Chapter 9: Pile Foundations

Introduction

Piles are structural members that are made of steel, concrete, or timber. They are used to build pile foundations, which are deep and which cost more than shallow foundations (See Chapters 4, 5, and 6). Despite the cost, the use of piles often is necessary to ensure structural safety. The following figure identifies some of the conditions that require pile foundations:

Figure 9.1 Conditions that require the use of pile foundations
Types of Piles and Their Structural Characteristics

(1) Steel Piles
Steel piles generally are either pipe piles or rolled steel H-section piles.

\[ Q_{\text{all}} = A_s f_s \]

where

\[ A_s = \text{cross-sectional area of the steel} \]
\[ f_s = \text{allowable stress of steel (≈0.33–0.5 f_y)} \]

Here are some general facts about steel piles:
- Usual length: 15 m to 60 m (50 ft to 200 ft)
- Usual load: 300 kN to 1200 kN (67 kip to 265 kip)
Concrete piles may be divided into two basic categories: (a) precast piles and (b) cast-in-situ piles. Some general facts about concrete piles are as follows:

- Usual length: 10 m to 15 m (30 ft to 50 ft)
- Usual load: 300 kN to 3000 kN (67 kip to 675 kip)
Timber piles are tree trunks that have had their branches and bark carefully trimmed off. The maximum length of most timber piles is 10 to 20 m (30 to 65 ft). To qualify for use as a pile, the timber should be straight, sound, and without any defects.

\[ Q_{\text{all}} = A_s f_s + A_c f_c \]

where

- \( A_s \) = area of cross section of steel
- \( A_c \) = area of cross section of concrete
- \( f_s \) = allowable stress of steel
- \( f_c \) = allowable stress of concrete

(3) Timber Piles
Timber piles are tree trunks that have had their branches and bark carefully trimmed off. The maximum length of most timber piles is 10 to 20 m (30 to 65 ft). To qualify for use as a pile, the timber should be straight, sound, and without any defects.
Composite Piles

Timber piles are tree trunks that have had their branches and bark.

\[ Q_{\text{all}} = A_p f_{w} \]

where

- \( A_p \) = average area of cross section of the pile
- \( f_{w} \) = allowable stress on the timber
**Estimating Pile Length**

Piles can be divided into three major categories, depending on their lengths and the mechanisms of load transfer to the soil: (a) point bearing piles, (b) friction piles, and (c) compaction piles.

**Point Bearing Piles**

The ultimate pile load may be expressed as:

\[
Q_u = Q_p + Q_s
\]

where

- \( Q_p \) = load carried at the pile point
- \( Q_s \) = load carried by skin friction developed at the side of the pile (caused by shearing resistance between the soil and the pile)

![Diagram of point bearing piles](image)

*Figure 9.6* (a) and (b) Point bearing piles; (c) friction piles

If \( Q_s \) is very small,

\[
Q_s = Q_p
\]

In this case, the required pile length may be estimated accurately if proper subsoil exploration records are available.
Friction Piles
If the value of $Q_p$ is relatively small, then:

$$Q_u \approx Q_s$$

Compaction Piles
Under certain circumstances, piles are driven in granular soils to achieve proper compaction of soil close to the ground surface. These piles are called compaction piles.

Equations for Estimating Pile Capacity
The ultimate load-carrying capacity $Q_u$ of a pile is given by the equation:

$$Q_u = Q_p + Q_s$$

where

$Q_p = \text{load-carrying capacity of the pile point}$

$Q_s = \text{frictional resistance (skin friction) derived from the soil–pile interface}$

Point Bearing Capacity, $Q_p$ (End or Point Resistance)
The point bearing of piles is:

$$q_{ult} = cN_c^* + q_o'N_q^* + \gamma DN_y^*$$

where:

$D = \text{pile diameter or width.}$

$q_o' = \text{effective overburden stress at pile tip.}$

$N_c^*, N_q^*, N_y^*$ are the bearing capacity factors which include shape and depth factors.

Since pile diameter is small $\gamma DN_y^* \approx 0$

$$Q_p = A_p(cN_c^* + q_o'N_q^*)$$

$A_p = \text{pile tip area}$
Consequently:

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

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

**Figure 9.11** Ultimate load-carrying capacity of pile

**Frictional Resistance, \( Q_s \) (Shaft Resistance)**

The frictional, or skin, resistance of a pile may be written as

\[ Q_s = \sum p \Delta L_f \]
where

\[ p = \text{perimeter of the pile section} \]
\[ \Delta L = \text{incremental pile length over which } p \text{ and } f \text{ are taken to be constant} \]
\[ f = \text{unit friction resistance at any depth } z \]

**Allowable Load, Qall**

After the total ultimate load-carrying capacity of a pile has been determined by summing the point bearing capacity and the frictional (or skin) resistance, a reasonable factor of safety should be used to obtain the total allowable load for each pile, or:

\[ Q_{all} = \frac{Q_d}{FS} \]

where

\[ Q_{all} = \text{allowable load-carrying capacity for each pile} \]
\[ FS = \text{factor of safety} \]

The factor of safety generally used ranges from 2.5 to 4, depending on the uncertainties surrounding the calculation of ultimate load.

**Meyerhof’s Method for Estimating Qp**

**Sand**

Qp should not exceed the limiting value \( A_pq_l \); that is,

\[ Q_p = A_pq_l N_q^* \leq A_pq_l \]

The variation of \( N_q^* \) with soil friction angle \( \phi' \) is shown in *Figure 9.13*. The interpolated values of \( N_q^* \) for various friction angles are also given in *Table 9.5*. 
The limiting point resistance is:

\[ q_l = 0.5 p_a N_q^* \tan \phi' \]

where

\[ p_a = \text{atmospheric pressure (} = 100 \text{ kN/m}^2 \text{ or } 2000 \text{ lb/ft}^2) \]

\[ \phi' = \text{effective soil friction angle of the bearing stratum} \]

**Clay (\( \phi = 0 \))**

For piles in saturated clays under undrained conditions (\( \phi = 0 \)), the net ultimate load can be given as:

\[ Q_p \approx N_q^* c_u A_p = 9c_u A_p \]

where \( c_u \) = undrained cohesion of the soil below the tip of the pile.

**Example 9.2**

See example 9.2 (a) in textbook, page number 423.
Correlations for Calculating Qp with SPT and CPT Results in Granular Soil

From SPT

On the basis of field observations, Meyerhof suggested that the ultimate point resistance $q_p$ in a homogeneous granular soil ($L = L_b$) may be obtained from standard penetration numbers as:

$$q_p = 0.4 p_a N_{60} \frac{L}{D} \leq 4 p_a N_{60}$$

where:

- $N_{60}$ = the average value of the standard penetration number near the pile point (about 10D above and 4D below the pile point).
- $p_a$ = atmospheric pressure ($\approx 100$ kN/m$^2$ or 2000 lb/ft$^2$).

Briaud et al. suggested the following correlation for $q_p$ in granular soil with the standard penetration resistance $N_{60}$:

$$q_p = 19.7 p_a (N_{60})^{0.36}$$

From CPT

Meyerhof suggested that:

$$q_p \approx q_c$$

where $q_c$ = cone penetration resistance.

Example 9.3

See example 9.3 in textbook, page number 425.
**Frictional Resistance (Qs) in Sand**

The frictional resistance is:

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

In making an estimation of f, several important factors must be kept in mind (see textbook, page number 426).

![Diagram](image)

*Figure 9.16* Unit frictional resistance for piles in sand

Taking into account the preceding factors, we can give the following approximate relationship for f:

\[ L' \approx 15D \]

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

\[ f = K\sigma_0' \tan \delta' \]

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

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

In these equations,

- \( K \) = effective earth pressure coefficient
- \( \sigma_0' \) = effective vertical stress at the depth under consideration
- \( \delta' \) = soil-pile friction angle
The following average values of K are recommended for use in the previous equation:

<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>

\[
Q_s = K \overline{\sigma_o}' \tan(0.8\phi')pL
\]

where
- \( \overline{\sigma_o}' = \) average effective overburden pressure
- \( \delta' = \) soil–pile friction angle = 0.8\( \phi' \)

For the case of a soil profile that has more than one layer:

\[
Q_s = P \times \sum k\sigma_{av} \tan(0.8\phi) L_i
\]

where:
- \( P: \) the perimeter of the pile cross section.
- \( L_i: \) the thickness of the layer being under consideration.

**Frictional (Skin) Resistance in Clay**

1. **\( \lambda \) Method**

The total frictional resistance may be calculated as:

\[
Q_s = pL f_{av}
\]

\[
f_{av} = \lambda (\overline{\sigma_o}' + 2c_u)
\]

where
- \( \overline{\sigma_o}' = \) mean effective vertical stress for the entire embedment length
- \( c_u = \) mean undrained shear strength (\( \phi = 0 \))
\[ c_u = \frac{c_u(1)L_1 + c_u(2)L_2 + \cdots}{L} \]

\[ \bar{\sigma}_o' = \frac{A_1 + A_2 + A_3 + \cdots}{L} \]

where \( A_1, A_2, A_3, A_n \) areas of the vertical effective stress diagrams.

**Figure 9.20** Application of \( \lambda \) method in layered soil
(2) α Method
The unit skin resistance in clayey soil can be represented by the equation:

\[ f = \alpha c_u \]

Where \( \alpha = \) empirical adhesion factor. The approximate variation of the value of \( \alpha \) is shown in Table 9.10.

<table>
<thead>
<tr>
<th>( c_u )</th>
<th>( \alpha )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p_a )</td>
<td>≤ 0.1</td>
</tr>
<tr>
<td></td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>2.8</td>
</tr>
</tbody>
</table>

Note: \( p_a = \) atmospheric pressure
\( \approx 100 \text{kN/m}^2 \) or \( 2000 \text{lb/ft}^2 \)

Therefore, the ultimate side resistance can thus be given as:

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

(3) β Method
The unit skin resistance in clayey soil can be represented by the equation:

\[ f = \beta \sigma_v' \]

where

\( \sigma_v' = \) vertical effective stress
\( \beta = K \tan \phi'_R \)
\( \phi'_R = \) drained friction angle of remolded clay
\( K = \) earth pressure coefficient
Conservatively, the magnitude of $K$ is the earth pressure coefficient at rest, or

$$ K = 1 - \sin \phi' $$  
(for normally consolidated clays)

and

$$ K = (1 - \sin \phi') \sqrt{OCR} $$  
(for overconsolidated clays)

where OCR = overconsolidation ratio.

With the value of $f$ determined, the total frictional resistance may be evaluated as:

$$ Q_s = \sum j_p \Delta L $$

Example 9.7
Discuss example 9.7 in textbook, page number 442.

(4) Correlation with Cone Penetration Test Results
The unit skin friction in clay (with $\phi = 0$) may be expressed as:

$$ f = \alpha' f_c $$

The variation of $\alpha'$ with the frictional resistance $f_c$ is shown in Figure 9.22.
Therefore, the total frictional resistance may be evaluated as:

\[ Q_s = \sum f_p(\Delta L) = \sum \alpha' f_c p(\Delta L) \]

**Example 9.8**
Discuss example 9.8 in textbook, page number 442.

**Point Bearing Capacity of Piles Resting on Rock**

Sometimes piles are driven to an underlying layer of rock. In such cases, the engineer must evaluate the bearing capacity of the rock. The ultimate unit point resistance in rock (Goodman, 1980) is approximately:

\[ q_p = q_u(N_\phi + 1) \]

where

\[ N_\phi = \tan^2(45 + \phi' / 2) \]

\[ q_u = \text{unconfined compression strength of rock} \]

\[ \phi' = \text{drained angle of friction} \]

\[ q_u(\text{design}) = \frac{q_u(\text{lab})}{5} \]

*Table 9.12* lists some representative values of (laboratory) unconfined compression strengths of rock. Representative values of the rock friction angle \( \phi \) are given in *Table 9.13*.

<table>
<thead>
<tr>
<th>Type of rock</th>
<th>( q_u )</th>
<th>( q_u(\text{design}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandstone</td>
<td>70–140</td>
<td>10,000–20,000</td>
</tr>
<tr>
<td>Limestone</td>
<td>105–210</td>
<td>15,000–30,000</td>
</tr>
<tr>
<td>Shale</td>
<td>35–70</td>
<td>5000–10,000</td>
</tr>
<tr>
<td>Granite</td>
<td>140–210</td>
<td>20,000–30,000</td>
</tr>
<tr>
<td>Marble</td>
<td>60–70</td>
<td>8500–10,000</td>
</tr>
</tbody>
</table>
A factor of safety of **at least 3** should be used to determine the allowable point bearing capacity of piles. Thus:

\[
Q_{p(\text{all})} = \frac{[q_{u(\text{design})}(N_\phi + 1)]A_p}{FS}
\]

**Problems**

Here a bunch of different external-source problems is to be demonstrated on the chapter as a whole.

**Group Piles**

To be continued…