Examples JRC-08
Example 1 - Pile foundation designed from static pile load tests

**Design situation**

Piles are required to support the following loads from a building:

- Characteristic permanent vertical load: \( G_k = 6.0 \, \text{MN} \)
- Characteristic variable vertical load: \( Q_k = 3.2 \, \text{MN} \)

The design involves determining the number of piles to support the building. The number of piles is to be determined on the basis of static pile load tests.

**Geometry**

It has been decided to use bored piles, 1.2m in diameter and 15m long.

**Measured pile resistance**

Static pile load tests have been performed on site on four piles of the same diameter and length as the chosen piles.

The results of the load-settlement curves are plotted in the figure opposite.

In accordance with 7.6.1.1(3), settlement of the pile top equal to 10% of the pile base diameter \( s_b = (10/100) \times 1.2 \times 10^3 = 120\text{mm} \) has been adopted as the "failure" criterion for the piles.

From the load-settlement graphs for each pile this gives:

- Pile 1: \( R_m = 2.14 \, \text{MN} \)
- Pile 2: \( R_m = 1.96 \, \text{MN} \)
- Pile 3: \( R_m = 1.73 \, \text{MN} \)
- Pile 4: \( R_m = 2.33 \, \text{MN} \)

Hence the mean and minimum measured pile resistances are:

\[
\begin{align*}
(R_m)_{\text{mean}} &= 2.04 \, \text{MN} \\
(R_m)_{\text{min}} &= 1.73 \, \text{MN}
\end{align*}
\]

**Characteristic resistance**

The characteristic pile resistance is obtained by dividing the mean and minimum measured pile resistances by the correlation factors \( \xi_1 \) and \( \xi_2 \) and choosing the minimum value.

For four load tests, recommended \( \xi \) values are \( \xi_1 = 1.1 \) and \( \xi_2 = 1.0 \)

Hence the characteristic pile resistance, \( R_{c,k} = \text{Min}(2.04/1.1;1.73/1.0) = \text{Min}(1.85;1.73) = 1.73 \, \text{MN} \)
Design Approach 1

Combinations of sets of partial factors

DA1.C1: A1 “+” M1 “+” R1
DA1.C2: A2 “+” M1 “+” R4

Design actions

DA1.C1 \[ F_{c;d} = \gamma_G G_k + \gamma_Q Q_k = 1.35 \times 6.0 + 1.5 \times 3.2 = 12.9 \text{ MN} \]
DA1.C1 \[ F_{c;d} = \gamma_G G_k + \gamma_Q Q_k = 1.0 \times 6.0 + 1.3 \times 3.2 = 10.2 \text{ MN} \]

Characteristic resistances

DA1.C1 \[ R_{c;d} = \frac{R_{ck}}{1.15} = 1.73 / 1.15 = 1.50 \text{ MN} \]
DA1.C2 \[ R_{c;d} = \frac{R_{ck}}{1.5} = 1.73 / 1.5 = 1.15 \text{ MN} \]

Design equation

\[ F_{c;d} \leq R_{c;d} \]

Hence equating design actions and design resistances for n piles:

DA1.C1 \[ 12.9 = 1.50 n \quad n = 12.9 / 1.5 \quad n = 8.6 \text{ piles} \]
DA1.C2 \[ 10.2 = 1.15 n \quad n = 10.2 / 1.15 \quad n = 8.9 \text{ piles} \]

Design pile length

Hence DA1.C2 controls the DA1 design and the number of piles required is 9.

Design Approach 2

Combinations of set of partial factors

DA2 A1 “+” M1 “+” R2

Design actions

\[ F_{c;d} = \gamma_G G_k + \gamma_Q Q_k = 1.35 \times 6.0 + 1.5 \times 3.2 = 12.9 \text{ MN} \]

Design resistances

\[ R_{c;d} = \frac{R_{ck}}{1.1} = 1.73 / 1.1 = 1.57 \text{ MN} \]

Design equation

\[ F_{c;d} \leq R_{c;d} \]

Hence equating design actions and design resistances:

DA2 \[ 12.9 = 1.57 n \quad n = 12.9 / 1.57 \quad n = 8.2 \text{ piles} \]

Design pile length

Hence using, the DA2, the number of piles required is 9.
Design Approach 3

Combinations of sets of partial factors

DA3: A1† or A2† “+” M2 “+” R3 † on structural actions
† on geotechnical actions

DA3 not to be used

Since the R3 recommended partial resistance factors used in DA3 are all equal to 1.0, no safety margin is provided if DA3 is used to calculate the design pile resistance from pile load tests and therefore piles should not be designed using DA3 and pile load tests unless the resistance factors are increased.

Conclusions from Example 1

• The same pile design length, 21m is required for both DA1 and DA2

• Since the partial resistance factors are 1.0 for DA3, this Design Approach should not be used for the design of piles from pile load tests unless the resistance factors are increased.
Example 2 - Pile foundation designed from soil test profile

**Design situation**
The piles for a building are each required to support the following loads:
- Characteristic permanent vertical load $G_k = 300$ kN
- Characteristic variable vertical load $Q_k = 150$ kN

The ground consists of dense sand beneath loose sand with soft clay and peat to 16.5m. One CPT test profile is available. The pile foundation design involves determining the design length, $L$ of the piles.

**Geometry**
It has been decided to use bored piles with a diameter $D = 0.45$m.

**Material properties**
1 CPT was carried out and the results are shown in the figure opposite.

Soil has an upper 11m layer of loose sand, soft clay and some peat over 5.5m of clay with peat seams.

In the upper layer:
- Cautious average $q_c = 2.5$ MPa

A stronger lower layer of medium to dense sand starts at depth of 16.5m

In the lower layer:
- Cautious average $q_c = 12.5$ MPa

Assume the soil above 16.5m provides no shaft resistance

The pile base and shaft resistances are calculated using Tables D.3 and D.4 of EN 1997-2 and, for simplicity, relating the single cautious average $q_c$ value in lower layer of stronger soil to the unit base and shaft resistances, $p_b$ and $p_s$.

Assume the ULS settlement of the pile head, $s_g$ so that the normalised settlement is 0.1.

Interpret linearly between relevant $q_c$ values to obtain $p_b$ and $p_s$ from these tables:

$$p_b = 2.5 \text{ MPa}$$
$$p_s = 0.1 \text{ MPa}$$

---

**Table D.3**
Unit base resistance $p_b$ of cast in-situ piles in coarse soil with little or no fines

<table>
<thead>
<tr>
<th>Normalised settlement $s/D_s$</th>
<th>$q_c = 10$</th>
<th>$q_c = 15$</th>
<th>$q_c = 20$</th>
<th>$q_c = 25$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.02</td>
<td>0.70</td>
<td>1.05</td>
<td>1.40</td>
<td>1.75</td>
</tr>
<tr>
<td>0.03</td>
<td>0.90</td>
<td>1.35</td>
<td>1.80</td>
<td>2.25</td>
</tr>
<tr>
<td>0.10 ($= s_g$)</td>
<td>2.00</td>
<td>3.00</td>
<td>3.50</td>
<td>4.00</td>
</tr>
</tbody>
</table>

**Table D.4**
Unit shaft resistance $p_s$ of cast in-situ piles in coarse soil with little or no fines

<table>
<thead>
<tr>
<th>Average cone penetration resistance $q_c$ (CPT) MPa</th>
<th>Unit shaft resistance $p_s$ MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>0.040</td>
</tr>
<tr>
<td>10</td>
<td>0.080</td>
</tr>
<tr>
<td>&gt; 15</td>
<td>0.120</td>
</tr>
</tbody>
</table>

**NOTE**  Intermediate values may be interpolated linearly.
**Characteristic pile resistance**

Pile base cross sectional area: \( A_b = \pi \times 0.45^2 / 4 = 0.159 \text{ m}^2 \)

Pile shaft area per metre length: \( A_s = \pi \times 0.45 = 1.414 \text{ m}^2/\text{m} \)

Length of pile in lower stronger layer providing shaft resistance = \( L_s \)

Calculated compressive pile resistance for the one profile of test results:

\[
R_{c,\text{cal}} = R_{b,\text{cal}} + R_{s,\text{cal}} = A_b \times p_b + A_s \times L_s \times p_s = (0.159 \times 2.5 + 1.414 \times L_s \times 0.1) \times 10^3 \text{ kN}
\]

\[ R_{c,\text{cal}} = 398 + 141 L_s \text{ kN} \]

Hence, applying the recommended correlation factors \( \zeta_3 \) and \( \zeta_4 \), which are both the same and equal to 1.4 for one profile of test results because the mean and minimum calculated resistances are the same so that \( \zeta_3 \) and \( \zeta_4 = \zeta = 1.4 \), and the characteristic base and shaft compressive pile resistances are:

\[
R_{b,k} = R_{b,\text{cal}} / \zeta = 398 / 1.4 = 284 \text{ kN}
\]

\[
R_{s,k} = R_{s,\text{cal}} / \zeta = 141 \times L_s / 1.4 = 101 \times L_s \]

**Design Approach 1**

**Design actions**

\[
DA1.C1 \quad F_{c,d} = \gamma_G G_k + \gamma_Q Q_k = 1.35 \times 300 + 1.5 \times 150 = 630 \text{ kN}
\]

\[
DA1.C1 \quad F_{c,d} = \gamma_G G_k + \gamma_Q Q_k = 1.0 \times 300 + 1.3 \times 150 = 495 \text{ kN}
\]

**Design resistances**

\[
DA1.C1 \quad R_{c,d} = R_{b,k} / \gamma_b + R_{s,k} / \gamma_s = 284 / 1.25 + 101 L_s / 1.0
\]

\[
DA1.C2 \quad R_{c,d} = R_{b,k} / \gamma_b + R_{s,k} / \gamma_s = 284 / 1.6 + 101 L_s / 1.3
\]

**Design equation**

\[ F_{c,d} \leq R_{c,d} \]

Hence equating design actions and design resistances:

\[
DA1.C1 \quad 630 = 284 / 1.25 + 101 L_s / 1.0 \quad L_s = 3.99 \text{ m}
\]

\[
DA1.C2 \quad 495 = 284 / 1.6 + 101 L_s / 1.3 \quad L_s = 4.08 \text{ m}
\]

**Design pile length**

Hence DA1.C2 controls the DA1 design and the DA1 design pile length \( L = 16.5 + L_s = 21 \text{ m} \)
Design Approach 2

Design actions

\[ F_{c,d} = \gamma_G G_k + \gamma_Q Q_k = 1.35 \times 300 + 1.5 \times 150 = 630 \text{ kN} \]

Design resistances

\[ R_{c,d} = \frac{R_{b,k}}{\gamma_b} + \frac{R_{s,k}}{\gamma_s} = \frac{284}{1.1} + 101 \times L_s / 1.1 \]

Design equation

\[ F_{c,d} \leq R_{c,d} \]

Hence equating design actions and design resistances:

\[ DA2 \quad 630 = \frac{284}{1.1} + 101 \times L_s / 1.1 \quad L_s = 4.05 \text{ m} \]

Design pile length

\[ \text{Hence the DA2 design pile length } L = 16.5 + L_s = 21 \text{ m} \]

Design Approach 3

As the R3 recommended partial resistance factors used in DA3 are equal to 1.0, no safety margin is provided if these are used in DA3 to calculate the design pile resistance from a CPT test profile. Hence, piles should not be designed from CPT test profiles using DA3 unless a model factor is applied to increase the partial resistance factors

Conclusions from Example 2

The same design pile length, 21m is required for both DA1 and DA2

Since the recommended partial resistance factors are 1.0 for DA3, this Design Approach should not be used for the design of piles from profiles of ground test results unless the partial resistance factors are increased.
**Examples JRC-08**

**Example 3 - Pile foundation designed from soil parameters**

*Design situation*

The piles for a proposed building in Dublin are each required to support the following loads:

- **Characteristic permanent vertical load** \( G_k = 600 \text{ kN} \)
- **Characteristic variable vertical load** \( Q_k = 300 \text{ kN} \)

The ground consists of about 3m Brown Dublin Boulder Clay over Black Dublin Boulder Clay to great depth. A large number of SPT results are available.

The pile foundation design involves determining the design length, \( L \) of the piles.

*Geometry*

It has been decided to use driven piles with a diameter \( D = 0.45 \text{ m} \).

*Material properties*

The figure opposite shows tests results of SPT \( N \) values plotted against depth. Shaft resistance in Brown Dublin Boulder Clay is ignored. The average \( N \) value in Black Dublin Boulder Clay:

\[ N_{av} = 57 \]

A cautious average \( N \) value:

\[ N_{av,cau} = 45 \]

Plasticity Index of the Dublin Boulder Clay:

\[ PI = I_p = 14\% \]

From Stroud and Butler plot of \( f_1 \) vs. \( N \):

Adopt \( f_1 = 6 \)

Hence the cautious undrained shear strength:

\[ c_u = f_1 \times N = 270 \text{ kPa} \]

*Pile resistances*

Pile base cross-sectional area:

\[ A_b = \pi \times 0.45^2 / 4 = 0.159 \text{ m}^2 \]

If length of pile in Black Dublin Boulder Clay providing shaft resistance = \( L_s \), then pile shaft area is:

\[ A_s = \pi \times 0.45 \times L_s = 1.414 \text{ m}^2 \]

Characteristic unit pile base resistance:

\[ q_{b,k} = N_q \times c_u = 9 \times 270 \text{ kPa} \]

Characteristic unit shaft resistance:

\[ q_{s,k} = \alpha \times c_u = 0.4 \times 270 \text{ kPa} \]

Hence

Characteristic base resistance:

\[ R_{b,k} = A_b \times q_{b,k} = 0.159 \times 9 \times 270 = 386 \text{ kN} \]

Characteristic shaft resistance:

\[ R_{s,k} = A_s \times q_{s,k} = 1.414 \times L_s \times 0.4 \times 270 = 153 \times L_s \]
**Design Approach 1**

Since the building is being constructed in Dublin, the Irish NA must be used.

The Irish NA requires that the pile partial resistance factors are increased by a model factor of 1.75.

**Design actions**

\[
\begin{align*}
DA1.C1 \quad F_{c,d} &= \gamma_G G_k + \gamma_Q Q_k = 1.35 \times 600 + 1.5 \times 300 = 1260 \text{kN} \\
DA1.C1 \quad F_{c,d} &= \gamma_G G_k + \gamma_Q Q_k = 1.0 \times 600 + 1.3 \times 300 = 990 \text{kN}
\end{align*}
\]

**Design resistances**

\[
\begin{align*}
DA1.C1 \quad R_{c,d} &= R_{b,k} / (\gamma_b \times \gamma_{R,d}) + R_{s,k} / (\gamma_s \times \gamma_{R,d}) \\
&= 386 / (1.0 \times 1.75) + 153 \times L_s / (1.0 \times 1.75) = 221 + 87.4 L_s \text{kN} \\
DA1.C2 \quad R_{c,d} &= R_{b,k} / (\gamma_b \times \gamma_{R,d}) + R_{s,k} / (\gamma_s \times \gamma_{R,d}) \\
&= 386 / (1.3 \times 1.75) + 153 \times L_s / (1.3 \times 1.75) = 170 + 67.3 L_s \text{kN}
\end{align*}
\]

**Design equation**

\[
F_{c,d} \leq R_{c,d}
\]

Hence equating design actions and design resistances:

\[
\begin{align*}
DA1.C1 \quad 1260 &= 221 + 87.4 L_s \quad \rightarrow \quad L_s = 11.9 \text{ m} \\
DA1.C2 \quad 990 &= 170 + 67.3 L_s \quad \rightarrow \quad L_s = 12.2 \text{ m}
\end{align*}
\]

**Design pile length**

Hence DA1.C2 controls the DA1 design and the DA1 design pile length \( L = 3 + L_s = 15.5 \text{ m} \)

**Design Approach 2**

As in the case of Design Approach 1, the Irish NA requires the pile partial resistance factors to be increased by a model factor of 1.75.

**Design actions**

\[
\begin{align*}
DA2 \quad F_{c,d} &= \gamma_G G_k + \gamma_Q Q_k = 1.35 \times 600 + 1.5 \times 300 = 1260 \text{kN}
\end{align*}
\]

**Design resistances**

\[
\begin{align*}
DA2 \quad R_{c,d} &= R_{b,k} / (\gamma_b \times \gamma_{R,d}) + R_{s,k} / (\gamma_s \times \gamma_{R,d}) \\
&= 386 / (1.1 \times 1.75) + 153 \times L_s / (1.1 \times 1.75) = 201 + 79.5 L_s \text{kN}
\end{align*}
\]

**Design equation**

\[
F_{c,d} \leq R_{c,d}
\]

Hence equating design actions and design resistances:

\[
\begin{align*}
DA2 \quad 1260 &= 201 + 79.5 L_s \quad \rightarrow \quad L_s = 13.3 \text{ m}
\end{align*}
\]

**Design pile length**

Hence the DA2 design pile length \( L = 3.0 + L_s = 16.5 \text{ m} \)
Design Approach 3

In DA3, the partial resistance factors are all unity, so the Irish NA requirement to increase the pile partial resistance factors by a model factor of 1.75 is not relevant. The pile design resistances are obtained by applying partial material factors to suitably cautious characteristic soil parameter values. It is assumed that the characteristic undrained strength is the value obtained from the cautious average N value = 45.

**Design actions**

\[ F_{c,d} = \gamma_G G_k + \gamma_Q Q_k = 1.35 \times 600 + 1.5 \times 300 = 1260 \text{ kN} \]

**Design resistances**

\[
R_{c;d} = R_{b;d} + R_{s;d}
= A_b q_{b;d} + A_s q_{s;d}
= (A_b N_q c_{u;k} / \gamma_{c_u}) / (\gamma_{R;d} x \gamma_{b}) + (\pi D L_s 0.4 c_{u;k} / \gamma_{c_u}) / (\gamma_{R;d} x \gamma_{s})
= (0.159 \times 9 \times 270/1.4)/(1.75 \times 1.0) + (1.414 \times L_s \times 0.4 \times 270/1.4)/(1.75 \times 1.0)
= 158 + 62.3 L_s
\]

**Design equation**

\[ F_{c;d} \leq R_{c;d} \]

Hence equating design actions and design resistances:

\[ DA3 \quad 1260 = 158 + 62.3 L_s \quad \rightarrow \quad L_s = 17.7 \text{ m} \]

**Design pile length**

Hence DA3 design pile length \( L = 3 + L_s = 21 \text{ m} \)

Conclusions from Example 3

- The design pile lengths obtained from ground strength parameters using the alternative procedure and the model factor in the Irish National Annex are:
  - DA1 \( L = 15.5 \text{ m} \)
  - DA2 \( L = 16.5 \text{ m} \)
  - DA3 \( L = 21.0 \text{ m} \)
- Application of the model factor of 1.75 as well as the material factor of 1.4 to obtain the design resistance when using DA3, results in DA3 providing a longer design pile length and hence the least economical Design Approach in Ireland
- If the building were to be constructed in Germany, the partial recommended in the German NA have been increased by a model factor of 1.27, compared to the model factor of 1.75 in the Irish NA, which gives a design pile length of 12.0 m in Germany using DA2 compared to 16.5 m using DA2 in Ireland.