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 $G_k = 6.0$ MN

Characteristic variable vertical load $Q_k = 3.2$ 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 $s_g = (10/100) \times 1.2 \times 10^3 =$ 120mm has been adopted as the "failure" criterion for the piles.

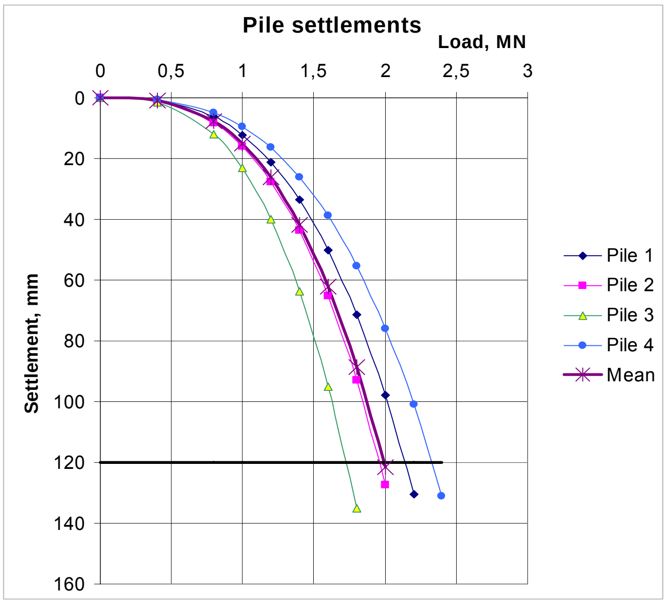
From the load-settlement graphs for each pile this gives:

Pile 1	$R_m = 2.14$ MN
Pile 2	$R_m = 1.96$ MN
Pile 3	$R_m = 1.73$ MN
Pile 4	$R_m = 2.33$ MN

Hence the mean and minimum measured pile resistances are:

$(R_m)_{mean} =$ 2.04 MN

$(R_m)_{min} =$ 1.73 MN



Characteristic resistance

The characteristic pile resistance is obtained by dividing the mean and minimum measured pile resistances by the correlation factors ξ_1 and ξ_2 and choosing the minimum value.

For four load tests, recommended ξ 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 MN**

Design Approach 1

Combinations of sets of partial factors

DA1.C1: A1 "+" M1 "+" R1

DA1.C2: A2 "+" M1 "+" R4

Design actions

DA1.C1 $F_{c;d} = \gamma_G G_k + \gamma_Q Q_k = 1.35 \times 6.0 + 1.5 \times 3.2 = 12.9$ MN

DA1.C1 $F_{c;d} = \gamma_G G_k + \gamma_Q Q_k = 1.0 \times 6.0 + 1.3 \times 3.2 = 10.2$ MN

Characteristic resistances

DA1.C1 $R_{c;d} = R_{c;k} / \gamma_t = 1.73 / 1.15 = 1.50$ MN

DA1.C2 $R_{c;d} = R_{c;k} / \gamma_t = 1.73 / 1.5 = 1.15$ MN

Design equation

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

Hence equating design actions and design resistances for n piles:

DA1.C1 $12.9 = 1.50\,n$ $n = 12.9 / 1.5$ $n = 8.6$ piles
DA1.C2 $10.2 = 1.15\,n$ $n = 10.2 / 1.15$ $n = 8.9$ 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

DA2 $F_{c;d} = \gamma_G G_k + \gamma_Q Q_k = 1.35 \times 6.0 + 1.5 \times 3.2 = 12.9$ MN

Design resistances

DA2 $R_{c;d} = R_{c;k} / \gamma_t = 1.73 / 1.1 = 1.57$ MN

Design equation

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

Hence equating design actions and design resistances:

DA2 $12.9 = 1.57\,n$ $n = 12.9 / 1.57$ $n = 8.2$ 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 calculated 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.

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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.

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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 = 0.45m.

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 MPa

p_s = 0.1 MPa

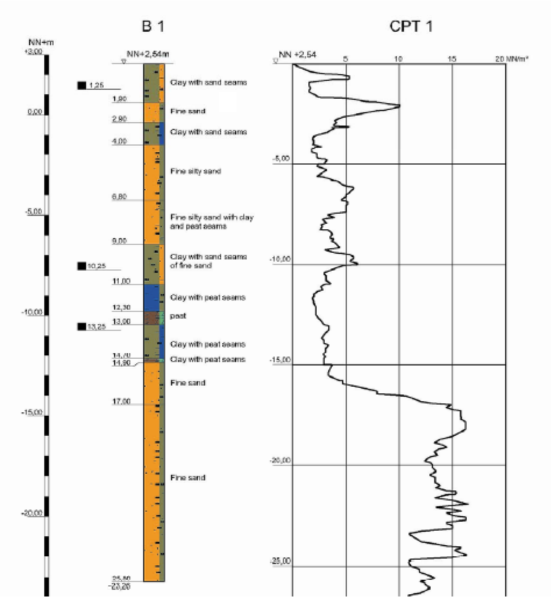

Table D.3
Unit base resistance p_b of cast in-situ piles in coarse soil with little or no fines

Normalised settlement s/D_s; s/D_b	**Unit base resistance p_b, in MPa, at average cone penetration resistance q_c (CPT) in MPa**			
	q_c = 10	**q_c = 15**	**q_c = 20**	**q_c = 25**
0,02	**0,70**	**1,05**	**1,40**	**1,75**
0,03	**0,90**	**1,35**	**1,80**	**2,25**
0,10 (= s_g)	**2,00**	**3,00**	**3,50**	**4,00**

NOTE Intermediate values may be interpolated linearly.
In the case of cast in-situ piles with pile base enlargement, the values shall be multiplied by 0,75.
s **is the normalised pile head settlement**
D_s is the diameter of the pile shaft
D_b is the diameter of the pile base
s_g is the ultimate settlement of pile head

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

Average cone penetration resistance q_c (CPT) MPa	Unit shaft resistance p_s MPa
0	0
5	0,040
10	0,080
$\geq$ 15	0,120

NOTE Intermediate values may be interpolated linearly

Characteristic pile resistance

Pile base cross sectional area: $A_b = \pi \times 0.45^2 / 4$ = $0.159\ m^2$

Pile shaft area per metre length: $A_s = \pi \times 0.45$ = $1.414\ m^2/m$

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

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

$$R_{c;cal} = R_{b;cal} + R_{s;cal} = A_b \times p_b + A_s \times L_s \times p_s$$

$$= (0.159 \times 2.5 + 1.414 \times L_s \times 0.1) \times 10^3 \text{ kN}$$

$$R_{c;cal} = 398 + 141\ L_s \text{ kN}$$

Hence, applying the recommended correlation factors ξ_3 and ξ_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 ξ_3 and ξ_4 = ξ = 1.4, and the characteristic base and shaft compressive pile resistances are:

$R_{b;k} = R_{b;cal} / \xi = 398 / 1.4$ = **284 kN**

$R_{s;k} = R_{s;cal} / \xi = 141 \times L_s / 1.4$ = **$101 \times L_s$**

<u>Design Approach 1</u>

Design actions

DA1.C1 $F_{c;d} = \gamma_G G_k + \gamma_Q Q_k = 1.35 \times 300 + 1.5 \times 150$ = **630 kN**

DA1.C1 $F_{c;d} = \gamma_G G_k + \gamma_Q Q_k = 1.0 \times 300 + 1.3 \times 150$ = **495 kN**

Design resistances

DA1.C1 $R_{c;d} = R_{b;k} / \gamma_b + R_{s;k} / \gamma_s$ = **$284 / 1.25 + 101\ L_s / 1.0$**

DA1.C2 $R_{c;d} = R_{b;k} / \gamma_b + R_{s;k} / \gamma_s$ = **$284 / 1.6 + 101\ L_s / 1.3$**

Design equation

$$F_{c,d} \leq R_{c,d}$$

Hence equating design actions and design resistances:

DA1.C1 $630 = 284 / 1.25 + 101\ L_s / 1.0$ $L_s = 3.99$ m

DA1.C2 $495 = 284 / 1.6 + 101\ L_s / 1.3$ $L_s = 4.08$ m

Design pile length

Hence DA1.C2 controls the DA1 design and the DA1 design pile length L = 16.5 + L_s = **21 m**

Design Approach 2

Design actions

DA2 $F_{c;d} = \gamma_G G_k + \gamma_Q Q_k = 1.35 \times 300 + 1.5 \times 150 =$ **630 kN**

Design resistances

DA2 $R_{c;d} = R_{b;k} / \gamma_b + R_{s;k} / \gamma_s$ = **284 / 1.1 + 101 x L_s / 1.1**

Design equation

$$F_{c,d} \leq R_{c,d}$$

Hence equating design actions and design resistances:

DA2 630 = 284 / 1.1 + 101 x L_s / 1.1 L_s = 4.05 m

Design pile length

Hence the DA2 design pile length L = 16.5 + L_s = **21 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

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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 $G_k = 600$ kN

Characteristic variable vertical load $Q_k = 300$ 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 = 0.45m.

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:

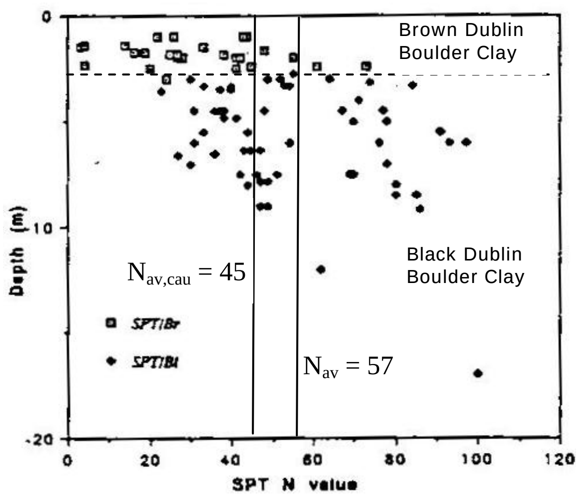
$PI = I_P = 14\%$

From Stroud and Butler plot of f_1 vs. N:

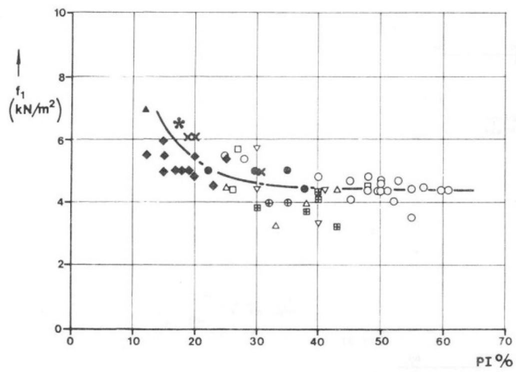
Adopt $f_1 = 6$

Hence the cautious undrained shear strength:

$\mathbf{c_u} = f_1 \times N =$ 270 kPa



SPT N values versus depth



f_1 vs. PI from Stroud and Butler

Pile resistances

Pile base cross-sectional area:

$A_b = \pi D^2/4 = \pi\ 0.45^2/4 = 0.159$ m^2

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

$A_s = \pi D L_s = \pi \times 0.45 \times L_s = 1.414\ L_s$ m^2

Characteristic unit pile base resistance:

$q_{b;k} = N_q \times c_u = 9\ c_u$

Characteristic unit shaft resistance:

$q_{s;k} = \alpha\ c_u = 0.4\ c_u$

Hence

Characteristic base resistance:

$R_{b;k} = A_b \times q_{b;k} = 0.159 \times 9 \times 270$ = **386 kN**

Characteristic shaft resistance:

$R_{s;k} = A_s\ q_{s;k} = 1.414 \times L_s \times 0.4 \times 270 = \mathbf{153\ L_s}$

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

DA1.C1 $F_{c;d} = \gamma_G G_k + \gamma_Q Q_k = 1.35 \times 600 + 1.5 \times 300 =$ **1260 kN**

DA1.C1 $F_{c;d} = \gamma_G G_k + \gamma_Q Q_k = 1.0 \times 600 + 1.3 \times 300 =$ **990 kN**

Design resistances

DA1.C1 $R_{c;d} = R_{b;k} /(\gamma_b \times \gamma_{R;d}) + R_{s;k} //(\gamma_s \times \gamma_{R;d})$

$= 386 / (1.0 \times 1.75) + 153 \times L_s /(1.0 \times 1.75) =$ **221 + 87.4 L_s kN**

DA1.C2 $R_{c;d} = R_{b;k} /(\gamma_b \times \gamma_{R;d}) + R_{s;k} //(\gamma_s \times \gamma_{R;d})$

$= 386 /(1.3 \times 1.75) + 153 \times L_s /(1.3 \times 1.75) =$ **170 + 67.3 L_s kN**

Design equation

$$F_{c,d} \leq R_{c,d}$$

Hence equating design actions and design resistances:

DA1.C1 $1260 = 221 + 87.4\ L_s \rightarrow L_s = 11.9$ m

DA1.C2 $990 = 170 + 67.3\ L_s \rightarrow L_s = 12.2$ m

Design pile length

Hence DA1.C2 controls the DA1 design and the DA1 design pile length $L = 3 + L_s =$ **15.5 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

DA2 $F_{c;d} = \gamma_G G_k + \gamma_Q Q_k = 1.35 \times 600 + 1.5 \times 300 =$ **1260 kN**

Design resistances

DA2 $R_{c;d} = R_{b;k} /(\gamma_b \times \gamma_{R;d}) + R_{s;k} //(\gamma_s \times \gamma_{R;d})$

$= 386 /(1.1 \times 1.75) + 153 \times L_s /(1.1 \times 1.75) =$ **201 + 79.5 L_s kN**

Design equation

$$F_{c,d} \leq R_{c,d}$$

Hence equating design actions and design resistances:

DA2 $1260 = 201 + 79.5\ L_s \rightarrow L_s = 13.3$ m

Design pile length

Hence the DA2 design pile length $L = 3.0 + L_s =$ **16.5 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

DA3 $F_{c,d} = \gamma_G G_k + \gamma_Q Q_k = 1.35 \times 600 + 1.5 \times 300 =$ **1260 kN**

Design resistances

DA3 $R_{c;d} = R_{b;d} + R_{s;d}$

$= A_b q_{b;d} + A_s q_{s;d}$

$= (A_b N_q c_{u;k} / \gamma_{cu})/(\gamma_{R;d} \times \gamma_b) + (\pi D L_s 0.4 c_{u;k} / \gamma_{cu})/(\gamma_{R;d} \times \gamma_s)$

$= (0.159 \times 9 \times 270/1.4)/(1.75 \times 1.0) + (1.414 \times L_s \times 0.4 \times 270/1./1.75 \times 1.0)$

$= \mathbf{158 + 62.3\, L_s}$

Design equation

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

Hence equating design actions and design resistances:

DA3 $1260 = 158 + 62.3\ L_s \rightarrow L_s = 17.7$ m

Design pile length

Hence DA3 design pile length L = 3 + L_s = **21 m**

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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 m
DA2	L = 16.5 m
DA3	L = 21.0 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.