Evolution of UK Pile Design to BS EN 1997-1:2004 (EC7) and the UK National Annex

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Traditional Pile Design to BS 8004

\[
\text{Applied Load} \leq \frac{\text{Ultimate Capacity}}{\text{FoS}}
\]

- Ultimate capacity based on calculation
- Factor of Safety varied between 2.0 and 3.0 for compression loads and \( \geq 3.0 \) for tension
- Actual FoS dependent on quality of GI, prior knowledge of ground conditions and whether preliminary non-working load tests or contract proof load tests were carried out

\[
\text{Ultimate Capacity} \quad Q_{ult} = Q_s + Q_b
\]

\[
\text{Shaft Capacity} \quad Q_s = q_s A_s
\]

\[
\text{Base Capacity} \quad Q_b = q_b A_b
\]

- Basic calculation methods have not changed
So what is different?

EC7 method is a Limit State Design method:

- **Ultimate Limit State (ULS)**
  - States associated with collapse, structural failure, excessive deformation or loss of stability of the whole of the structure or any part of it

- **Serviceability Limit State (SLS)**
  - States that correspond to conditions beyond which specified service requirements are no longer met
So what is different?

- Separation of ULS and SLS condition
- Permanent and variable actions
- Favourable and unfavourable actions
- Use of characteristic ground properties
- Use of several partial factors
- Partial factors avoid failure but not necessarily movement
EC7 Limit States

- So what is different?

- Adopts five distinct ultimate limit states:
  - EQU – Loss of equilibrium (tilt or rotation)
  - STR – Internal failure or excessive deformation
    [Strength of structural material is significant]
  - GEO – Failure or excessive deformation of the ground
    [Strength of soil or rock is significant]
  - UPL – Uplift or buoyancy
  - HYD – Hydraulic heave, erosion or piping

- STR and GEO most important for pile design
So what is different?

Basic inequality to be checked:

\[ E_d \leq R_d \]

- \( E_d \) is the design value of the effect of all the actions
- \( R_d \) is the design value of the corresponding resistance of the ground or structure

For pile design, this inequality compares the design action \( F_d \) (usually load) against the design resistance \( R_d \)

\[ F_d \leq R_d \]
Effect of Actions $E_d$

- $E_d$ is the design value of the effect of all the actions:

$$E_d = E \left\{ \gamma_F F_{rep} \cdot \frac{X_k}{\gamma_m} \cdot a_d \right\}$$

- $F_{rep}$ is the representative action (usually load)
- $X_k$ is the characteristic value of the material property
- $a_d$ is the design value of a geometrical property
- $\gamma_F$ and $\gamma_m$ are relevant partial factors
- Design values:

$$F_d = \gamma_F F_{rep} \quad X_d = \frac{X_k}{\gamma_m} \quad a_d = a_{nom} \mp \Delta a$$
UK National Annex

- UK has adopted Design Approach 1 - DA1
- This requires two calculations:
  - A1 + R1 + M1 Combination 1
  - R4 + A2 + M1/M2 Combination 2
    - (Use M1 for calculating resistances)
    - (Use M2 for unfavourable actions such as NSF)
- For Combination 1, partial factors > 1.0 are applied to the actions only and does not usually control pile length
- For Combination 2, partial factors > 1.0 are applied to resistances with smaller factors applied to variable actions
- Both combinations should be checked
Design Actions $F_d$

- $F_d$ is the design action

\[ F_d = \gamma_F F_{\text{rep}} \]

- $F_{\text{rep}}$ is the representative action (usually load)

\[ F_{\text{rep}} = G_k + \psi Q_k + A_k \]

\[ \psi = 1.0 \text{ for leading action or } = \psi_0, \psi_1 \text{ or } \psi_2 \]

- $G_k$ is the characteristic permanent action
- $Q_k$ is the characteristic variable action
- $A_k$ is the characteristic accidental action
- $\psi$ is the factor for combination of variable actions
## Partial Factors on Actions

<table>
<thead>
<tr>
<th>Action</th>
<th>UK NA Factor Set</th>
<th>EC7 Factor Set</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A1</td>
<td>A2</td>
</tr>
<tr>
<td>Permanent</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unfavourable</td>
<td>1.35</td>
<td>1.0</td>
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<tr>
<td>Favourable</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Variable</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unfavourable</td>
<td>1.5</td>
<td>1.3</td>
</tr>
<tr>
<td>Favourable</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**Notes:**
1. Factors can be applied to Actions or the Effect of Actions.
2. Factors given above are for buildings which remain unchanged from EC7 values.
3. Combination factors for actions that can exist simultaneously are given in the UK NA to BS EN 1990.
4. There are a wider range of factors for bridges.
Ground Characterisation

- EC7 says a lot about determining characteristic or representative soil properties
- Cautious estimate affecting the occurrence of the limit state
- Similar to BS 8002 and CIRIA 104
- But most engineers already adopting cautious estimates
- Engineering judgement required
- Statistics can be applied, but is difficult because of the usual limited number of samples and test data

- For pile design, not a great deal of difference between soil parameters for EC7 design compared to BS 8004 design
Design Soil Parameters

- Design values are obtained by dividing the characteristic or representative property by a partial factor

\[ X_d = \frac{X_k}{\gamma_m} \]

- Usual properties to be factored are strength [but stiffness may need to be factored for horizontal load design]

- Either effective stress strength, \( c' \) and \( \Phi' \), or undrained shear strength \( c_u \), or unconfined compressive strength UCS for rocks

- For pile design to the UK NA, factored design soil parameters are not used except for negative shaft friction
## Partial Factors on Soil Parameters

<table>
<thead>
<tr>
<th>Soil Property</th>
<th>UK NA Factor Set</th>
<th>EC7 Factor Set</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M1</td>
<td>M2</td>
</tr>
<tr>
<td>Friction Angle tan $\phi'$</td>
<td>1.0</td>
<td>1.25</td>
</tr>
<tr>
<td>Effective Cohesion $c'$</td>
<td>1.0</td>
<td>1.25</td>
</tr>
<tr>
<td>Undrained Shear Strength $Cu$</td>
<td>1.0</td>
<td>1.4</td>
</tr>
<tr>
<td>Unconfined Strength $UCS$</td>
<td>1.0</td>
<td>1.4</td>
</tr>
<tr>
<td>Unit Weight $\gamma$</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

UK NA gives no factor for unit weight so presume 1.0; other factors remain unchanged. Not used directly for pile design, but may be used for Negative Shaft Friction.
If not factored soil properties, what?

For pile design, it is necessary to compare the design action $F_d$ (usually load) against the design resistance $R_d$

$$F_d \leq R_d$$

But note that this is now in terms of compression or tension load and compression or tension resistance:

$$F_{c;d} \leq R_{c;d} \quad F_{t;d} \leq R_{t;d}$$

As is usual, the design resistance $R_{c;d}$ can be assumed to be the sum of the end bearing and shaft design resistances:

$$R_{c;d} = R_{b;d} + R_{s;d}$$
The design resistances $R_{c;d}$ or $R_{t;d}$ are obtained from the characteristic end bearing and shaft friction by using partial resistance factors:

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

$$R_{c;k} = R_{b;k} + R_{s;k}$$

The characteristic end bearing and shaft friction can be computed using existing and recognisable methods either by calculation, back analysis of static or dynamic load testing, direct measurement from load testing or correlation with CPT or other insitu ground testing.
Pile Design by Calculation

- The characteristic base resistance and shaft resistance can be calculated from the characteristic end bearing and shaft friction stresses as follows:

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

- These are similar to the approach used for BS 8004 but include an additional model factor \( \gamma_{Rd} \) to 'correct' the partial resistance factors (applied to the characteristic resistances to obtain the design resistance \( R_{c;d} \))

- At present, EC7 includes the above equations in clause 7.6.2.3 as an ‘alternative procedure’ This is not reasonable for such an important approach for pile design
Pile Shaft Friction

- Effective Stress Approach – Granular
  \[ q_s = \sigma'_v \, k_s \tan \delta \]

- Total Stress Approach – Cohesive or Rock (Weak Mudstone)
  \[ q_s = \alpha \, c_u \]

- Beta Method – Soft Soils or Chalk
  \[ q_s = \sigma'_v \, \beta \quad \beta = k_s \tan \delta \]
  \[ \beta = 0.45 \text{ to } 0.80 \text{ for Chalk} \]

- UCS Method – Sandstone, Limestone or Strong Mudstone
  \[ q_s = a \, \text{UCS}^b \]
  \[ a = 200 \rightarrow 450 \quad b = 0.4 \rightarrow 0.6 \]

- Basic calculation methods have not changed
Pile End Bearing

- Effective Stress Approach – Granular
  \[ q_b = \sigma'_v \ N_q \]

- Total Stress Approach – Cohesive or Rock (Weak Mudstone)
  \[ q_b = c_u \ N_c \]

- SPT Method – Chalk
  \[ q_b = 200 \text{ to } 300 \times \text{SPT N} \]

- UCS Method – Sandstone, Limestone or Strong Mudstone
  \[ q_b = \frac{UCS}{2} \ N_c \]

- Basic calculation methods have not changed
Partial Resistance Factors

- The design resistance $R_d$ 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.

- The proposed model factor $\gamma_{Rd}$ used to ‘correct’ the partial resistance factors also depends on whether a ULS load test is proposed.
## Partial Resistance Factors for Driven Piles

<table>
<thead>
<tr>
<th>Component</th>
<th>UK NA Factor Set</th>
<th>EC7 Factor Set</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R1</td>
<td>R4 (No SLS)</td>
</tr>
<tr>
<td>Base</td>
<td>1.0</td>
<td>1.7</td>
</tr>
<tr>
<td>Shaft</td>
<td>1.0</td>
<td>1.5</td>
</tr>
<tr>
<td>Total</td>
<td>1.0</td>
<td>1.7</td>
</tr>
<tr>
<td>Tension</td>
<td>1.0</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Main differences for resistance factors relate to:

1. Factor set R4 where different values depend on whether SLS behaviour is verified or not (test or calculation).
2. Model factor to be applied to ground properties to derive characteristic values or directly to the calculated shaft or end bearing capacities.
3. Model factor 1.4, but can be reduced to 1.2 if a load test is completed to calculated unfactored ultimate resistance (ULS check).
Partial Resistance Factors for Bored Piles

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<th>EC7 Factor Set</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R1</td>
<td>R4 (No SLS)</td>
</tr>
<tr>
<td>Base</td>
<td>1.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Shaft</td>
<td>1.0</td>
<td>1.6</td>
</tr>
<tr>
<td>Total</td>
<td>1.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Tension</td>
<td>1.0</td>
<td>2.0</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>Pile Type</th>
<th>Actions</th>
<th>Resistance Factors</th>
<th>Model Factor</th>
<th>Lumped FoS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>R4 (No SLS)</td>
<td>R4 (SLS)</td>
<td></td>
</tr>
<tr>
<td>Driven End Bearing</td>
<td>A2</td>
<td>1.1</td>
<td>1.7</td>
<td>2.6/2.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>Driven End &amp; Shaft</td>
<td>A2</td>
<td>1.1</td>
<td>1.7/1.5</td>
<td>2.2/2.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.5/1.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>Bored Shaft Friction</td>
<td>A2</td>
<td>1.1</td>
<td>1.6</td>
<td>2.1/1.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.2</td>
<td></td>
</tr>
</tbody>
</table>

1. Partial factor on actions assumes 70% permanent and 30% variable.
2. British Standard BS 8004 lumped FoS ranged from 2.0 to 3.0.
3. Model factor 1.2 requires load test to be completed to calculated unfactored ultimate resistance.
4. Lower value for resistance factors dependent on SLS behaviour being verified (by load test or reliable calculation).
Evolution of Pile Design

- Earlier presentations have explained how Eurocodes are under review and evolving:
  - Remove clutter and unnecessary detail
  - Simplify rules where possible
  - Harmonise design across Europe

- For pile design:
  - UK’s main target was to have design by calculation on an equal footing as design by static or dynamic load testing, pressuremeter or CPT
  - Also to keep the benefit of pile load testing
Evolution of Pile Design

- Harmonisation is very difficult:
- Wide range of design methods:
  - UK – calculation based on GI data
  - Germany – based on published experience
  - France – correlation with pressuremeter
  - Holland – CPT and dynamic load testing
  - Sweden/Norway – dynamic load testing
- Design Approach varies:
  - DA1 in UK
  - DA2 in France, Germany, Italy, Sweden, Norway……
  - DA3 in Holland and Denmark
Evolution of Pile Design

- But all have in common:
  - Use resistance factors
  - Use design by calculation to deal with varying ground sections or where test conditions are different to final conditions (e.g., basements)
  - Use design by calculation for NSF
  - Use design by calculation for horizontal load
Evolution of Pile Design

- How do we harmonise?
  - Remove Design Approaches
  - All use the same resistance factors

- But what about:
  - Different pile types
  - Benefit of load testing
  - Design situation
    - [Persistent, transient, accidental or earthquake]
  - Importance (Geotechnical Categories)
    - [Major structure high risk, minor structure low risk]
Evolution of Pile Design

- What does this mean to UK?
  - Most countries use DA2
  - DA2 factors actions and resistances using larger partial factors than the UK DA1 combination 2 \([R4 + A2]\)
  - DA2 resistance factors are smaller
  - Design approaches will be dropped but the Resistance Factor Approach is essentially DA2

- To harmonise, UK will have to change methods yet again
  - We will do this on our terms
  - Include what is best from the current UK approach
Evolution of Pile Design


<table>
<thead>
<tr>
<th>Partial factors on actions GEO</th>
<th>Resistance Factor Approach</th>
<th>Other Possible Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unfavourable permanent</td>
<td>$\gamma_{G,geo}$</td>
<td>$K_{F,I}$</td>
</tr>
<tr>
<td>Unfavourable variable</td>
<td>$\gamma_{Q,geo}$</td>
<td>$K_{F,DS}$</td>
</tr>
<tr>
<td>Favourable permanent</td>
<td>$\gamma_{G,fav}$</td>
<td>$0.9-1.1$</td>
</tr>
<tr>
<td>Favourable variable</td>
<td>$\gamma_{Q,fav}$</td>
<td>$0.8-1.0$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Partial factors on actions STR</th>
<th>Resistance Factor Approach</th>
<th>Other Possible Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unfavourable permanent</td>
<td>$\gamma_{G,str}$</td>
<td>$K_{F,I}$</td>
</tr>
<tr>
<td>Unfavourable variable</td>
<td>$\gamma_{Q,str}$</td>
<td>$K_{F,DS}$</td>
</tr>
<tr>
<td>Favourable permanent</td>
<td>$\gamma_{G,fav}$</td>
<td>$0.9-1.1$</td>
</tr>
<tr>
<td>Favourable variable</td>
<td>$\gamma_{Q,fav}$</td>
<td>$0.8-1.0$</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>Partial factors on pile resistance</th>
<th>Resistance Factor Approach</th>
<th>Other Possible Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pile shaft resistance</td>
<td>$\gamma_s$</td>
<td>$\gamma_{Rd}$</td>
</tr>
<tr>
<td>Pile base resistance</td>
<td>$\gamma_b$</td>
<td>$K_{R,Test}$</td>
</tr>
<tr>
<td>Pile total resistance</td>
<td>$\gamma_t$</td>
<td>$K_{R,Settlement}$</td>
</tr>
<tr>
<td>Pile shaft (tension)</td>
<td>$\gamma_{s,t}$</td>
<td>$K_{R,Pile}$</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>$K_{R,Test}$</th>
<th>$K_{R,Settlement}$</th>
<th>$K_{R,Pile}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.85-1.0</td>
<td>0.85-1.0</td>
<td>0.9-1.0</td>
</tr>
</tbody>
</table>
## Equivalent Lumped FoS

<table>
<thead>
<tr>
<th>Pile Type</th>
<th>STR Actions</th>
<th>Resistance Factor</th>
<th>Model Factor</th>
<th>$K_{R,\text{Test}}$</th>
<th>$K_{R,\text{Settlement}}$</th>
<th>$K_{R,\text{Pile}}$</th>
<th>Lumped FoS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driven</td>
<td>1.4</td>
<td>1.1</td>
<td>1.8</td>
<td>0.85</td>
<td>0.85</td>
<td>0.9</td>
<td>1.80</td>
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<td></td>
<td>0.85</td>
<td>1.0</td>
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<td>2.10</td>
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<td></td>
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<td>2.50</td>
</tr>
<tr>
<td>Bored</td>
<td>1.4</td>
<td>1.1</td>
<td>1.8</td>
<td>0.85</td>
<td>0.85</td>
<td>1.0</td>
<td>2.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
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<td>0.85</td>
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<td></td>
<td></td>
<td></td>
<td>2.75</td>
</tr>
</tbody>
</table>

1. Partial factor on actions assumes 70% permanent and 30% variable.
2. British Standard BS 8004 lumped FoS ranged from 2.0 to 3.0.
3. $K_{R,\text{Test}} = 0.85$ requires load test to be completed to calculated unfactored ultimate resistance otherwise set to 1.0.
4. $K_{R,\text{Settlement}} = 0.85$ dependent on SLS behaviour being verified (by load test or reliable calculation) otherwise set to 1.0.
Evolution of Pile Design

- What has EG7 achieved to date?
  - A lot of technical discussion and hot air but not much conclusion or agreement

- But:
  - Chapter 7 has been restructured and does now include design by calculation on an equal footing with design by static and dynamic load testing, pressuremeter and CPT
  - Agreement in principle to harmonise pile design to use the Resistance Factor Approach [RFA] with consistent factors
  - It is still a very steep uphill route.