb under-reamed pile and approximately 73% higher than that of the uniform cross-sectional area pile. The half-bulb under-reamed pile also had a higher maximum tensile carrying capacity than a pile of uniform cross-sectional area of the same length and different volume. The maximum tensile carrying capacity of under-reamed piles is approximately 90% higher than that of uniform cross-sectional area piles of the same length.

Several studies [10-17] have examined the behaviour of under-reamed piles inserted in sandy soils, authors determined the pull-out and axial compression static carrying capacity of these piles. In the present study, a comparison between the ultimate compression carrying capacity of a single pile of uniform cross-sectional area inserted in single layer of sandy soil and supporting a machine load and that of different shape of under-reamed bulb piles supporting the same machine load is undertaken. Four types of under-reamed piles are evaluated using PLAXIS 3D software, as different configurations of under-reamed bulb are considered: single cone, double cone, half sphere, and full sphere located at the centre of embedded depth of pile.

2. Properties of Materials Used

The properties of soil and materials used in the present study are divided into three parts:

2.1. Soil properties

The sandy soil used in the present study was obtained from Karbala city. The standard geotechnical tests were performed at the laboratory of soil mechanics at the University of Baghdad to calculate the geotechnical properties of the soil that necessary to produce input data for the theoretical analysis. The particle-size distribution curve of Karbala sand is shown in Figure 1; according to the USCS, the sand can be classified as poorly graded sand (SP). The geotechnical properties of the soil used as input data in PLAXIS 3D software are listed in Table 1. The dimensions of the soil box used in the theoretical
analysis were assumed to be 80×80×100 cm. The interface between soil and pile material was also assumed to be one unit as input data in the analysis.

![Figure 1. Particle-size distribution curve of the sandy soil sample.](image)

**Table 1.** Geotechnical properties of soil used in test.

| Property                               | Unit  | Value | Specification         |
|----------------------------------------|-------|-------|-----------------------|
| Specific gravity, Gs                   |       | 2.66  | ASTM (D854)           |
| Coefficient of uniformity, Cu          |       | 2.0   |                       |
| Coefficient of curvature, Cc           |       | 0.96  | ASTM (D422)           |
| Classification (USCS)                  |       | SP    |                       |
| Maximum, γ_d,max.                      | kN/m³ | 16.80 | ASTM (D4253)          |
| Minimum, γ_d,min.                      | kN/m³ | 14.90 | ASTM (D4254)          |
| Dry unit weight (Used), kN/m³          | kN/m³ | 15.38 |                       |
| Young’s modulus, E                     | kPa   | 18000 | ASTM (D4253)          |
| Poisson’s ratio, ν                     |       | 0.3   | Assumed               |
| Angle of internal friction, φ          | degree| 32    | ASTM (D2850)          |
| Cohesion, c                            | kPa   | 5.0   | ASTM (D4253)          |
| Dilation angle, ψ                      | degree| 22    | ASTM (D3080)          |

2.2. Pile Cap and Pile Model
The pile cap used in this study was made of thick steel plate. The dimensions and mechanical properties of pile and pile cap used in the present study are given in Table 2.

**Table 2.** Dimensions and properties of pile cap and under-reamed pile.

| Material          | Dimensions          | E    | γ    | ν   |
|-------------------|---------------------|------|------|-----|
| Pile              | 60 (length) × 2.5 (diameter) | 30×10³ | 24   | 0.15 |
| Steel pile cap    | 10×10×1             | 200×10³ | 76   | 0.15 |
The pile models used in this study were made of reinforced concrete, with the diameter of the piles being 2.5 cm, and the length of the embedded section being 60 cm. The embedment ratio was thus L/D = 24, where L represents the embedded depth of pile and D is the diameter of the pile, generating a flexible pile of slenderness ratio > 20 [18, 19]. The behaviour of long or flexible piles are more complicated than those of short or rigid piles, and flexible piles have several applications in the design of deep foundations. Five types of piles were studied, with different geometries of under-reamed bulb: a reference pile of uniform cross-sectional area, an under-reamed pile of single cone shape, an under-reamed pile of double cone shape, an under-reamed pile of half sphere shape, and an under-reamed pile of spherical shape. The shapes and dimensions of the studied piles are shown in Figure 2. The total length of pile in each case was 62 cm, with 60 cm is embedded in the soil and a 2 cm gap between the soil surface and pile cap.

![Figure 2. Shapes and dimensions of studied under-reamed piles.](image)

3. Validation of Numerical Model

The main objective of this work was to study the behaviour of under-reamed piles with different shapes of bulb using a finite element method (FEM) under machine vibration. The accuracy and performance of the proposed FEM program, PLAXIS 3D Software, were evaluated by comparing the deformation calculated by the program with those calculated by Kurian and Srilakshmi [20], who used the finite element method with ANSYS Software, to study the behaviour of under-reamed pile with bulb diameter of 75 cm. The dimensions of the model and properties of soil used to validate of PLAXIS 3D software are given in Table 3. The modelling of under-reamed pile and soil using ANSYS Software is shown in Figure 3 [20], and the distribution of vertical displacement of under-reamed pile obtained from ANSYS Software is shown in Figure 4. The validity of PLAXIS 3D Software in the analysis of under-reamed piles is shown by comparison of the load-settlement curve, where good agreement is noted with the curve obtained using ANSYS software, as shown in Figure 5.

| Table 3. Properties and dimensions of pile and soil used in the analysis of Kurian and Srilakshmi [20]. |
|---|
| Material | Dimensions \( m \) | \( E \) kPa | \( \gamma \) kN/m\(^3\) | \( \nu \) | \( c \) kPa | \( \varphi \) Degree | \( \psi \) Degree | \( R \) interface |
| Pile | 4.5 (len.) \( \times 0.3 \) (dia.) | \( 25 \times 10^3 \) | 25 | 0.15 | - | - | - | - |
| Soil | 10\(\times10\times8\) | \( 8\times10^3 \) | 17 | 0.30 | 50 | 10 | 10 | 0.12 |
Kurian and Srilakshmi model
Mesh of soil
Mesh of under-reamed pile

**Figure 3.** Modelling of under-reamed pile by Kurian and Srilakshmi [20].

Kurian and Srilakshmi model
Verification model

**Figure 4.** Vertical displacement of the model tested by Kurian and Srilakshmi [20].

**Figure 5.** Load-settlement obtained from PLAXIS software compared with Kurian and Srilakshmi [20].
4. Numerical Analysis

In the current study, PLAXIS 3D software 2013 was used in the analysis of under-reamed piles with different shapes of bulb subjected to machine load. In this Finite Element Analysis software, four types of element are used: 10-node tetrahedral elements are used for modelling the soil and the pile cap is modelled as a triangular plate element of six nodes with six degrees of freedom per node. The embedded depth of pile is modelled by 3-node line elements with six degrees of freedom per node and the interface elements are composed of 12-node interface elements [5]. The under-reamed pile is considered to consist of a linearly elastic material and the Mohr-Coulomb model is invoked for the soil. The motor is fixed on the pile cap and applies a dynamic load of 1 N/cm² with a machine frequency of 10 Hz. The dimensions of the soil used in the analysis were selected to prevent the generation of stresses at the boundary of steel box model, with the exception of the top surface. However, Vipulanandan et al. [21] stated that the minimum distance between the pile tip and the base of the chamber penetration should not be less than eight times its own radius, and Gui [22] conducted centrifuge tests in sandy soil and concluded that the ratio of soil container diameter to the pile diameter should be greater than 40 to ensure the stresses are zero at the edge of container. The dimensions of the container in this study are 80x80x100 cm, which offers a ratio of 36, close to that proposed by Gui [22]. Five configurations of under-reamed piles were analysed using PLAXIS 3D software under machine load to calculate the distribution of vertical displacement and to measure the effect of under-reamed bulbs in terms of mitigation of oscillation and reduction in the magnitude of vertical displacement.

5. Results and Discussion

Numerical analysis methods are considered adequate techniques for modelling the behaviours of under-reamed piles of different geometries. The finite element mesh of the interfaces of piles as analysed in the present study are shown in Figure 6, and the thematic distribution of vertical displacement calculated by PLAXIS 3D software for different configurations of under-reamed piles are shown in Figures 7 to 11. The mechanism of soil failure is considered a good tool for understanding the behaviour of soil surrounding the piles, which in turn is helpful for revealing soil-pile interaction mechanisms during the application of dynamic loading, as shown in Figures 7 to 11. The pile of uniform cross-sectional area exhibited plunging failure, while the under-reamed piles exhibited general shear failure.

![Figure 6. Interface modelling of under-reamed piles.](image-url)
Figure 7. Distribution of vertical displacement of pile of uniform cross-sectional area.

Figure 8. Distribution of vertical displacement of pile under-reamed in single cone shape.
Figure 9. Distribution of vertical displacement of pile under-reamed in double cone shape.

Figure 10. Distribution of vertical displacement of pile under-reamed in half sphere shape.
According to the results showed in Figures 7 to 11, the soil surrounding the pile of uniform cross-sectional area exhibited higher displacement than that surrounding the under-reamed piles. Using double cone, half sphere, and sphere configurations of under-reaming helps to mitigate the vertical displacement of interface between soil and pile resulting from the application of machine load. The maximum displacements in the pile shafts are 1.80, 0.20, 0.30, 0.24, and 0.28 mm for the reference pile and the cone, double cone, half sphere, and sphere configurations of under-reamed piles, respectively. The reduction in vertical displacement ranged from 500 to 800%, while, the vertical displacement in soil was 1.2, 0.14, 0.8, 0.4, and 0.4 mm for reference pile, and the cone, double cone, half sphere, and sphere configurations of under-reamed pile respectively. The oscillation of vertical displacement of each pile with time is shown in Figure 12; the under-reamed single cone pile shows the best mitigation of oscillation for vertical displacement (reduction of 1,670%). The sphere bulb under-reaming is considered the worst case among the studied configurations due to reduced bearing area from the rounded surface of the bulb, which facilitates the penetration of soil and reduces the bearing capacity and increasing the displacement of pile foundation.

**Figure 11.** Distribution of vertical displacement of pile under-reamed in full sphere shape.
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Figure 12. Variation of settlement with time under the vibration of machine load for different configurations of under-reamed piles.

6. Conclusions
In the present study, a 3D finite element analysis was used to calculate the distribution of vertical displacement for different shapes of under-reamed piles and the surrounding soil. According to the results of numerical simulations using PLAXIS 3D software, the following conclusions can be drawn:

- The shapes of under-ream bulbs have significant effects on the failure of under-reamed piles in soil mass.
- The geometrical nature of under-reamed piles can change soil pile interaction and changes the type of soil mass failure from punching, which occurred in the pile of uniform cross sectional area, to local failure or general shear failure, which occurred in the under-reamed piles.
- Bearing area has more efficiency than frictional area in under-reamed piles subjected to machine loading. The mitigation in vertical displacement of under-reamed piles and soil reached up to 1,670% compared with that seen in a pile of uniform cross-sectional area.
- Using a full sphere as the under-ream bulb shape is the worst choice, as it has fewer useful effects on the distribution of vertical displacement and stresses than using other configurations of bulb such as single cone, double cone, and half sphere.

7. References
[1] Gazetas G 1983 Analysis of machine foundation vibrations: state of the art International Journal of Soil Dynamics and Earthquake Engineering 2(1) pp2-42
[2] Patra N R, Deograthias M and James M 2004 Pullout capacity of anchor piles Electronic Journal of Geotechnical Engineering (EJGE) pp 2004-0340
[3] Zhao N, Geng H X, Ma K and Li K N 2011 Elastic-plastic analysis on damaged multi-tower isolation structure with an enlarged base In Advanced Materials Research Trans Tech Publications 255 pp 2550-2554.
[4] Nazir R, Moayed H, Pratikso A and Mosallanezhad M 2015 The uplift load capacity of an enlarged base pier embedded in dry sand Arabian Journal of Geosciences 8(9) pp7285-7296
[5] Brinkgreve R B J, Engin E and Swolfs W M 2013 PLAXIS 3D 2013 user manual Plaxis bv Delft.
[6] Chae D, Cho W and Na H Y 2012 Uplift capacity of belled pile in weathered sandstones International Journal of Offshore and Polar Engineering 22(04)
[7] Lin J G, Hsu S Y and Lin S 2015. The new method to evaluate the uplift capacity of belled piles in sandy soil Journal of Marine Science and Technology 23(4) pp523-533
[8] Bharathi M and Dubey R N 2018 Dynamic lateral response of under-reamed vertical and batter piles Construction and Building Materials 158 pp 910-920
[9] Farokhi A S, Hamid A and Zahra M 2014 Optimizing the performance of under-reamed piles in clay using numerical method Electron. J. Geotech. Eng 19 pp 1507-1520
[10] Bharathi M, Dhiraj R, Dubey R N and Mukerjee S 2016 Numerical simulation of dynamic vertical tests on piles 6th International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics Greater Noida India
[11] Sakr M 2014 Relationship between installation torque and axial capacities of helical piles in cohesionless soils Canadian Geotechnical Journal 52(6) pp 747-759
[12] Harris D E and Madabhushi G S P 2015 Uplift capacity of an under-reamed pile foundation Proceedings of the Institution of Civil Engineers-Geotechnical Engineering 168(6) pp 526-538
[13] Peter J A, Lakshmanan N and Devadas Manoharan P 2006 Investigations on the static behavior of self-compacting concrete under-reamed piles Journal of materials in civil engineering 18(3) pp 408-414
[14] Qi C G, Liu G B, Wang Y and Deng Y B 2015 Theoretical study on setup of expanded-base pile considering cavity contraction Journal of Central South University 22(11) pp 4355-4365
[15] Qian Y M, Yu H and 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 pp 1891–1894
[16] Yongmei Q, Xihui W and Guanghan X 2014 Analysis of the shape of bearing push-extend reamed affecting the bearing capability of the pile of push-extend multi-under-reamed pile through the finite element method Scientific Research and Essays 9(9) pp 325–330
[17] Qian Y M, Zhao D P and 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 pp 232–235
[18] Meyerhof G, Mathur S K and Valsangkar A J 1981 Lateral resistance and deflection of rigid wall and piles in layered soils Canadian Geotech. J. 18(2) pp 159-170
[19] Meyerhof G and Sastry V R N 1985 Bearing capacity of rigid piles under eccentric and inclined loads Canadian Geotech. J. 22(3) pp 267-276
[20] Kurian N P and Srilakshmi G 2004 Studied on the geotechnical features of under reamed piles by the finite element method In proceeding of international e-Conference on Modern Trends in Foundation Engineering: Geotechnical Challenges and Solutions Madras January 5(14) pp 1-14
[21] Vipulanandan C, Wong D, Ochoa M and O'Neill M W 1989 Modelling of displacement piles in sand using a pressure chamber In Foundation engineering: Current principles and practices ASCE pp 526-541
[22] Gui M W 1995 Centrifuge and numerical modelling of pile and penetrometer in sand Doctoral dissertation University of Cambridge