Pile Foundations

CIVL 451 – Foundation Engineering – Classroom Notes
Geotechnical Design of Pile Foundations

- Types of pile foundations
- Load transfer mechanisms
- Single pile geotechnical design,
  - Clay,
  - Sand,
  - Rock socket
Types of Pile Foundations

- Axial and lateral Loads are transferred from weak strata to deeper stronger layers via:
  - Skin friction
  - Socket friction
  - Base resistance
Types of Pile Foundations

• Various types are available which can be classified in terms of the construction (installation) methodology, materials and load transfer mechanism. The main classification can be carried out based on the former;
  – Replacement Piles (the ground is drilled or excavated and replaced by pile materials):
    • Bored and cast-insitu (concrete) piles; reinforced concrete piles, continuous flight auger piles (CFA), grouted piles, franki piles, piles by deep soil mixing.
  – Displacement Piles (the ground is displaced during pile installation):
    • All Driven piles such as; timber piles, steel piles, hollow tubular piles or caissons, pre-cast reinforced concrete piles.
Types of Pile Foundations

• Concrete pile types;

![Diagram of various concrete pile types](image)

*Figure 11.4 Cast-in-place concrete piles*
Load transfer mechanism for Pile Foundations

• Piles are also classified in accordance with the load transfer mechanism such as; Floating Piles or Friction Piles and End-bearing or Point bearing piles.

\[ Q_u = Q_p + Q_s \]

• If the total pile capacity is significantly comprised of skin friction then the pile is classified as Friction piles.

*Figure 11.6* (a) and (b) Point bearing piles; (c) friction piles
Load transfer mechanism for Pile Foundations

Axial Load transfer with depth in a friction pile.

Variation of friction around the Pile with depth.

Vesic’s pile end bearing capacity.
Bearing Capacity of Pile Foundations

- Total bearing capacity = Skin friction + Point bearing resistance
- Skin friction resistance (general expression)

\[ Q_s = \Sigma p \Delta L f \]

where

- \( p \) = perimeter of the pile section
- \( \Delta L \) = incremental pile length over which \( p \) and \( f \) are taken to be constant
- \( f \) = unit friction resistance at any depth \( z \)

- Point bearing resistance (general expression for drained soils)

\[ Q_p = A_p q_p = A_p (c' N_c^* + q' N_q^*) \]

where

- \( A_p \) = area of pile tip
- \( c' \) = cohesion of the soil supporting the pile tip
- \( q_p \) = unit point resistance
- \( q' \) = effective vertical stress at the level of the pile tip
- \( N_c^*, N_q^* \) = the bearing capacity factors
Bearing Capacity of Pile Foundations

- SAND (or granular soils in general)
- Skin friction

Figure 11.16 Unit frictional resistance for piles in sand

\[ Q_s = \sum p \Delta L f \]

For \( z = 0 \) to \( L' \),

\[ f = K \sigma_o' \tan \delta' \]

and for \( z = L' \) to \( L \),

\[ f = f_{z=L'} \]

In these equations,

- \( K \) = effective earth pressure coefficient
- \( \sigma_o' \) = effective vertical stress at the depth under consideration
- \( \delta' \) = soil-pile friction angle

<table>
<thead>
<tr>
<th>Pile type</th>
<th>( K )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bored or jetted</td>
<td>( \approx K_o = 1 - \sin \phi' )</td>
</tr>
<tr>
<td>Low-displacement driven</td>
<td>( \approx K_o = 1 - \sin \phi' ) to ( 1.4K_o = 1.4(1 - \sin \phi') )</td>
</tr>
<tr>
<td>High-displacement driven</td>
<td>( \approx K_o = 1 - \sin \phi' ) to ( 1.8K_o = 1.8(1 - \sin \phi') )</td>
</tr>
</tbody>
</table>

H-piles: \( K = 1.65 \)

Steel pipe piles: \( K = 1.26 \)

Precast concrete piles: \( K = 1.5 \)
Bearing Capacity of Pile Foundations

- **SAND** (or granular soils in general)
- **End bearing**

---

**Table 11.5** Interpolated Values of $N_c^*$ Based on Meyerhof’s Theory

<table>
<thead>
<tr>
<th>Soil friction angle, $\phi$ (deg)</th>
<th>$N_c^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>12.4</td>
</tr>
<tr>
<td>21</td>
<td>13.8</td>
</tr>
<tr>
<td>22</td>
<td>15.5</td>
</tr>
<tr>
<td>23</td>
<td>17.9</td>
</tr>
<tr>
<td>24</td>
<td>21.4</td>
</tr>
<tr>
<td>25</td>
<td>26.0</td>
</tr>
<tr>
<td>26</td>
<td>29.5</td>
</tr>
<tr>
<td>27</td>
<td>34.0</td>
</tr>
<tr>
<td>28</td>
<td>39.7</td>
</tr>
<tr>
<td>29</td>
<td>46.5</td>
</tr>
<tr>
<td>30</td>
<td>56.7</td>
</tr>
<tr>
<td>31</td>
<td>68.2</td>
</tr>
<tr>
<td>32</td>
<td>81.0</td>
</tr>
<tr>
<td>33</td>
<td>96.0</td>
</tr>
<tr>
<td>34</td>
<td>115.0</td>
</tr>
<tr>
<td>35</td>
<td>143.0</td>
</tr>
<tr>
<td>36</td>
<td>168.0</td>
</tr>
<tr>
<td>37</td>
<td>194.0</td>
</tr>
<tr>
<td>38</td>
<td>231.0</td>
</tr>
<tr>
<td>39</td>
<td>276.0</td>
</tr>
<tr>
<td>40</td>
<td>346.0</td>
</tr>
<tr>
<td>41</td>
<td>420.0</td>
</tr>
<tr>
<td>42</td>
<td>525.0</td>
</tr>
<tr>
<td>43</td>
<td>650.0</td>
</tr>
<tr>
<td>44</td>
<td>780.0</td>
</tr>
<tr>
<td>45</td>
<td>930.0</td>
</tr>
</tbody>
</table>

**Table 11.8** Variation of $N_c^*$ with $I_r$ for $\phi = 0$ Condition based on Vesic’s Theory

<table>
<thead>
<tr>
<th>$I_r$</th>
<th>$N_c^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>6.97</td>
</tr>
<tr>
<td>20</td>
<td>7.90</td>
</tr>
<tr>
<td>40</td>
<td>8.82</td>
</tr>
<tr>
<td>60</td>
<td>9.36</td>
</tr>
<tr>
<td>80</td>
<td>9.75</td>
</tr>
<tr>
<td>100</td>
<td>10.04</td>
</tr>
<tr>
<td>200</td>
<td>10.97</td>
</tr>
<tr>
<td>300</td>
<td>11.51</td>
</tr>
<tr>
<td>400</td>
<td>11.89</td>
</tr>
<tr>
<td>500</td>
<td>12.19</td>
</tr>
</tbody>
</table>

\[
Q_p = A_p q_p = A_p (c' N_c^* + q' N_q^*)
\]

**Figure 11.12** Nature of variation of unit point resistance in a homogeneous sand

\[
I_r = 347 \left( \frac{c_u}{P_a} \right) - 33 \leq 300
\]

---

*Unit point resistance, $q_p$*

*(UD = L_b / D)*

*Note: $P_a$ = atmospheric pressure ≈ 100 kN/m² or 2000 lb/ft².*

The preceding values can be approximated as
Bearing Capacity of Pile Foundations

- CLAY (or cohesive soils in general)
- Skin friction

\[ f = \alpha c_u \]

**Table 11.10** Variation of \( \alpha \) (interpolated values based on Terzaghi, Peck and Mesri, 1996)

<table>
<thead>
<tr>
<th>( \frac{c_u}{p_a} )</th>
<th>( \alpha )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \leq 0.1 )</td>
<td>1.00</td>
</tr>
<tr>
<td>0.2</td>
<td>0.92</td>
</tr>
<tr>
<td>0.3</td>
<td>0.82</td>
</tr>
<tr>
<td>0.4</td>
<td>0.74</td>
</tr>
<tr>
<td>0.6</td>
<td>0.62</td>
</tr>
<tr>
<td>0.8</td>
<td>0.54</td>
</tr>
<tr>
<td>1.0</td>
<td>0.48</td>
</tr>
<tr>
<td>1.2</td>
<td>0.42</td>
</tr>
<tr>
<td>1.4</td>
<td>0.40</td>
</tr>
<tr>
<td>1.6</td>
<td>0.38</td>
</tr>
<tr>
<td>1.8</td>
<td>0.36</td>
</tr>
<tr>
<td>2.0</td>
<td>0.35</td>
</tr>
<tr>
<td>2.4</td>
<td>0.34</td>
</tr>
<tr>
<td>2.8</td>
<td>0.34</td>
</tr>
</tbody>
</table>

Undrained cohesion. Sladen (1992) has shown that

\[ \alpha = C \left( \frac{\bar{\sigma}_o'}{c_u} \right)^{0.45} \]

where

- \( \bar{\sigma}_o' \) = average vertical effective stress
- \( C \approx 0.4 \) to 0.5 for bored piles and \( \geq 0.5 \) for driven piles

The ultimate side resistance can thus be given as

\[ Q_s = \Sigma f_p \Delta L = \Sigma \alpha c_u p \Delta L \]

*Note: \( p_a \) = atmospheric pressure

\( \approx 100 \text{ kN/m}^2 \) or 2000 lb/ft\(^2\)
Bearing Capacity of Pile Foundations

- CLAY (or cohesive soils in general)
- End bearing

\[ Q_p \approx N_c c_u A_p = 9c_u A_p \]
Excercises

Example 11.1
Consider a 15-m long concrete pile with a cross section of 0.45 m × 0.45 m fully embedded in sand. For the sand, given: unit weight, \( \gamma = 17 \text{kN/m}^3 \); and soil friction angle, \( \phi' = 35^\circ \). Estimate the ultimate point \( Q_p \) with each of the following:

Example 11.2
Consider a pipe pile (flat driving point—see Figure 11.2d) having an outside diameter of 406 mm. The embedded length of the pile in layered saturated clay is 30 m. The following are the details of the subsoil:

<table>
<thead>
<tr>
<th>Depth from ground surface (m)</th>
<th>Saturated unit weight, ( \gamma ) (kN/m(^3))</th>
<th>( c_u ) (kN/m(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–5</td>
<td>18</td>
<td>30</td>
</tr>
<tr>
<td>5–10</td>
<td>18</td>
<td>30</td>
</tr>
<tr>
<td>10–30</td>
<td>19.6</td>
<td>100</td>
</tr>
</tbody>
</table>

The groundwater table is located at a depth of 5 m from the ground surface. Estimate \( Q_p \) by using
Excercises

Example 11.7

Refer to the pile in saturated clay shown in Figure 11.22. For the pile,

a. Calculate the skin resistance \((Q_s)\) by (1) the \(\alpha\) method, (2) the \(\lambda\) method, and (3) the \(\beta\) method. For the \(\beta\) method, use \(\phi'_R = 30^\circ\) for all clay layers. The top 10 m of clay is normally consolidated. The bottom clay layer has an OCR = 2. (Note: diameter of pile = 406 mm)

b. Using the results of Example 11.2, estimate the allowable pile capacity \((Q_{all})\). Use FS = 4.

---

**Diagram:**

- Saturated clay
  - \(c_u(1) = 30\, \text{kN/m}^2\)
  - \(\gamma = 18\, \text{kN/m}^3\)
- Groundwater
- Clay table
  - \(c_u(1) = 30\, \text{kN/m}^2\)
  - \(\gamma = 18\, \text{kN/m}^3\)
- Clay
  - \(c_u(2) = 100\, \text{kN/m}^2\)
  - \(\gamma_{sat} = 19.6\, \text{kN/m}^3\)
Example 11.8

A concrete pile 305 mm × 305 mm in cross section is driven to a depth of 20 m below the ground surface in a saturated clay soil. A summary of the variation of frictional resistance \( f_c \) obtained from a cone penetration test is as follows:

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Friction resistance, ( f_c ) (kg/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–6</td>
<td>0.35</td>
</tr>
<tr>
<td>6–12</td>
<td>0.56</td>
</tr>
<tr>
<td>12–20</td>
<td>0.72</td>
</tr>
</tbody>
</table>

Estimate the frictional resistance \( Q_f \) for the pile.

Solution

We can prepare the following table:

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>( f_c ) (kN/m²)</th>
<th>( \alpha' ) (Figure 11.21)</th>
<th>( \Delta L ) (m)</th>
<th>( \alpha'f_c p(\Delta L) ) [Eq. (11.63)] (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–6</td>
<td>34.34</td>
<td>0.84</td>
<td>6</td>
<td>211.5</td>
</tr>
<tr>
<td>6–12</td>
<td>54.94</td>
<td>0.71</td>
<td>6</td>
<td>285.5</td>
</tr>
<tr>
<td>12–20</td>
<td>70.63</td>
<td>0.63</td>
<td>8</td>
<td>434.2</td>
</tr>
</tbody>
</table>

(Note: \( p = (4)(0.305) = 1.22 \) m)

Thus,

\[
Q_f = \sum \alpha' f_c p(\Delta L) = 931 \text{ kN}
\]
Pile Settlement under Axial Loading

• Full Scale Testing of Pile Performance (Pile Load Tests, Static Load Tests)
  – **Preliminary Pile Tests**: carried out prior to geotechnical design, results analysed to be used in the design. Usually carried out for various diameter and lengths, also installation methods may be varied to achieve best performance. The maximum test load is chosen to be near or at ultimate capacity as far as it could be calculated in preliminary calculations.

  – **Design Verification Tests**: carried out prior to and/or during construction stage to verify the pile installation method and pile performance. The results are used as part of pile acceptability assessments. The maximum test load is optional however usually up to 1.5 to 2.0 times the serviceability loads. Usually the maximum test load equals to the Design Verification Load, which is accompanied by a settlement tolerance dictated in the design.

  – Pile Load Tests (PLT) or Static Load Tests are regarded as destructive tests, hence the test piles are not part of the foundation system. PLT are carried out as Maintained Load Tests, in which the pile is loaded with stepped increments of typically 25% of the maximum test load, with a waiting period at each load step to account for time dependent response of the pile to the applied load.
Pile Settlement under Axial Loading

- Method of Load Application in a PLT
  - Kentledge System: in this method a set of dead weights are applied on the pile head and the corresponding settlement is measured.

Pile Settlement under Axial Loading

- Method of Load Application in a PLT
  - Kentledge System: continued.
Pile Settlement under Axial Loading

- **Method of Load Application in a PLT**
  
  - Reaction Pile System: extra piles or anchors are installed around the test pile to provide reaction against the load applied to the test pile.
Pile Settlement under Axial Loading

• Method of Load Application in a PLT
  – Anchor System:

Source: https://www.baw.de/content/files/projekte/poster/0/pfahlprobebelastungen_3.jpg
Pile Integrity

• Non-destructive Testing of Pile Construction Performance
  – **Sonic Echo Integrity testing:** all piles installed can be tested with ease using this method which involves hitting pile head with a hammer and measuring the reflection of stress waves down the pile using a sensor placed on pile head. Significant defects can be detected from the analysis of the wave data.

Source: [http://www.esg.co.uk/media/28649/PIT-testing-2.jpg](http://www.esg.co.uk/media/28649/PIT-testing-2.jpg)

Source: [http://www.geotech-indonesia.com/image/product/pit03.jpg](http://www.geotech-indonesia.com/image/product/pit03.jpg)

*The output of PIT is a graph of the velocity signal versus pile length as shown above. Piles with flawless shafts show a reflection from the pile toe as in the auger cast-in-place pile example above (top). Defective piles show early reflections from the damage location as in the bottom portion of the figure above. As a rule of thumb, toe reflections should be observed with embeds less than 30 diameters.*

Source: [http://www.geotech-indonesia.com/image/product/pit03.jpg](http://www.geotech-indonesia.com/image/product/pit03.jpg)
Pile Integrity

- Non-destructive Testing of Pile Construction Performance
  - **Single or Crosshole Logging Integrity testing:** the test piles are selected from the working piles, not all piles can be tested, a pre-installed pile/tube access is present in pile bore for a movable geo-phone which is sunk in the pile to detect the waves generated. A continuous profile of the reflected waves across the pile section can be obtained. The test can also be carried out in two access tubes through the pile for better accuracy.
Pile Settlement under Axial Loading

- Pile Settlement has two components for bored and cast-in-place piles:
  - Elastic Compression of the Pile itself and,
  - Settlement due to ground displacement during mobilisation of pile resistance. This component is further divided into two as; displacement along the pile shaft and displacement at pile tip.

\[
S_e = S_e(1) + S_e(2) + S_e(3)
\]

- \(S_e(1)\) = elastic settlement of pile
- \(S_e(2)\) = settlement of pile caused by the load at the pile tip
- \(S_e(3)\) = settlement of pile caused by the load transmitted along the pile shaft

\[
S_e(1) = \frac{(Q_{wp} + \xi Q_{ws})L}{A_p E_p}
\]

\(Q_{wp}\) = load carried at the pile point under working load condition
\(Q_{ws}\) = load carried by frictional (skin) resistance under working load condition
\(A_p\) = area of cross section of pile
\(L\) = length of pile
\(E_p\) = modulus of elasticity of the pile material

\(\xi\) varies between 0.5 and 0.67

\[
S_e(2) = \frac{q_{wp}D}{E_s} (1 - \mu_s^2) I_{wp}
\]

\(q_{wp}\) = point load per unit area at the pile point = \(Q_{wp}/A_p\)
\(E_s\) = modulus of elasticity of soil at or below the pile point
\(\mu_s\) = Poisson’s ratio of soil
\(I_{wp}\) = influence factor = 0.85

\[
S_e(3) = \left(\frac{Q_{ws}}{pL}\right) \frac{D}{E_s} (1 - \mu_s^2) I_{ws}
\]

\(p\) = perimeter of the pile
\(L\) = embedded length of pile
\(I_{ws}\) = influence factor

\[
I_{ws} = 2 + 0.35 \sqrt{\frac{L}{D}}
\]
Exercises

Example 11.10

The allowable working load on a prestressed concrete pile 21-m long that has been driven into sand is 502 kN. The pile is octagonal in shape with $D = 356$ mm (see Table 11.3a). Skin resistance carries 350 kN of the allowable load, and point bearing carries the rest. Use $E_p = 21 \times 10^6$ kN/m$^2$, $E_s = 25 \times 10^3$ kN/m$^2$, $\mu_s = 0.35$, and $\xi = 0.62$. Determine the settlement of the pile.

11.12 A concrete pile is 18 m long and has a cross section of 0.406 m $\times$ 0.406 m. The pile is embedded in a sand having $\gamma = 16$ kN/m$^3$ and $\phi' = 37^\circ$. The allowable working load is 900 kN. If 600 kN are contributed by the frictional resistance and 300 kN are from the point load, determine the elastic settlement of the pile. Given: $E_p = 2.1 \times 10^6$ kN/m$^2$, $E_s = 30 \times 10^3$ kN/m$^2$, $\mu_s = 0.38$, and $\xi = 0.57$ [Eq. (11.73)].

11.13 Solve Problem 11.12 with the following: length of pile = 15 m, pile cross section = 0.305 m $\times$ 0.305 m, allowable working load = 338 kN, contribution of frictional resistance to working load = 280 kN, $E_p = 21 \times 10^6$ kN/m$^2$, $E_s = 30,000$ kN/m$^2$, $\mu_s = 0.3$, and $\xi = 0.62$ [Eq. (11.73)]