Laboratory Study of Lateral Load Capacity and Behaviour of Short Piles in Clayey Soil.

Hijran Aboud Aljanabi¹, Jafar Bolouri Bazaz ²

¹ Hijran Aboud Aljanabi / M.Sc. Geotechnical Engineering – Civil Engineering, Directorate of Kerbala Water, Iraq.
² Corresponding Author, Jafar Bolouri Bazaz / Associate Professor, Civil Engineering Department, Ferdowsi University of Mashhad, Iran.
Email Address: bolouri@um.ac.ir

Abstract This research is an experimental study investigating the lateral loading capacity of piles in clayey soil. Important factors considered in this study included pile diameter, embedded length of pile, effective unit weight, and degree of saturation of soil, which were studied for their effects on the lateral loading capacity of short driven piles. The experimental study involved testing six specimens in the laboratory, each made of galvanized iron of 21.7 and 27 mm diameter and L/d (embedded length/diameter) ratios of 10, 14, and 18. The specimens were subjected to lateral loadings while embedded in clayey soil with effective unit weights of 13, 15, and 15.6 kN/m³ and degrees of saturation of 30, 41 and 97%, to simulate true pile behaviour. The obtained pile responses were then plotted as force-displacement diagrams. The varying parameters were thus diameter and embedded depth of pile, effective unit weight, and degree of soil saturation. The results of this experimental study on the behaviours of the piles under the influence of lateral loading in the clay were also compared with the predicted lateral capacity of the piles based on work by other researchers. Moisture content and degree of saturation were found to have the greatest effects on pile behaviour. This study thus aids understanding of the behaviours of short piles embedded in clayey soil under lateral loading to allow designers to take practical steps and choose an appropriate method when designing a pile.

Keywords: short piles, clayey soil, driven piles, lateral load capacity, experimental study.

1. Introduction

Piles are the primary and most important supporting structures under vertical loads such as pressure resulting from the live and dead weights on installations. However, such vertical loads are often accompanied by lateral loads that affect the behaviour of such structures, and almost all types of pile foundation are exposed to lateral loads [1-14]. Indeed, in many cases, the lateral loads, have a greater impact than the vertical, particularly in the case of buildings exposed to water waves and flooding such as coastal buildings and those which are exposed to wind such as billboards and establishments located in areas under the influence of earthquakes. Lateral loads and moments are generally caused by structure shape, soil pressure, wind, or earthquakes. Testing the lateral bearing capacity of piles is thus necessary to help understand and explain the expected behaviours of the...
piles bases of a given structure, particularly in such environments. According to studies conducted by previous researchers, the parameters that affect the lateral load capacity of the piles include the shape, type, diameter, length, specific weight, bulk unit weight of piles, soil density, and degree of soil saturation as well as the degree of pile roughness [1]. Many theories have been suggested to predict and calculate the lateral bearing capacity of piles in cohesive soils, including those by Machmer [2], Hansen [9], Broms [4], Meyerhof et al [11], Budhu and Davies [7]. All piles which are liable to horizontal force are usually divided into two divisions, short and long, and these analysis methods are generally based on ultimate bearing capacity and allowable horizontal displacement for short and long piles, and they all depend on soil pressure, assuming that the pressure is distributed along the pile. In practice, the Broms method has become the most popular, as it is simple and usable for both long and short piles [4-5]. The bearing capacity of long piles depends on the strength of pile, while for short piles, it depends on the resistance of the soil. The behaviour of free-head short piles under lateral forces can also be modelled as a rigid body rotating around a centre of rotation as seen in Figure 1 [1].

2. Study Aim

There have been many complex theories for estimating the ultimate lateral bearing capacity of pile loads proposed by various researchers [1-9]. In many cases, the load bearing capacity of shallow foundations of exposed loads is insufficient, and the use of deep foundations or piles is required as a more practical approach. Many practical and laboratory studies on the behaviour of both types of piles in non-cohesive soils have been previously conducted by researchers. However, studies on the behaviour of such foundations in clayey soils are fewer in number due to the sensitivity of clayey soil and the effects on its behaviour of several key factors, including the degree of saturation. In this study, the effect of several of these factors and parameters is taken into account with regard to short piles’ behaviours under lateral loads based on laboratory testing to better understand these behaviours and the effects of changing several factors on lateral load capacity. Laboratory tests were used to estimate the lateral bearing capacity and behaviour of piles under horizontal loads, as well as to examine the force-displacement relationship, the point of rotation and the effect of parameters such as effective unit weight, degree of saturation of soil, and the length and diameter of piles.

![Figure 1. Short vertical pile under horizontal load (a) Free pile head and (b) Fixed pile head [2].](image)

3. Criteria of Pile Behaviour

The failure mechanism of short piles under lateral loads depends entirely on the length of the pile, the load bearing capacity, the type of soil, and the boundary condition of the pile head (fixed or free), as seen in Table 1. Short piles under a lateral load act as rigid bodies and they will rotate around a rotation centre,
while long piles bend under lateral loads. Short rigid piles and long flexible pile behaviours thus depend on the relative stiffness of the pile–soil system. Table 1 outlines the various criteria normally adopted to classify flexible and rigid pile behaviours [3].

**Table 1. Criteria for classification of pile behaviour**

| No. | Source | Rigid behaviour Criterion | Flexible behaviour Criterion |
|-----|--------|---------------------------|-----------------------------|
| 1   | [4, 5] | L/R ≤ 2                   | L/R ≥ 4                     |
| 2   | [1]    | Kr > 10^2                 | Kr < 10^2                   |
| 3   | [6]    | SH < 5                    | SH > 5                      |
| 4   | [7]    | L < 1.5BE^0.36            | L > 1.5BE^0.36              |
| 5   | [8]    | L < Lc/3                  | L > Lc                      |

Where

\[ R = (EI / k)^{0.25} \]  
\[ Kr = (EI / E_sB^4) \]  
\[ SH = (L / B) / (E / E_s)^{0.25} \]  
\[ K = (E / E_s) \]  
\[ Lc = 4.44(EI / E_s)^{0.25} \]  
\[ k = E_s / (1 - \mu_s^2) \]

**Note:** L is pile length (m), B is pile diameter (m), E_p is pile elastic modulus (kPa), I_p is pile moment of inertia (m^4), E_s is the elastic modulus of soil (kPa), R is the characteristic length, \( \mu_s \) is the Poisson’s ratio, k is the coefficient of subgrade reaction, L_c is the critical pile length, K is the stiffness ratio, and SH and Kr are flexibility factors.

### 4. Theoretical methods of calculating lateral load capacity for short piles

The Brinch Hansen method is used to estimate the ultimate lateral resistance of short rigid piles as it is a simple method that can be applied both to uniform and layered soils, as well as being well suited to spreadsheet calculations. Rigid pile rotation about the centre of rotation point is given by the sum of the moments of the soil resistance above and below this point [9]:

\[ P_{ux} = \sigma'_{z} K_q + c K_c \]  

Where \( P_{ux} \) = ultimate lateral resistance, \( \sigma'_{z} \) = the effective overburden pressure at depth \( z \), \( c \) = the cohesion of the soil at depth \( z \), and \( K_q \) and \( K_c \) are the passive pressure coefficients for the frictional and cohesive components, respectively, at depth \( z \), with \( K_q = 0 \) for clay soil. The established value of, \( K_c \), is dependent on the depth, \( z \), and the width of the pile, B, in the direction of rotation, as shown in Figure 2. The Broms method for determining the lateral resistance of vertical piles has the same basic mechanism outlined above. In the case of a short pile and cohesive soil, the amount of lateral resistance from soil on the pile from the soil surface to a depth 1.5B is equal to zero [4, 5]. Broms’s solution for calculating the ultimate load resistance for short piles embedded in cohesive soil is given in Figure 3.

\[ P = 9CuD \]  

Meyerhof’s method is proposed to estimate the ultimate lateral load capacity of a pile in clay and sand soil [10], as seen in Figure 4, based on experiments and a theoretical method, based on the estimate of the bearing capacity of pile or a retaining wall [11].
\[ Qu = (0.12 \gamma L K_{br} + 0.4 c K_{cr}) DL < Q_{nl} \]  
(9)

\[ Q_{nl} = 0.4 P_{1} L D \]  
(10)

For clay soil  
\[ P_{1} = c N_{c} \]  
(11)

For drilled piles,  \( N_{c} = 6 \), and for bored piles,  \( N_{c} = 8 \) [12]. Values of  \( K_{cr} \) can be found in figure (4).

![Figure 2. The Brinch Hansen coefficients \( K_{c} \) [9].](image)

![Figure 3. Ultimate lateral load capacity of short pile in cohesive soils [4].](image)

![Figure 4. Lateral soil pressure coefficients for rigid piles under ultimate load in clay soil [10].](image)

The Budhu and Davis method describes the behaviour of piles under lateral load in soft clay [13]. This method is based on the undrained shear strength of the soil, and the ultimate lateral capacity is obtained by means of a simple equation:

\[ \frac{P_{u}}{(C_{u} D L^{2})} = \frac{1.2}{(\frac{D}{L})^{1.8} + 0.88} \]  
(12)

5. Equipment and Materials

This research work aimed to understand the behaviour of piles under static lateral loads, and also to measure horizontal displacement for piles embed in clay with different densities at the soil surface. Accordingly, controlled tests were carried out in a laboratory using an experimental apparatus designed for this purpose. Details of the scale model, equipment and materials used in this research are described in the following sections.

A. Soil

The sample of clayey soil used in the laboratory tests was brought from Nishapur city (Iran). A laboratory unconfined compression test was used to determine the un-drained shear strength of the clay as seen in Table 2, shows a summary of the properties of the clay. As seen in Figure 5 (plasticity chart), the soil is
classified as clay (CL). Distribution of grain size was determined by sieve and hydrometer analysis as shown in Figure 6, and the Atterberg limits and the specific gravity of the clay were also determined.

![Figure 5. Plasticity chart](image1)

![Figure 6. Nishapur Clay soil grain size distribution](image2)

B. Pile

Close-ended galvanized pipes were used as piles for these experimental tests. The outer diameters of the pipes were 21.7 and 27 mm, and the wall thickness was 2.4 mm. The length to diameter ratios (L/D) of piles were 10, 14, and 18. The length was varied to investigate short rigid pile behaviour as affected by the relative stiffness of the soil–pile system. Tensile tests were carried out on these pipes, and the results are shown in table 3.

C. Experimental Setup

The dimension of the test facility was based on the effective stress zone of soil mass around the pile. The lateral stress was distributed in the soil behind the pile when a pile was subjected to lateral loading, and the soil was placed in a tank with diameter 10 times the diameter of the pile in the direction of loading, as recommended by previous research works [1, 15]. The reservoir was a plastic tank with a diameter of 570 mm and a height of 600 mm, as seen in Figure 5. The static lateral load was applied by means of a dead weight placed on a hanger connected to a flexible steel wire strung over a pulley supported by a loading steel frame. After the tank was filled with clay, a thin wire was connected to the pile with a dial gauge to measure the horizontal displacement. To obtain a uniform density, the clay was compacted in 10 cm layers, then the pile was inserted into the clay. Lateral loading was then applied according to ASTM-D3699-07 [16]. A dial gauge was used to measure the horizontal movement of the pile during the horizontal load application at the top surface of clay as shown in Figures 5 and 6. Each of tests was defined with a code of the form "Ga-D-L", where "Ga" indicates that the substance of the pile is galvanized while "D" and "L" represent the outer diameter (mm) and embedment length (mm) of the pile, respectively; thus, "Ga - D27 - L270" indicates that the pile is galvanized with a 27 mm outer diameter and embedment length of 270 mm.
Figure 7. Setup of model tests.  
Figure 8. Model Plan pile lateral load test setup.

### Table 2. Properties of Clay

| Tests                              | Value  | Standards               |
|------------------------------------|--------|-------------------------|
| Natural water content ($\omega$) (%)| 12.25  | ASTM D4959-05[17]       |
| Bulk unit weight ($\gamma_{bulk}$) (kN/m$^3$)| 19.8   | BS-E1377-[15]           |
| Atterberg limits                   |        |                         |
| Liquid limit (L.L) (%)             | 44.73  |                         |
| Plastic limit (P.L) (%)            | 18.57  | ASTM D431-10[18]        |
| Plasticity index (P.I) (%)         | 26.16  |                         |
| Sieve analysis                     |        |                         |
| Wet method (Soil passed from sieve NO. 200) (%)| 86     | ASTM-C117-03[19]       |
| Hydrometer method (particles smaller than 2 microns) (%)| 27     | ASTM D7928-[17]        |
| Specific Gravity (Gs)              | 2.67   | ASTM D854-92[20]        |
| Standard Proctor test              |        |                         |
| Optimum water content ($\omega$) (%)| 15.9   | ASTM D698-E12-07[21]    |
| Dry unit weight ($\gamma_{dry}$) (kN/m$^3$)| 17.78  |                        |
| Unconfined Compression test        |        |                         |
| $Cu$ (kN/m$^2$)                    | 26     | ASTM-D2166-98[22]      |
| Soil type                          | CL     | Unified Classification  |

### Table 3. Piles characteristics according Bazaz and Keshavarz [14]

| NO | Outside diameter (mm) | Wall thickness (mm) | weight (kg/m) | Young's modulus (GPa) | Tensile strength (MPa) |
|----|-----------------------|---------------------|---------------|-----------------------|------------------------|
| 1  | 21.7                  | 2.4                 | 1             | 196                   | 311                    |
| 2  | 27                    | 2.4                 | 1.3           | 196                   | 311                    |
6. Test Results and Discussion

The laboratory test results indicated that the behaviour of all piles was that of short piles. The ultimate bearing capacity of all tested piles were estimated according Hansen, Broms [5], Meyerhof et al. [11] and Budhu and Davis [13], with the ultimate lateral load capacity defined as the lateral load generating lateral displacement of 20% of the pile diameter at the head of the pile [4, 5].

The ultimate bearing capacities of piles with diameters of 21.7 and 27 mm in clayey soil with $\gamma_d$ of 15.6 (kN/m$^3$) and degree of saturation of 97% are shown in Table 5, while the predictions obtained from different theories are shown in Table 6. The ultimate lateral capacity obtained from the laboratory tests is also specified on the force-displacement curves that for comparison and better understanding of the laboratory test results (Figures 10 and 11).

| No. | Pile code | Diameter, $D$ (mm) | Embedded length, $L$ (mm) | L/D Ratio |
|-----|-----------|--------------------|--------------------------|-----------|
| 1   | Ga – D21.7 – L 217 | 21.7               | 217                      | 10        |
| 2   | Ga – D21.7 – L 304 | 21.7               | 304                      | 14        |
| 3   | Ga – D21.7 – L 391 | 21.7               | 391                      | 18        |
| 4   | Ga – D27 – L 270  | 27                 | 270                      | 10        |
| 5   | Ga – D27 – L 378  | 27                 | 378                      | 14        |
| 6   | Ga – D27 – L 486  | 27                 | 486                      | 18        |

Table 5. State of clay

| Z states | Water content $(\omega)$ % | Dry unit weight $(\gamma_d)$ (kN/m$^3$) | Degree of saturation $(S)$ % |
|----------|---------------------------|----------------------------------------|----------------------------|
| 1        | $12 \pm 0.5$              | $13 \pm 0.2$                           | 30                        |
| 2        | $12 \pm 0.5$              | $15 \pm 0.2$                           | 41                        |
| 3        | $25 \pm 0.5$              | $15.6 \pm 0.2$                         | 97                        |

Table 6. Estimated lateral bearing capacity

| Pile code     | L (m) | Hansen 1961 | Broms 1964 | Meyerhof 1985 | Budhu 1988 | 20% $D$ (Test) |
|---------------|-------|-------------|------------|---------------|------------|----------------|
| Ga – D21.7 – L 217 | 0.217 | 118         | 129        | 113           | 40         | 42             |
| Ga – D21.7 – L 304 | 0.304 | 225         | 247        | 167           | 71         | 80             |
| Ga – D21.7 – L 391 | 0.391 | 334         | 391        | 224           | 117        | 136            |
| Ga – D27 – L 270  | 0.27  | 210         | 265        | 175           | 70         | 72             |
| Ga – D27 – L 378  | 0.378 | 365         | 480        | 253           | 136        | 140            |
| Ga – D27 – L 486  | 0.486 | 432         | 670        | 346           | 198        | 196            |
**Figure 9.** Force - Displacement curves in soil surface for pipes with 21.7mm diameter.

**Figure 10.** Force - Displacement curves in soil surface for pipes with 27mm diameter.
7. Conclusion

1. Increasing the diameter and length of the pile increases the bearing capacity of the pile. However, increasing length is more effective than increasing diameter in terms of lateral bearing capacity.

2. Variation in the degree of soil saturation, along with variation in pile length and diameter, has a significant effect on the lateral bearing capacity of short piles.

3. The lateral bearing capacity of short piles in equals 97% saturated clay reaches its lowest value.

4. The depth of rotation point of a pile depends on the embedded length of the pile and the dry unit weight.

5. Lateral bearing capacity of a pile decreases with the increase of saturation degree when clay soil has a constant dry unit weight.

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3rd International Conference on Engineering Sciences

IOP Conf. Series: Materials Science and Engineering 671 (2020) 012120
doi:10.1088/1757-899X/671/1/012120

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