PILE FOUNDATION.

One or more of the followings:
(a) Transfer load to stratum of adequate capacity
(b) Resist lateral loads.
(c) Transfer loads through a scour zone to bearing stratum
(d) Anchor structures subjected to hydrostatic uplift or overturning

\[ Q_u = Q_p + Q_s \]

Check settlements of pile groups
Do not use piles if:

Driving may cause damage to adjacent structures, soil may heave excessively, or in boulder fields.

**Pile Installation**

**Hammers**

**Drop hammer**

1

Very noisy, simple to operate and maintain, 5-10 blows/minute, slow driving, very large drop, not suited for end bearing piles, used on Franki piles.
Single acting hammer

Double acting:

Differential acting:

Diesel:

Vibratory:

Jacking:

Predrilling or Jetting

---

1 Uses pressure for up stroke and down stroke. Design limits prevent it to deliver as much energy as single acting, but greater speed, used mostly for sheet piles
2 Has two pistons with different diameters, allowing it to have heavy ram as for single acting and greater speed as double acting
3 Difficult to drive in soft ground, develops max energy in hard driving
4 Rotating eccentric loads cause vertical vibrations, most effective in sand
PILE TYPE

- Timber
- Concrete
- Steel

Timber piles

Butt dia 12" to 20", tip 5" to 10". Length 30-60'
Bark always removed.

Concrete piles

Pre-cast
- Reinforce and prestressed

Cast in place
- With or without casing.
- More common than precast.

Steel Piles

- Steel H-Pile
- Unspliced 140', spliced > 230', load 40 to 120 tons.

1more economical but more risk in their installation.
PILES CLASSIFICATION

1. Material (wood, steel, etc.).

2. Method of installation:

3. Effect on surrounding soils during installation.

Pile load capacity prediction

• Full-scale load test

• Static formulae

• Dynamic method

1 (driven: blow of a hammer, vibrations, pressure from a jack, etc.; jetted, augured, screwing, etc.).
2 displacement, non-displacement
### Pile shape effect and pile selection

<table>
<thead>
<tr>
<th>Shape characteristics</th>
<th>Pile type</th>
<th>Placement effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement</td>
<td>Closed ended steel</td>
<td>Increase lateral ground stress</td>
</tr>
<tr>
<td></td>
<td>Precast concrete</td>
<td>Densifies granular soils, weakens clays</td>
</tr>
<tr>
<td>Tapered</td>
<td>Timber, monotube, thin-walled shell</td>
<td>High capacity for short length in granular soils</td>
</tr>
<tr>
<td>Non-displacement</td>
<td>Steel H</td>
<td>Minimal disturbance to soil</td>
</tr>
<tr>
<td></td>
<td>Open ended steel pipe</td>
<td>Not suitable for friction piles in granular soils, often show low driving resistance, field varification difficult resulting in excessive pile length</td>
</tr>
</tbody>
</table>

1 *Setup time for large groups up to 6-months*
Load Transfer

\[ Q_u = Q_p + Q_s \]

Settlement for full load transfer

- \( Q_p \rightarrow 0.1D \) (driven), 0.25 D (bored)
- \( Q_s \rightarrow 0.2'' - 0.3'' \)
End or Point Resistance

\[ q_{ult} = cN^*_c + q'^*_o N^*_q + \gamma DN^*_\gamma \]

D = pile diameter or width

\( q'^*_o \) = effective overburden stress at pile tip

\( N^*_c, N^*_q, N^*_\gamma \) are the b.c. factors which include shape and depth factors

Since pile dia is small \( \gamma DN^*_\gamma \approx 0 \)

\[ Q_p = A_p (cN^*_c + q'^*_o N^*_q) \]

\( A_p \) = pile tip area
**Meyerhof's Method**

Point resistance increases with depth reaching a maximum value at \( L_b/D \) critical.

\( (L_b/D)_{\text{crit}} \) varies with \( \phi \) and \( c \). Fig 9.12

\( L_b = \) embedment length in bearing soil

For values of \( N^*_c, N^*_q \) see Fig 9.13
Piles in Sand

\[ Q_p = A_p \cdot q_o \cdot N_q^* \leq A_p \cdot q_l \]

where \( q_l(tsf) = 0.5N_q^* \cdot \tan\phi \)

\( \phi \) in terms of 'N' or \( D_r \)

\[ \phi = \sqrt{20N} + 15^\circ \]

\[ \phi = 28^\circ + 15D_r \]

Point resistance from SPT

\[ q_p(tsf) = \frac{0.4 \cdot N \cdot L}{D} \leq 4 \cdot N \]

\( N = \) avg value for 10D above and 4D below pile tip

1For a given initial \( \phi \) unit point resistance for bored piles =1/3 to 1/2 of driven piles, and bulbous piles driven with great impact energy have up to about twice the unit resistance of driven piles of constant section
Example 1

A pile with \( L = 65' \), x-section = 18"×18" is embedded in sand with \( \phi = 30^\circ \), \( \gamma = 118.3 \) pcf. Estimate point bearing resistance.

**Solution (Meyerhof)**

\[
Q_p = A_p \cdot q_o \cdot N_q^* \leq A_p \cdot q_l
\]

\[
Q_p = 1.5 \times 1.5 \times 118.3 \times 65 \times 55 \div 2000 = 476 \text{ tons}
\]

\[
Q_p = A_p \cdot q_l = 1.5 \times 1.5 \times 0.5 \times 55 \times \tan30 = 36 \text{ tons}
\]
Upper weak lower firm soil

\[ q_p = q_{l(l)} + \frac{L_b}{10D} (q_{l(d)} - q_{l(l)}) \leq q_{l(d)} \]

- \( q_{l(l)} \): limiting point resistance in loose sand
- \( q_{l(d)} \): limiting point resistance in dense sand

**Piles in Saturated Clay**

If embedded length \( \geq 5D \), \( N_c^* = 9 \)

\[ Q_p = 9 \cdot c_u \cdot A_p \]
Example 2

Timber piles, 25' log with 10" point diameter, were driven through a silty sand with $\phi = 25^\circ$ into underlying dense sandy gravel with $\phi = 40^\circ$. Penetration into the sandy gravel was 3'. Determine point bearing capacity of a pile.

Solution

$q_l$ (silty sand) = $0.5N_q \times \tan \phi = 0.5 \times 25 \times \tan 25 = 5.82$ tsf

$q_l$ (sandy gravel) = $0.5 \times 350 \times \tan 40 = 146.8$ tsf

$q_p = 5.82 + \frac{36}{10 \times 10} (146.8 - 5.82) = 56.6$ tsf < 146.8

$Q_p = \left(\frac{10}{12 \times 2}\right)^2 \times \pi \times 56.6 = 30.9$ tons
**Shaft Resistance**

It is due to skin friction and adhesion

\[ Q_s = \Sigma f \cdot A_s \]

\( A_S = \) area of shaft surface

\( f = \) unit shaft resistance

\[ f = K\sigma_v' \tan \delta + c_a \]

\( \delta = \) soil-pile friction angle

\( c_a = \) is adhesion

\( K = \) earth pressure coefficient

---

1 which is difficult to evaluate between at-rest and passive state
Shaft Resistance in Sand

Since $c_a = 0$

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

Like tip resistance a critical depth is reached after which 'f' does not increase. Use $(L'/D)_{critical} = 15$

Values of K

<table>
<thead>
<tr>
<th>Pile type</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bored or jetted</td>
<td>$K_o = 1 - \sin \phi$</td>
</tr>
<tr>
<td>low disp. driven</td>
<td>$K_o$ to $1.4 \times K_o$</td>
</tr>
<tr>
<td>high disp. driven</td>
<td>$K_o$ to $1.8 \times K_o$ or $0.5 + 0.008 \times D_r$</td>
</tr>
</tbody>
</table>

\(^1\) $D_r = relative\ density\ (%)$
<table>
<thead>
<tr>
<th>Pile material</th>
<th>$\delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>steel</td>
<td>20°</td>
</tr>
<tr>
<td>concrete</td>
<td>0.75 $\phi$</td>
</tr>
<tr>
<td>wood</td>
<td>0.67$\phi$</td>
</tr>
</tbody>
</table>

$Q_s = \Sigma p \cdot f \cdot \Delta L$

$p =$ perimeter

$\Delta L =$ incremental pile length for constant $p$ and $f$. 
**SPT - basis for shaft resistance in sand**

Meyerhof

\[
f_{avg}(tsf) = \frac{\bar{N}}{50} \quad \text{high disp. driven piles}
\]

\[
f_{avg}(tsf) = \frac{\bar{N}}{100} \quad \text{small disp. driven (H-pile)}
\]

\[
f_{avg}(tsf) = 1.5 \cdot \frac{\bar{N}}{50} \quad \text{pile tapered > 1%}
\]

\(\bar{N} = \text{avg 'N' within embedded pile length}\)
Skin Resistance in Clay

λ Method:

\[ f_{av} = \lambda \left( \sigma'_v + 2c_u \right) \]

\( \sigma'_v \) = mean effective vertical stress on pile length

\( \lambda \) - given in Fig. 8.17

\[ Q_s = p \cdot f_{av} \cdot L \]

For layered soils use mean values of \( c_u \) and \( \sigma \).

\[ c_u = \frac{c_{u(1)}L_1 + c_{u(2)}L_2 + \ldots}{L} \]

---

1. Some problems 1. Increase in pore water pressure 2. Low initial capacity 3. Enlarged hole near ground surface-water may get in and soften clay. 4. Ground and pile heaving. 5. Drag down effect from soft upper soils

2. Short pile were driven in stiff clay OCR>1 but the long piles penetrated lower soft clay as well
\[ \bar{\sigma}_v = \frac{A_1 + A_2 + A_3 + \ldots}{L} \]

\(A_1, A_2, \ldots\) are areas of the effective stress diagrams
**Example 3**

A 12 m prestressed concrete pile 450 mm square is installed in a clay with water table at 5 m depth. Upper clay layer is 5 m thick, with \( \gamma = 17.4 \text{ kN/m}^3 \) and \( c_u = 50 \text{ kPa} \). Lower clay has \( \gamma = 18.1 \text{ kN/m}^3 \), \( c_u = 75 \text{ kPa} \). Determine pile capacity using \( \lambda \) - method.

**Solution: (\( \lambda \) - method)**

\[
\sigma_5' = 17.4 \times 5 = 87 \text{ kPa}, \quad \sigma_{12}' = 87 + (18.1-9.81) \times 7 = 145 \text{ kPa}
\]

\[
c_u = \frac{50 \times 5 + 75 \times 7}{12} = 64.58 \text{kPa}
\]

\[
\sigma_v' = \frac{0.5 \times 87 \times 5 + 7 \times \frac{87 + 145}{2}}{12} = 85.79 \text{kPa}
\]
\[ \lambda = 0.24 \]

\[ f_{\text{avg}} = 0.24(85.79 + 2 \times 64.58) = 51.6 \text{ kPa} \]

\[ Q_s = 4 \times 0.45 \times 51.6 \times 12 = 1114 \text{ kN} \]
Example 4. Redo Example 3 using $\alpha$ - method

$f = F \cdot \alpha \cdot c_u$

Upper clay, \( \frac{c_u}{\sigma_o} = \frac{50}{87} = 0.57 \)

\[
\alpha = 0.5 + \frac{1 - 0.5}{0.8 - 0.35} (0.8 - 0.57) = 0.756
\]

$L/D = 12/0.45 = 26.7, \quad F = 1$

Lower clay

\[
\frac{c_u}{\sigma_o} = \frac{75}{145} = 0.517
\]

$\alpha = 0.814,$

\[ f_1 = 1 \times 0.756 \times 50 = 37.8 \text{ kPa} \]

\[ f_2 = 1 \times 0.814 \times 75 = 61.05 \text{ kPa} \]

\[ Q_s = 4 \times 0.45 \times 5 \times 37.8 + 4 \times 0.45 \times 7 \times 61.05 = 1109 \text{ kN} \]
Example 5. Redo the Example 3 assuming 200 mm pipe
L/D = 12/0.2 = 60

\[ F = 0.7 + \frac{(1 - 0.7)(120 - 60)}{120 - 50} = 0.95 \]

\[ f_1 = 0.95 \times 0.756 \times 50 = 35.9 \text{ kPa} \]

\[ f_2 = 0.95 \times 0.814 \times 75 = 58.0 \text{ kPa} \]

\[ Q_s = \pi (0.2) \times (5 \times 35.9 + 7 \times 58.0) = 368 \text{ kN} \]
Example 6

Draw number of blows per inch versus $R_u$ for the following conditions using EN formula, modified Engineering News formula, and Janbu formula. Steel HP10×57, coefficient of restitution ($n$) = 0.8, efficiency ($E$) = 0.85, Vulcan 08 hammer. $C = 0.1"$. Use two pile lengths 20' and 80'. Elastic modulus = $29 \times 10^3$ ksi

Solution

Hammer energy 26 k-ft, Ram weight 8 kips. Area of steel = 16.8 in$^2$.

$$C_d = 0.75 + 0.15 \frac{57 \times 20}{8000} = 0.771$$

Assume $S = 0.1"$

$$\lambda = \frac{0.85 \times 20 \times 12 \times 26}{16.8 \times 29 \times 10^3 \times (0.1)^2} = 13.06$$

$$K_u = 0.771 \left(1 + \sqrt{1 + \frac{13.06}{0.771}}\right) = 40.382$$

$R_u$ (20 ft for $S = 0.1"$) = 657 kips

$R_u$ (80 ft for $S = 0.1"$) = 354 kips

---

1 For plotting graphs assume several $R_u$ and compute set.
Ru - Janbu 20', Ru1 - Janbu 80', Rmn = Modified EN 20', Rmn1 = Modified EN 80'

From Modified Engineering New Formula, the following results will be obtained.

\[ R_u (20 \text{ ft for } S=0.1") = 1266 \text{ kips} \]

\[ R_u (80 \text{ ft for } S=0.1") = 1153 \text{ kips} \]
Practical applications

Design

- Using laboratory and field soil data determine $Q_u$ based on static formulae

Test pile

- Drive test piles using same equipment as proposed for production piles.
- If possible use pile driving analyser (PDA) incorporating strain and acceleration data on test pile. Prepare bearing graph.
- Make records of pile driving and correlate with boring logs to ensure that piles have penetrated the bearing soils.
- Load test the pile/s.
- If possible load to failure to establish actual factor safety.
- For small jobs load tests are not justifiable.
- When piles rest on sound bedrock load tests may not be necessary.
- Based on load test adjust design capacity, increase penetration depth, alter driving criteria as necessary.

Construction stage

- Record driving resistance for full depth of penetration
- Driving record must correspond to bearing graph of test pile.
• If not additional penetration into bearing material or greater driving resistance may be necessary.
Wave Equation

- Hammer, cushions, pile cap, and pile are modeled as discrete elements.

- Each element has a mass and there are springs between element of appropriate stiffness

- Soil-pile interface modeled as spring-dash pot. Springs model resistance to driving as a function of displacement and dash pots as function of velocity.

Computations

- Ram of mass $M_1$ with velocity $v_1$ travels a distance $v_1 \times \Delta t$ compresses spring $K_1$ with the same amount.

- Force in $K_1$ actuates $M_2$ from which displacements are computed.

- Process is continued for all masses for successive time intervals until pile tip stops moving.

- Software - TTI and WEAP (Wave Equation Analysis of Pile)
**Pile Driving Analyser**

- Two strain transducers and two accelerometers mounted near pile head
- A pile driving analyser (PDA)

**PDA monitors strain and acceleration and yields:**

- Force in pile - from strain, E and pile x-sectopm
- Particle velocity - from integration of acceleration
- Pile set - from integration of velocity

**CAPWAP(Case Pile Wave Analysis Program):**

Hammer and accessories - replaced by force-time and velocity-time data from PDA, thus eliminating deficiencies of wave equation.