Impact of Inclined Load on the Performance of Under-Reamed Piles in Clay Soil

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Abstract. This research aims to study the behavior of under-reamed piles under the influence of inclined loads. Four piles of length 350 mm, 20 mm in diameter containing (0, 1, 2, and 3) of bulbs each one has 40 mm in diameter used, and they were inserted into stiff clay and sandy soils (CH and SP) so that the end of the pile sits on dense sandy soil, and the ultimate load capacity of the pile was calculated. The bearing capacity increase reaches more than 76% due to the presence of bulbs in a pile, and the increase reaches after there are two bulges to 15%. The lateral displacement of the pile was also studied by using the lateral load and the compound load and on four stages of the allowable load. The results showed that the effect of the compound load is limited in the normal pile, but in the under-reamed pile, the higher the vertical load, the less the lateral displacement. As for the moments resulting from the combined loads, the effect was up to 10% in the presence of an inclined load compared to the lateral load, and the effect of the presence of bulb in a pile near the ground level appeared to reduce the moments generated for the same load.

Keywords: Under-reamed piles; bulb; strain gauge; inclined load; lateral load.

1. Introduction
Under reamed piles are of bored compaction concrete and bored cast in situ having one bulb or more than produce by acceptable suitably enlarging the hole pile shaft by using an appropriate cutting machine. Under-reamed piles employed in many types of soils like clay, sandy (loose and medium) and silty soil. These piles extensively used for multistory buildings, bridge abutments, towers, shed structures are exposed to axial compressive loads also to a considerable number of horizontal loads and uplift forces. The presence of the bulb increases the ultimate pile capacity of the pile raised twice and sometimes more instead of using longer piles and larger diameters. Moreover, the behavior of under-reamed piles strongly depends on the soil state at the site. For example, applying the under-reamed piles in expansive soils generates broadening at enclosing of piles similar a moment, leading to stabilizing the pile. Furthermore, by placing a bulge heave on the piles, the load-carrying capacity of the under-reamed piles in remolded and yet soft soils may be increased. Bulb diameters are taken by 2–3 times other than shaft diameters IS:2911 PART III-1980.

Several theoretical works studied the influence of the pile diameter, bulb diameter, length, distance from the bulb to the pile tip, the influence of the proportion of the bulb diameter to the shaft diameter, in addition to the ratio of the length of the pile to the diameter on the pile Q\textsubscript{u}. Also, they considered the influence of preceding factors on pile settlement. The results showed that an increase in length and number of bulbs leads to an increase in Q\textsubscript{u} and a reduction in pile settlement [2-5].

Prakash and Ramakrishna [6] found that the under-reamed pile of one-bulb, the closer the bulb is to the ground level in clay soil, the greater its bearing strength for lateral loads, as well as for sandy soils, the best location for bulb at a distance of 0.4 to 0.6 of the length of the pile gives the best resistance to
lateral loads. As for the pile that contains more than one bulb, the best bearing of the lateral forces is the closer the expansion is to the ground level. The ability of the under-reamed pile to carry the lateral load increases with the increase in the number of bulbs in the pile until it reaches three, as it is proven, and there is no effect of increasing after this number. Prakash [7] Conducted site tests on an under-reamed pile of one bulb with a diameter of 300 mm, the bulb was 750 mm, and a total length of 3.5 meters in sandy soil, its behavior as a short rigid pile and the point of rotation was in the middle of the pile, and this means that the presence of bulb made the pile of the short rigid type and otherwise It becomes flexible for the same diameter and length.

Soneja and Garg [8] used a dual-expansion substrate in sandy alluvial soils, and the substrates were of different diameters and lengths, and the results indicated an increase in the bearing strength of the substrate for the lateral load with an increase in the ratio (L / D) and an increase in the diameter of the substrate as well. Suppose the L/D ratio is doubled. In terms of comparison, the percentage of increase in lateral bearing strength between the normal substrate and the expanding substrate reaches a ratio of approx. 60% if the lateral bearing strength of the single expansion substrate converged with the two expansions, and the tests also showed a remarkable increase in the expansion substrate from the normal, by up to 15%. Also, a clear effect of the expansion site where there was an increase of up to 20% in the case of expansion at the beginning of the substrate On his presence at the bottom. Polus and Davis [9] stated that in piles subjected to inclined load, the ultimate load capacity is a function of both the lateral and vertical loads' resistance. When the applied load deviates only slightly from the vertical, the failure will mainly be caused by vertical slip and the tip's failure for downward loading. As for lateral failure, it occurs when the inclination of the load is very high. The failure cases can be represented as follows:

1) Vertical failure occurs when the ultimate lateral capacity is higher than the lateral component of the ultimate inclined load, as in the equation:
\[ H_u > Q_u \sin \delta \quad \text{or} \quad H_u > P_u \tan \delta \] (1)

\( Q_u = \) Ultimate inclined load capacity of pile.  
\( H_u = \) Ultimate lateral capacity of pile.  
\( P_u = \) Ultimate axial load capacity of the pile.  
\( \delta = \) Angle of inclination of load from vertical.

2) Lateral failure occurs when the maximum lateral load is less than the horizontal net inclined load, as in the equation:
\[ H_u < P_u \tan \delta \] (2)

For clay soils, it is logical to assume that the maximum vertical load does not depend on the lateral load-bearing and vice versa as well. The following two minimum values can calculate the capacity of the tilted load:

a) For axial failure
\[ Q_u = P_u \sec \delta \] (3)

b) For lateral failure
\[ Q_u = H_u \csc \delta \] (4)

This paper will study the effect of the compound load and the lateral load on the lateral displacement and moments of normal and under-reamed piles.

2. Properties of materials used
The specifications of the materials used in the tests are divided into three sections:

2.1 Soil specifications
Two layers of soil were used in this work, the upper layer is a strong clay layer classified as (CH) 29 cm thick, and the lower layer is a dense sandy layer with a thickness of 55 cm, classified as (SP) Soil physical tests were
conducted in the laboratories of the University of Baghdad, and the soil characteristics used were as shown in Figure 1 and Table 1.

![Particle Size Distribution of Soils](image)

**Figure 1.** Particle Size Distribution of Soils.

### 2.2 Pile models

The piles used in the research are 350 mm long concrete with a compressive strength of 21 kN/m$^3$ and with four piles and contain bulbs of (0, 1, 2, 3) respectively, the pile with a diameter of 20 mm, the bulb with a diameter of 40 mm (full sphere), and the distance between two bulbs and another 60 mm as shown in Figures 2.

### Table 1. Geotechnical properties of soil used in the test.

| Test Name                  | Standard        | Soil Property            | Value          |
|----------------------------|-----------------|--------------------------|----------------|
| Specific gravity           | ASTM D-854      | Specific Gravity         | Clay 2.78      |
|                            |                 |                           | Sand 2.67      |
| Atterberg’s limits         | ASTM D-4318     | Liquid Limit (LL)         | 100            |
|                            |                 | Plastic Limit (PL)        | 46             |
|                            |                 | Plasticity Index (PI)     | 54             |
|                            |                 | Clay                      | 30%            |
|                            |                 | Silt                      | 45%            |
| Grain size analysis        | ASTM D-422      | Sand                      | 25%            |
|                            |                 | (USCS)                    | Clay (CH)      |
|                            |                 |                           | Sand (SP)      |
| Standard compaction test   | ASTM D-1557     | Optimum Moisture Content (O.M.C) | 14.27 kN/m$^3$ |
|                            |                 | Initial Void Ratio (e$_0$) | 27.5%          |
|                            |                 |                           | 0.91           |
| Unit weight of soil        | ASTM D-4253     | Maximum, $\gamma_d$, max | 17.775 kN/m$^3$ |
|                            | ASTM D-4254     | Minimum, $\gamma_d$, min | 16.32 kN/m$^3$ |
|                            |                 | Dry unit weight, $\gamma_d$, used | 17.75 kN/m$^3$ |
| Direct shear test for sand | ASTM D-3084     | Angle of internal friction, $\phi$ | 39° |
| Unconfined compression     | ASTM D-2216     | Unconfined Compressive Strength ($q_u$) kPa | 140 |
|                            |                 | Undrained Cohesion (Cu) KPa | 70 |
The dimensions of the piles were according to the Indian standard specifications, in addition to reinforcing the pile with three bars with a diameter of 2 mm and linking with a spiral iron with a distance of 5 mm and a diameter of 0.4 mm. For the purposes of pouring the concrete piles, aluminum molds were manufactured. Concrete was used with reinforcement inside the mold, and then the concrete piles were left inside the water for 28 days.

2.3 Physical model test
In this study, an iron model of dimensions 800×800×800 mm and a thickness of 6 mm was used. It rests on an iron base that rises from the ground by 30 cm. An iron frame is formed on it, carrying a loading engine with a capacity of 2 tons, connected to a load cell for reading, and then a steel tube to transport the load to the base, as shown in Figures 3. For the purposes of fixing the piles in the specified location of the soil, a steel structure has been constructed, consisting of two connected beams. The distance between them is 270 mm. Each beam contains four holes with a diameter of 21 mm, and the distance between them is 180 mm. The piles were stitched at a distance of 12.5d from the edge of the box and at a distance of 25d higher than the bottom of the box and the distance between one pile and another 9d to ensure that the stresses do not overlap among them [11,12,13].

3. Results and discussion
In this work, the tests that were performed were in three stages. The first was to check the allowable bearing capacity of the under-reamed piles according to the ASTM D-1143 with a drop rate of 1 mm per minute, through which it was possible to predict the bearing capacity of the piles for the lateral load, which is estimated at 10% of the working or allowable load. The second stage was to measure the bearing capacity of the piles for the lateral load and according to the ASTM D3966/D3966M-07 and the third stage, which is under-reamed pile loading with a compound load which is divided into three stages, the horizontal load according to the previous specification and the vertical load being (1/3, 2/3, and 3/3) respectively from the allowable load. The last two stages aim to know the maximum lateral displacement of the pile and the most significant moment in it. The tests were carried out by using four piles of 350 mm length, 290 mm of which are embedded in clay soil and 60 mm outside for vertical and lateral load purposes. The soil modeled in the model on the two layers the upper layer that contains the piles is clay, 290 mm thick and density 17.6 kN/m³ and the second layer on which the piles sit is dense sandy with a thickness of 550 mm and a density 17.5 kN/m³ A square plate of aluminum with a thickness of 22 mm

Figure 2. Dimensions (mm) and shapes of studied under-reamed piles.
and a side length was used. The 100 mm has a circular hole of 21 mm and a depth of 20 mm above the pile head from the top for loading purposes. The safety factor that was used in this research was 2.5.

![Figure 3. Experimental test setup.](image)

![Figure 4. Load settlement profile of under-reamed piles.](image)

![Figure 5. Relation between the number of the bulb and ultimate bearing capacity.](image)

The ultimate bearing capacity of the pile showed a clear difference between the normal pile and the under-reamed piles, as shown in Figures 4 and 5. It was found that there is a clear increase between the normal pile and the other piles with an increased rate ranging from 76% to 148% in addition to the increase between the pile has two bulbs, and the three reaches 15%, as shown in Table 2. This increase
is due to the presence of bulbs in the pile where it contains more than one end bearing compared to the normal pile.

| Table 2. Bearing capacity of under-reamed piles. |
|------------------------------------------------|
| Number of bulbs | 0  | 1  | 2  | 3  |
| Ultimate bearing capacity (N) | 1018 | 1795 | 2185 | 2525 |
| Allowable bearing capacity (N) | 407  | 718  | 874  | 1010 |
| Increasing % | 0  | 76  | 21  | 15  |
| Allowable lateral load 10% from Allowable Bearing Capacity (N) | 40.7 | 71.8 | 87.4 | 101 |

To measure the moments along the piles embedded in the soil, strain gages (5 mm) were used along with the piles in the soil at varying distances for the purpose of covering the complete length. It was by four strain gages. For the purpose of calculating the moments generated from the lateral load, a calibration test was carried out using a known weight load at one end of the pile and fixing the other end. The moments are calculated theoretically from knowing the length of the load arm and knowing the corresponding reading of the strain by the strain indicator, as shown in Figure:

\[
\text{Moment (N.M) = 0.01 \times (strain gage reading) - 0.0474} \tag{5}
\]

Concerning the tests related to the lateral load, it was noted that there is a noticeable difference between the normal pile and the other piles, as it was found that the combined load does not affect the normal pile as much as the lateral displacement is reduced by 8.5% in the case of allowable load applied. While the displacement Lateral in the under-reamed piles, the decrease reaches (25%) in the piles contain (1) bulb and in the last two piles (2 and 3 bulbs) the amount of the decrease is completely equal(29%), that is, the effect of increasing the bulbs goes away when the pile has more than two bulbs as shown in Figure 7.

The moments obtained from the tests also showed a clear difference between the piles, as there is a decrease of up to 10% in the case of the inclined presence than in the case where the lateral load is only. In addition to the clear effect of the presence of bulb near the surface of the soil from its presence in the middle of the pile, which is clear between the piles with two bulbs and between the three, there is a clear difference of up to about 40%, as shown in the two Figures 8 and 9. The reason is that the moment is highly dependent on the moment of inertia,
Figure 7. Relation between lateral displacement and load. A (0 bulb), B (1 Bulb), C (2 Bulbs) and D (3 Bulbs).

Figure 8. Profile of the piles moment under lateral load only.

Figure 9. Profile of the piles moment under lateral load and allowable vertical load.
Which in turn depends on the diameter of the pile. The greater the number of bulbs, the lower the moment generated by the combined load. It is clear from the preceding that there are two essential factors whose effect is clear, the first is the presence of the bulb, and the second is its location relative to the ground level. The first factor causes the presence of more than one end bearing in a pile, thus an increase in its ultimate bearing capacity, and if the bulbs exceed two, another effect appears, which is the soil confined between two bulbs, which acts as the pile work. This is in terms of ultimate bearing capacity. The second factor is the presence and location of the bulb, which in turn reduces the lateral displacement, and whenever the bulb is close to the ground level, the displacement decreases, and the moments generated decrease.

4. Conclusion

- There is a clear increase due to the presence of bulbs in the under-reamed pile than normal, and the increase reaches more than 140% in the event of three bulbs, and the increase between the pile has two and three bulbs is reduced to 15%.
- There is no significant effect between the inclined load and the horizontal load on the straight shaft pile on the lateral displacement as the displacement in the first is less by 8.5%, while in the under-reamed piles, the decrease in the single bulb reaches 25% and is fixed in a pile has 2 or 3 bulbs to 29%.
- There is a clear effect on the presence of bulbs in a pile on the moments generated by the lateral and inclined load. As the number of bulbs increases, the moment for the same applied load decreases, and as the bulb approaches the soil surface, the moments decrease by a large percentage of up to 30%, and this is clear between the piles have 2 and 3 bulbs.

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