General Report - Pile Design Calculation Methods Based on Soil Parameters

Chris Raison
Raison Foster Associates
Calculation Methods Based on Soil Parameters

- What do we mean?
  - Design based on fundamental geotechnical ground parameters such as $c'$, $\phi'$, $G$, $E'$, but could also include $C_u$, UCS and $E_u$ for clays and rocks
  - These extend into derived parameters such as $N_c$, $N_y$ and $N_q$ for bearing capacity, $K_q$ and $K_c$ factors for horizontal loads on piles or $K_a$, $K_{ac}$, $K_p$ and $K_{pc}$ for ground retention
  - But we also need some empirical factors such as $K_s$ for granular, $\alpha$ for clay, $\beta$ for Chalk
Calculation Methods Based on Soil Parameters

- This is what Geotechnical Engineers do

- Calculate
- Carry out analyses
- Evaluate foundation capacity
- Predict ground and structure movements
- Interact with Structural Engineers who carry out calculations for buildings and structures
Calculation Methods Based on Soil Parameters

- There are many types of geotechnical problem where it is just not possible or it is impractical to design by load test, or where there are no direct correlations with field tests, or the observational method cannot help us.

- To deal with these:
  - Use calculation based on soil parameters
  - Numerical analysis based on soil parameters
Calculation Methods Based on Soil Parameters

- Some Examples: Shallow Pad Footings
Calculation Methods Based on Soil Parameters

- Some Examples: Retaining Walls
Calculation Methods Based on Soil Parameters

- Some Examples: Slope Stability

![Diagram of slope stability analysis with various methods and parameters.]

- Assessed bedrock profile
- Sandy gravelly silt/clay
- Regraded slope profile
- Proposed soil nail length (m)
- Some Examples: Slope Stability
  - HA 68/94 two part wedge
  - LS-GEO multi wedge critical surface
  - SLOPE critical failure circle
Calculation Methods Based on Soil Parameters

- So what is so different about pile foundations?

- In the past, piles were driven to a refusal
- Self-evident that the pile resistance is proportional to the drive energy
- Every driven pile has some sort of test – drive blows
- But this does not work for bored or drilled piles as there is no feedback from installation
Calculation Methods Based on Soil Parameters

- Ground and environmental conditions in many areas [UK and elsewhere] meant bored piles rather than driven piles were more suitable

- Design needed to adapt to the change in pile type
Calculation Methods Based on Soil Parameters

- Static load testing is very attractive for design
- But testing can be uneconomic and time consuming:
  - Complex variable ground conditions
  - Variable loading
  - Difficult to deal with NSF
  - Difficult to deal with changes to vertical stress

- As with other types of geotechnical problem, pile designers therefore looked at calculation based on theoretical soil mechanics theory
Calculation Methods Based on Soil Parameters

- The usual approach is to divide the ground into layers and assign ground parameters to each layer.

- For bearing capacity, this is just $\phi'$, $c'$, $C_u$ and UCS. From these we get $N_c$, $N_y$ and $N_q$ for bearing capacity or $K_q$ and $K_c$ for horizontal loads.

- For settlement checks we need $G$, $E_u$ and $E'$.

- Design can be by the ‘alternative procedure’ or by the ‘model pile method’ which uses correlation factors.
Calculation Methods Based on Soil Parameters

- Design can be based on measured $\phi'$, $c'$, $C_u$ and UCS usually from laboratory testing of undisturbed samples.

- More common to use empirical relationships between in-situ CPT, SPT, PMT and other measurements to estimate these parameters.

- We can measure $G$, $E_u$, and $E'$ in the laboratory, but again it is more common to use empirical relationships.
Calculation Methods Based on Soil Parameters

- Pile design calculations assume shaft friction and end bearing can be considered independently

\[ R_{c;d} = R_{b;d} + R_{s;d} \]
Calculation Methods Based on Soil Parameters

- Who does design this way?
  - UK
  - Ireland
  - Macedonia
  - Spain
  - Denmark [model pile/correlation factors]
  - France [model pile/correlation factors and PMT/CPT]
  - Italy [model pile/correlation factors and CPT]

Based on National Reports received for Symposium
Calculation Methods Based on Soil Parameters

- And who does not design this way?
  - Austria [experience/tables]
  - Belgium [CPT and PMT]
  - Estonia [CPT, dynamic test and tables]
  - Finland [mainly probe and static/dynamic testing]
  - Germany [experience/tables]
  - Hungary [CPT]
  - Netherlands [CPT]
  - Poland [CPT]
  - Sweden [calculation for clays but mainly dynamic testing]

Based on National Reports received for Symposium
Calculation Methods Based on Soil Parameters

- And how do we estimate pile shaft friction and end bearing from ground parameters?
  - Following description is a UK viewpoint
  - Similar methods used elsewhere
  - But often different insitu/laboratory testing
Pile Shaft Friction

- **Effective Stress Approach**
  Granular Soils
  \[ q_s = \sigma'_v \cdot k_s \cdot \tan \delta \]

- **Total Stress Approach**
  Cohesive or Rock (Weak Mudstone)
  \[ q_s = \alpha \cdot c_u \]
Standard Penetration Test – Granular Soils

Diagrams from Equipe Group Geotechnica

SPT undergoing calibration
Standard Penetration Test – Granular Soils

\[ (N_1)_{60} = (N)_{60} \times C_N \]

Relative density \( Dr \) (%)

<table>
<thead>
<tr>
<th>Relative density ( Dr ) (%)</th>
<th>Medium</th>
<th>Dense</th>
<th>V. dense</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>35</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>65</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>85</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[ \tan(\phi') = \frac{c'}{\lambda} \]

Angle of internal friction \( \phi' \) (degs)

\[ \lambda = \frac{E_s}{E} \]

\[ (N_1)_{60} \]

Relative density \( Dr \) (%)

<table>
<thead>
<tr>
<th>Relative density ( Dr ) (%)</th>
<th>Medium</th>
<th>Dense</th>
<th>V. dense</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>35</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>65</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>85</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[ \tan(\phi') = \frac{c'}{\lambda} \]

Angle of internal friction \( \phi' \) (degs)
Standard Penetration Test – Clay Soils

\[ C_u = f_1 \times (N)^{60} \]

\[ f_1 = 4.0 \text{ to } 6.0 \]

**Fig 19** Variation of \( f_1 = c_u / N_{60} \) with plasticity index for overconsolidated clays (after Stroud and Butler, 1975)
Laboratory Testing – Undrained Shear Strength

Triaxial Testing

![Triaxial Testing Setup]

![Graphs of Undrained Shear Strength]

- Deviator Stress vs. Strain
- Shear Stress vs. Normal Stress
Insitu Testing – CPT

Cu in clays
Φ’ in granular soils
GI Using CPT

\[ C_u = \frac{q_c}{N_k} \]

\[ N_k = 15 \text{ to } 30 \]

\[ N_k = 20 \] taken for Glacial Till in this example
Pile Shaft Friction

- Beta Method
  Soft Soils or Chalk

\[ q_s = \sigma_v' \beta \quad \beta = k_s \tan \delta \quad \beta = 0.45 \text{ to } 0.80 \text{ for Chalk} \]

- UCS Method
  Sandstone, Limestone or Strong Mudstone

\[ q_s = a UCS^b \quad a = 200 \rightarrow 450 \quad b = 0.4 \rightarrow 0.6 \]
Rock Testing

Point Load Testing

Uniaxial Compression Test

On site Rock Core Point Load testing
Pile End Bearing

- **Effective Stress Approach**
  
  Granular

  \[ q_b = \sigma'_v \ N_q \]

- **Total Stress Approach**
  
  Cohesive or Rock (Weak Mudstone)

  \[ q_b = c_u \ N_c \]
Pile End Bearing

Berezantzev Bearing Capacity
Nq versus $\varphi'$

Brinch Hansen Bearing Capacity
Nq versus $\varphi'$

Brinch Hansen Bearing Capacity
Scdc versus Depth/Diameter Ratio

Friction Angle $\varphi'$ (deg)

Friction Angle $\varphi'$ (deg)

Depth/Diameter Ratio

Scdc Factor

Prenzl Nq

Depth/Diameter Ratio

45°

40°

35°

30°

25°

0°
Pile End Bearing

- **SPT Method**
  - Chalk
    - \( q_b = 200 \text{ to } 300 \times \text{ SPT N} \)

- **UCS Method**
  - Sandstone, Limestone or Strong Mudstone
    - \( q_b = \frac{\text{UCS}}{2} \text{ N}_c \)
Calculation Methods Based on Soil Parameters

- In the UK the characteristic base resistance and shaft resistance are calculated from the characteristic end bearing and shaft friction stresses as follows:

\[ R_{b;\text{k}} = \frac{A_b \ \eta_{b;\text{k}}}{\gamma_{\text{Rd}}} \quad R_{s;\text{k}} = \frac{\sum A_{s;i} \ \eta_{s;i;\text{k}}}{\gamma_{\text{Rd}}} \]

- A model factor \( \gamma_{\text{Rd}} \) is used to ‘correct’ the partial resistance factors (applied to the characteristic resistances to obtain the design resistance \( R_{c;d} \))
Pile Load Tests – Preliminary to ULS

- **Pile Load Tests – Preliminary to ULS**

<table>
<thead>
<tr>
<th>LOAD (MN)</th>
<th>DISPLACEMENT (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0</td>
</tr>
<tr>
<td>0.5</td>
<td>5</td>
</tr>
<tr>
<td>1.0</td>
<td>10</td>
</tr>
<tr>
<td>1.5</td>
<td>15</td>
</tr>
<tr>
<td>2.0</td>
<td>20</td>
</tr>
<tr>
<td>2.5</td>
<td>25</td>
</tr>
<tr>
<td>3.0</td>
<td>30</td>
</tr>
<tr>
<td>3.5</td>
<td>35</td>
</tr>
<tr>
<td>4.0</td>
<td>40</td>
</tr>
<tr>
<td>4.5</td>
<td>45</td>
</tr>
<tr>
<td>5.0</td>
<td>50</td>
</tr>
<tr>
<td>5.5</td>
<td>55</td>
</tr>
</tbody>
</table>

**Resistance at 10% diameter**

- **5,200kN**

**Load Test to ULS Allows lower $\gamma_{Rd}$ to be used**
Correlation Factors

- The characteristic resistance $R_{c;k}$ can also be obtained from empirical relationships with ground test results (such as CPT) using the following similar relationship:

$$R_{c;k} = \text{Min} \left[ \frac{\text{Mean } R_{c;cal}}{\xi_3} \right] \text{ or } \left[ \frac{\text{Minimum } R_{c;cal}}{\xi_4} \right]$$

- Values for $\xi_3$ and $\xi_4$ depend on the number of ground test results with values decreasing as the number of profiles increases.

- Correlation factors $\xi_3$ and $\xi_4$ are used with the model pile design approach.
Calculation Methods Based on Soil Parameters

- EC7 has been written with much more emphasis on SLS behaviour regarding pile settlement and horizontal movement.
- EC7 adopts lower partial factors but on the understanding that movements are considered.
- The partial resistance factors in the UK National Annex have therefore been modified to take account of the type of pile and whether the serviceability behaviour is to be determined either by load test or a rigorous and reliable calculation.
Partial Resistance Factors

- The design resistance $R_{c;d}$ is obtained from the characteristic end bearing and shaft friction by using partial resistance factors

$$R_{c;d} = \left[ \frac{R_{b;k}}{\gamma_b} + \frac{R_{s;k}}{\gamma_s} \right] \text{ or } \left[ \frac{R_{c;k}}{\gamma_t} \right]$$

- The partial resistance factors in the UK National Annex have been modified to take account of the type of pile and whether the serviceability behaviour is to be determined either by load test or a rigorous and reliable calculation
Pile Settlement

- Empirical method: Pile settlements are dependent on the stiffness properties of the founding soil or rock, the pile geometry, and the mechanism of load transfer to the ground.
- Typically:
  - Shaft friction is mobilised at a movement equal to about 1% of the pile diameter
  - End bearing is mobilised at a movement equal to about 10% of the pile diameter
- Good for understanding behaviour but not rigorous
Pile Settlement – Typical ‘Real’ Behaviour

![Graph showing pile settlement behavior](image-url)
Pile Settlement – Simplified Idealisation

![Graph showing load vs. settlement for pile design.](image)

- **TOTAL**
- **SHAFT**
- **BASE**

<table>
<thead>
<tr>
<th>LOAD (kN)</th>
<th>SETTLEMENT (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>250</td>
<td>5</td>
</tr>
<tr>
<td>500</td>
<td>10</td>
</tr>
<tr>
<td>750</td>
<td>15</td>
</tr>
<tr>
<td>1000</td>
<td>20</td>
</tr>
<tr>
<td>1250</td>
<td>25</td>
</tr>
</tbody>
</table>

**1% Diam**

**10% Diam**
Pile Settlement

- Computational approaches for assessing pile settlements are now available for use in the commercial design office in the form of computer programs:

  - **PIGLET**: Closed form elastic continuum equations
  - **CEMSET**: Hyperbolic functions for pile base & shaft
  - **PILE**: Iterative approach based on Mindlin
  - **REPUTE**: Based on boundary elements
Pile Load Test – Working Load Test to DVL + 50%

DVL = Design Verification Load = Nominal plus Temporary support and NSF allowance
Load Test Back Analysis

Bearing capacity calculation based on soil parameters and CEMSET settlement calculation used to back analyse load test

Very good match
Negative Shaft Friction

NSF occurs when ground settlement exceeds pile settlement at any point.

Complex problem that cannot be designed by load test.

Need soil-structure interaction software.
Negative Shaft Friction

Typical software output:

100mm ground settlement
10mm pile settlement
Pile Horizontal Load

- Can carry out ULS horizontal load analyses but these depend on the assumed mechanism of behaviour.
Pile Horizontal Load

- But real piles have flexural stiffness (EI)
- Horizontal behaviour is controlled by head fixity

Larger pile movements

- Free head
- BM_{\text{max}}

- Fixed head
- BM_{\text{max}}

Fixity at depth

Smaller BM
Pile Horizontal Load

- Soil-structure interaction software can be used:
  - Options in UK are ALP or WALLAP
  - Pile is modelled as beam elements
  - Ground is modelled as springs
  - Analysis can be based on factored horizontal actions or factored soil strength (and stiffness)
  - Best to analyses without factors
  - Apply partial factors to the effects of the actions [BM & SF]
ALP uses Brinch Hansen $k_q$ and $k_c$ coefficients
Calculation Methods Based on Soil Parameters

- So why use this approach?

  - It is versatile and can adapt to complex ground models and variations in applied loads
  - It can deal with negative shaft friction
  - It can deal with horizontal loads
  - It can allow settlement behaviour to be predicted

  - It is simple to apply
  - It is based on fundamental engineering
Calculation Methods Based on Soil Parameters

Discussion and Questions