Foundation settlements

Settlements of foundations

I skimped a little on the foundation but no one will ever know the difference.

Settlement

Cracks
Stress distribution below point load

\[ \Delta \sigma_v = \frac{3Q}{2\pi z^2} \left[ \frac{1}{1 + \left(\frac{z}{a}\right)^2} \right]^{\frac{3}{2}} \]

Equal stress increase (Pressure bulb)

Stress below strip load

\[ \frac{\Delta \sigma_v}{q} \]

Depth, \( z/a \)
Stress below strip load

2:1 - method

\[ Q = qBL \]

\[ \Delta \sigma_y = \frac{Q}{(B+2z)(L+2)z} \]
2:1 - method at corner of footing

\[ \Delta \sigma_v = \frac{2Q}{(L+z)(2B+z)} \cdot \frac{L}{2} \]

\[ = \frac{Q}{(L+z)(2B+z)} \]

Loaded area

2:1 - method.

Settlement below footing

Settlement

Clay, silt
Immediate settlement \( S_i \), \( S_p \)
Primary settlement \( S_p \), \( S_p \)
Secondary settlement \( S_i \), \( S_p \)

Sand
First loading
Cyclic loading
Settlements in clay and silt

Based on lab tests

Settlements, Clay and Silt.

Initial settlement: \( E \mu (\mu = 0.5) \) (Estimated from \( C_u \))

Primary settlement: \( C_c, M \)
(from oedometer tests or estimated from \( I_p \))

Secondary settlement: \( \alpha \)
(from oedometer tests or estimated)

Settlements in sand

Based on in situ tests

Settlements, Sand.

Compression modulus \( E \)

First loading: \( M, E \)
(from static or dynamic penetration tests
SPT, CPT, WST
Also from pressure-meter tests, plate load tests)

Coefficient of subgrade reaction \( k \)
(from plate load tests)

Cyclic loading: \( SPT \)-tests
(liquefaction)
Triaxial and direct shear tests
Elastic settlement of flexible and rigid foundations

Perfectly flexible:

\[ S_e = q_0 (\alpha B') \left( 1 - \frac{\mu_s^2}{E_s} \right) \frac{I_s I_f}{I_s + I_f} \]

- \( E_s \): averaged modulus of elasticity for \( z = 0 \sim 4B \)
- \( I_s \): shape factor
- \( I_f \): depth factor
- \( \alpha \): depends on location

\[ S_{e\text{(rigid)}} = 0.93 S_{e\text{(flexible,center)}} \]

---

Elastic settlement below the center of a foundation

Weighted average of \( E_s \):

\[ E_s = \frac{\sum E_s(i) \Delta z}{\Delta z} \]

- \( E_s(i) \): modulus of elasticity within depth \( \Delta z \)
- \( \bar{z} \): min(H ,5B)
Immediate settlements in clay

Clay: Immediate settlement
(Theory of elasticity: $E/\mu$)

\[ \delta_i = \frac{qB}{E_s} \left( 1 - \frac{\mu^2}{\mu_1^2} \right) I_w \frac{\mu_1}{\mu_2} \]

- Poisson’s ratio (\(\mu=0.35\))
- Correction factor for depth to bedrock
- Influence factor (0.79 circular, 0.82 square)
- Correction factor for depth below ground surface (\(E_s\))

\[ \delta_i = \frac{0.9B}{E_s} \frac{\mu_1}{\mu_2} \]

Estimate of modulus of elasticity in clay

\[ q_u = 2c_u \]

Modulus of elasticity

Clay, \(c_u\)

- Overconsolidated
  \[ E_s = 250 - 500c_u \quad (300c_u) \]
- Normally consolidated
  \[ E_s = 1000c_u \quad (OCR<2) \]
Determination of compression index

\[ \Delta e = C_c \log \left( \frac{p_1'}{p_0'} + \frac{\Delta p}{p_0'} \right) \]

Determination of settlements from compression test

\[ \Delta e = C_c \left( \log \left( \frac{p_1' + \Delta p}{p_0'} \right) - \log \left( \frac{p_0}{p_0'} \right) \right) \]

\[ \frac{\Delta e}{\log \left( \frac{p_1' + \Delta p}{p_0'} \right) - \log \left( \frac{p_0}{p_0'} \right)} = \frac{C_c}{1 - \frac{p_0}{p_0'}} \]
Principle of settlement calculation

Settlement, $\delta$

$$\delta = \frac{e_0 H_o}{1 + e_0} - \frac{e_1 H_o}{1 + e_0} = \frac{\Delta e H_o}{1 + e_0}$$

Primary settlement

Settlement below footing

$$\delta_p = \frac{H_o}{1 + e_0}$$

Effective stress $p'$ (log scale)
Determination of precosolidation pressure

Determination of coefficient of consolidation (logarithmic)
Coefficient of consolidation (square root)

\[ C_v = \frac{0.197 H^2}{t_{50}} \text{ cm}^2/\text{s}, \text{ m}^2/\text{year} \]

Coefficient of consolidation

Secondary consolidation

\[ \delta_3 = \frac{H}{1 - e_0} \cdot C_\infty \log \frac{t_{life}}{t_{100}} \]
Summary of settlement on clay

\[ \delta_T = \delta_i + \delta_p + \delta_s \]

- Can be important for soft clay
- Usually most important
- Important for organic

- To get an accurate estimate of settlement, must have good estimate of \( \sigma'_p \)
- Important to adjust for 3-D effect (Skempton-Bjerum Modification): \( \delta_p = \psi \delta_p, \psi \leq 1.0 \)

Settlement on Sand

- Schmertmann's Method

\[ \delta = C_1 C_2 C_3 q' \sum \frac{I \varepsilon \Delta z}{E_s} \]

- Net bearing pressure
- Strain influence factor at midpoint of soil layer
- Thickness of soil layer
- Equivalent modulus

- Depth factor
- Secondary creep factor
- Shape factor

\[ C_1 = 1 - 0.5 \left( \frac{\sigma'_p - \sigma}{q'} \right) \]
\[ C_2 = 1 + 0.2 \log \left( \frac{t}{0.1} \right) \]
\[ C_3 = 1.03 - 0.03 L / B \geq 0.73 \]
Soil modulus from cone penetration test (CPT)

\[ I_{eq} = 0.5 + 0.1 \sqrt{\frac{q'}{\sigma'_{zp}}} \]

- \( z_f \) = Depth Below Bottom of Footing
- \( B \) = Width of Footing
- \( L \) = Length of Footing

\[ E_s = 3q_c \] for Sand
\[ E_s = 300 c_u \approx 15q_c \] for Clay

\[ \frac{1}{20} q_c \] (Bowles \( 2+8q_c \))
Estimate of modulus of elasticity from Standard penetration test (SPT)

\[ E_s = 0.5(N+15) \text{ MPa} \]

Clay: \[ E_s = 0.6(N+5) \text{ MPa} \]

Settlement analysis based on plate load test

\[ \delta = \frac{q}{k_s} \]

Coefficient of subgrade reaction.
Estimate of settlements below footing on sand

\[ S = qB \frac{(1-\mu^2)}{E_s} I \]

- Sand, \( \mu = 0.3 \)
  \[ S = 0.72 \frac{qB}{E_s} \]
- Clay, \( \mu = 0.5 \)
  \[ S = 0.6 \frac{qB}{E_s} \]

Settlements of footing on clay

\[ q_u = q_{u,0.3} \]
Effect of plate diameter on bearing capacity of plate on sand

\[ q_u = q_u,0.3 \times \frac{B}{0.3} \]

Allowable settlement below building

\[ \delta_{allow} = \]
Damage due to foundation settlements

Floating foundation

\[ W_{\text{building}} = W_{\text{soil}} \]

Floating foundation
Effect of ground water lowering from tunnel on building settlements

- 2m lowering
- $\Delta V = 2 \times 10^{-2} \text{m}^3$
- $\Delta h = 1 \text{m}$ of fill
- $\beta = 10 \text{kN/m}^3$

Effect of trees on ground water near building

Trees

Settlements within this area
Differential settlements between adjacent buildings

Negative skin friction due to ground water lowering
Swelling potential of soil below building

<table>
<thead>
<tr>
<th>Swelling Potential</th>
<th>Ip</th>
<th>$\omega_L$</th>
<th>$\omega_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>25-40</td>
<td>50-70</td>
<td>7-12</td>
</tr>
<tr>
<td>Very high</td>
<td>&gt; 35</td>
<td>&gt; 70</td>
<td>&lt; 11</td>
</tr>
</tbody>
</table>

Effect of pile installation on adjacent building
Allowable differential settlements below structure

\[ \tan \theta = \frac{S}{L} \]

- 1/300 cracking
- 1/150 structural damage
- Door and windows are difficult to open (1 cm)
- Floors not level

USSR Code
- Crane runways 1/300
- Clay: 1/100 - 1/500
- Sand: 1/1000 - 1/1000
- Steel and concrete frames 1/100 - 1/500
- One story mill building 1/1000
- Smoke stacks, water towers 1/250

Tolerable settlement of buildings

Definitions of parameters for differential settlement
## Limiting Angular Distortion for Various Structures (Bjerrum, 1963)

<table>
<thead>
<tr>
<th>Potential damage</th>
<th>$\beta_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safe limit for flexible brick wall</td>
<td>1/150</td>
</tr>
<tr>
<td>Danger of structural damages to most buildings</td>
<td>1/150</td>
</tr>
<tr>
<td>Cracking of panel and brick walls</td>
<td>1/150</td>
</tr>
<tr>
<td>Visible tilting of tall rigid buildings</td>
<td>1/250</td>
</tr>
<tr>
<td>First cracking of panel walls</td>
<td>1/300</td>
</tr>
<tr>
<td>Safe limit for non-cracking of buildings</td>
<td>1/500</td>
</tr>
<tr>
<td>Danger to frame with diagonals</td>
<td>1/600</td>
</tr>
</tbody>
</table>

## Limiting Values for Serviceability (EC Standardization)

<table>
<thead>
<tr>
<th>item</th>
<th>parameter</th>
<th>magnitude</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limiting values</td>
<td>$S_T$</td>
<td>25mm</td>
<td>Isolated shallow foundation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50mm</td>
<td>Raft foundation</td>
</tr>
<tr>
<td>$\Delta S_T$</td>
<td></td>
<td>5mm</td>
<td>Frame with rigid cladding</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10mm</td>
<td>Frame with flexible cladding</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20mm</td>
<td>Open frame</td>
</tr>
<tr>
<td>$\beta$</td>
<td></td>
<td>1/500</td>
<td></td>
</tr>
<tr>
<td>Maximum acceptable</td>
<td>$S_T$</td>
<td>50mm</td>
<td>Isolated shallow foundation</td>
</tr>
<tr>
<td></td>
<td>$\Delta S_T$</td>
<td>20mm</td>
<td>Isolated shallow foundation</td>
</tr>
<tr>
<td></td>
<td>$\beta$</td>
<td>1/500</td>
<td></td>
</tr>
</tbody>
</table>
技術規範

基礎若產生沉陷首先將影響建築物之粉刷、裝飾或設備之正常使用，沉陷量若過大，則將導致構造物產生龜裂或損壞。所謂容許沉陷量規定要求之標準而定，設計者應視建築物型式審慎評估之，除建築美觀或結構上有特殊需求者外，基礎沉陷所導致角變量及總沉陷量之一般容許標準如下：

(1)容許角變量：建築物相鄰兩柱或相鄰兩支點間，因差異沉陷引致之角變量，應不得使建築物發生有害之裂縫，或影響其使用功能。角變量與建築物損壞程度之關係如表-表 4.4-1 所示，此表僅係一般之原則，對於特定之構造物應視其狀況而定。

<table>
<thead>
<tr>
<th>角變量</th>
<th>建 築 物 損 壞 程 度</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/600</td>
<td>斜撐之構架有受損之危險</td>
</tr>
<tr>
<td>1/500</td>
<td>建築物不容許裂縫產生的安全限度(含安全係數)</td>
</tr>
<tr>
<td>1/300</td>
<td>隔間牆開始發生裂縫(不含安全係數)</td>
</tr>
<tr>
<td>1/250</td>
<td>剛性之高層建築物開始有明顯的傾斜</td>
</tr>
<tr>
<td>1/150</td>
<td>隔間牆及磚牆產生相當多的裂縫</td>
</tr>
<tr>
<td>1/150</td>
<td>可撓性磚牆之安全限度(含安全係數)</td>
</tr>
<tr>
<td>1/150</td>
<td>建築物產生結構性損壞</td>
</tr>
</tbody>
</table>

（2）容許沉陷量：建築物因基礎載重引致之總沉陷量，原則上不得超過表-表 4.4-2 所示之值，惟須注意構造物之實際狀況，有時在較小沉陷量即有可能產生損壞。

表-表 4.4-2 容許沉陷量（單位：公分）

<table>
<thead>
<tr>
<th>構造物種類</th>
<th>混 凝 土</th>
<th>鋼 筋</th>
<th>混 凝 土</th>
</tr>
</thead>
<tbody>
<tr>
<td>基礎型式</td>
<td>連續基腳</td>
<td>獨立及聯合基腳</td>
<td>連續基腳</td>
</tr>
<tr>
<td>總沉陷量</td>
<td>4.0</td>
<td>10.0</td>
<td>20.0</td>
</tr>
</tbody>
</table>