European Commission

Worked examples – design of pile foundations

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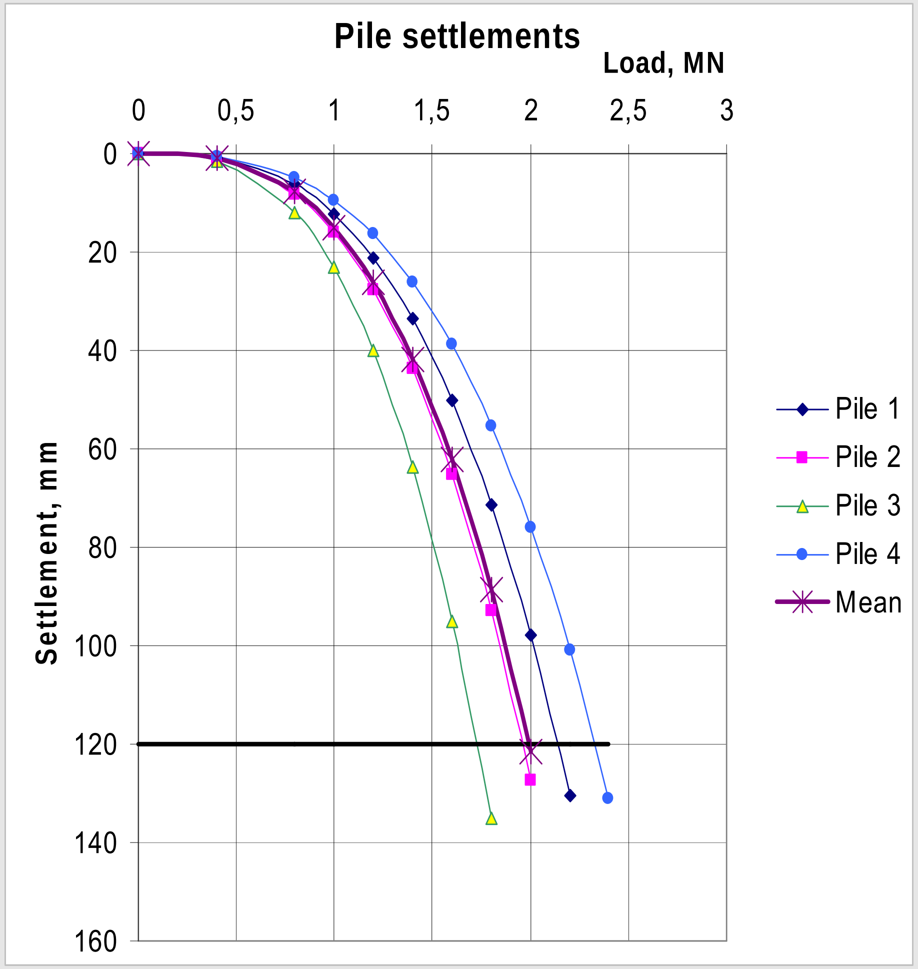
Worked example 1 –
design of pile foundations from load tests
DESIGN SITUATION

Design situation for a pile designed from static load test results

- Pile foundations 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
- It has been decided to use bored piles 1.2m in diameter and 15m long
- The pile foundation design is to determine how many piles are required

Pile load test results

- Load tests have been performed on site on four piles of the same diameter and same length
- The results of load-settlements curves are plotted in Figure 1
- Adopt settlement of the pile top equal to10% of the pile base diameter as the "failure" criterion (7.6.1.1(3))



Worked example 1 –
design of pile foundations from load tests
SOLUTION

Measured pile resistances

- Adopting the pile load at a settlement of the top of the piles equal to 10% of the pile diameter as the ultimate resistance means using the measured resistances at a settlement of:

$$12.0 \times (10/100) \times 10^3 = 120\text{mm}$$

- 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 :

$$R_{m,\,mean} = 2.04 \text{ MN}$$

$$R_{m,\,min} = 1.73 \text{ MN}$$

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:

$$R_{c;k} = \mathrm{Min}\left\{\frac{(R_{c;m})_{mean}}{\xi_1};\frac{(R_{c;m})_{min}}{\xi_2}\right\}$$

- For four load tests, recommended ξ_1 and ξ_2 values are:

$$\xi_1 = 1.1$$
$$\xi_2 = 1.0$$

- Hence the characteristic pile resistance:

$$R_{c;k} = \mathrm{Min}\left\{\frac{2.04}{1.1};\frac{1.73}{1.0}\right\} = \mathrm{Min}\{1.85;1.73\} = 1.73$$

Design Approach 1 partial factors

- Combinations of sets of partial factors

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

  DA1.C2 A2 "+" M1 or M2 "+" R4

- Partial actions factors

  A1 $\gamma_G = 1.35$ $\gamma_Q = 1.5$

  A2 $\gamma_G = 1.0$ $\gamma_Q = 1.3$

- Partial material factors

  M1 and M2 not relevant ($\gamma_{\phi'} = 1.0$ and not used)

- Partial resistance factors

  R1 $\gamma_t = 1.15$ (Total/combined compression)

  R4 $\gamma_t = 1.5$

Design Approach 1 - pile design

Design equation $\mathbf{F_{c,d} \leq R_{c,d}}$

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

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

For a single pile

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**

Assuming no pile group effect, for n piles, resistance = n x $R_{c,d}$

Hence DA1.C1 $n \geq F_{c,d} / R_{c,d}$ **=** $12.9/1.5 = 8.6$

DA1.C2 $n \geq F_{c,d} / R_{c,d}$ **=** $10.2/1.15 = 8.9$

Therefore DA1.C2 controls and no. piles required: **n = 9**

Design Approach 2 partial factors

- Combination of sets of partial factors

  DA2   A1 "+" M1 "+" R2

- Partial actions factors

  A1 $\gamma_G = 1.35$ $\gamma_Q = 1.5$

- Partial material factors

  M1 not relevant   ($\gamma_{\phi'} = 1.0$ and not used)

- Partial resistance factor

  R2 $\gamma_t = 1.1$ (Total/combined compression)

Design Approach 2 - pile design

Design equation $\mathbf{F_{c,d} \leq R_{c,d}}$

$F_{c,d} = 1.35\ G_k + 1.5\ Q_k = 1.35 \cdot x\ 6.0 + 1.5 \cdot x\ 3.2 = \mathbf{12.9\ MN}$

For a single pile

$R_{c,d} = R_{c,k} / \gamma_t = 1.73 / 1.1 = \mathbf{1.57\ MN}$

Assuming no pile group effect, for n piles, resistance = n x $R_{c,d}$

Hence $\mathbf{F_{c,d} \leq n\ R_{c,d}}$

Therefore no. piles required: **n** = $F_{c,d}$ / $R_{c,d}$ = 12.9 / 1.57 **= 9 piles**

Design Approach 3 partial factors

- Combination of sets of partial factors:

  DA3 A1 "+" M1 "+" R3

- Partial resistance factor:

  R3 γ_t = 1.0 (Total/combined compression)

- Since the R3 recommended partial resistance factor is equal to 1.0, no safety margin on the resistance is provided if DA3 is used to calculated the design pile resistance from pile load test results

- Hence piles should not be designed from load test results using Design Approach 3 and the recommended partial resistance factor

Conclusions from pile worked example 1

- The same design number of piles, 9 is obtained 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 pile load test results unless the partial resistance factors are increased

Worked example 2 –

design of pile foundations from test profiles

DESIGN SITUATION

Design situation for a pile designed from a CPT test profile

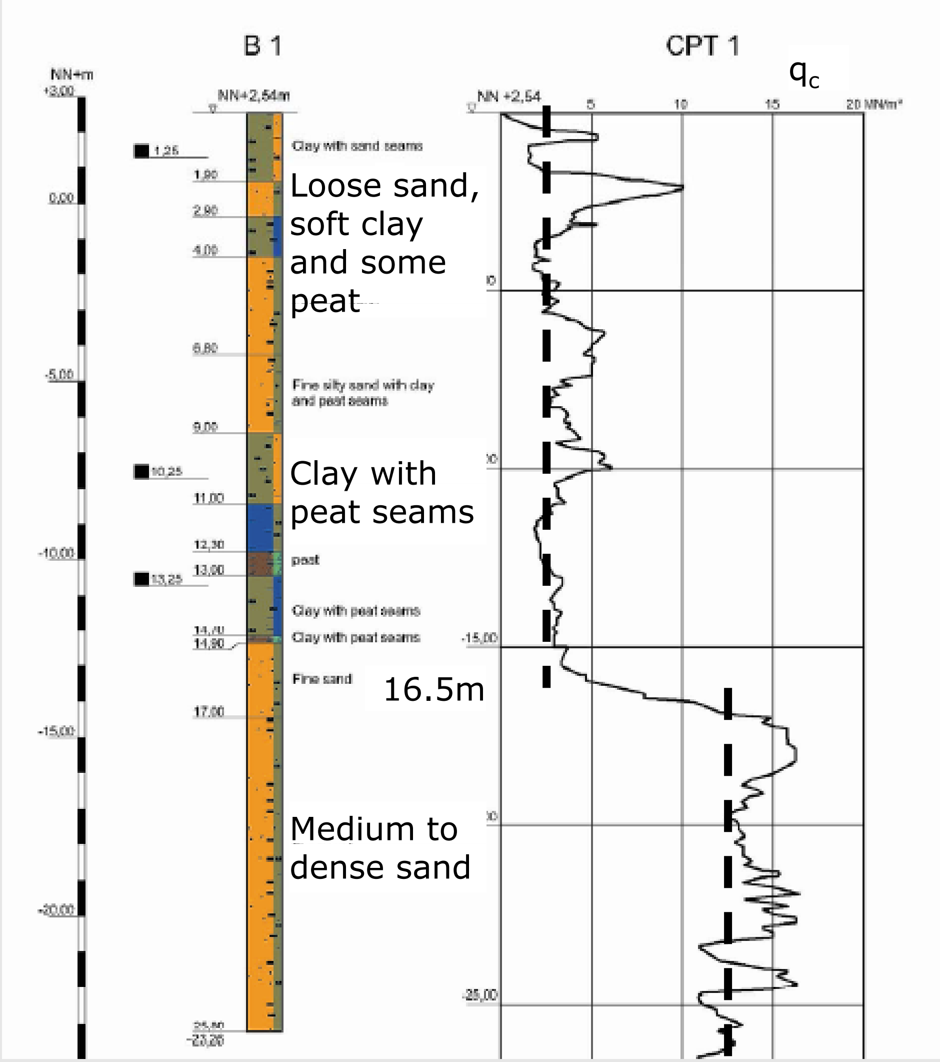
- The piles for a building are each required to support the following loads:
    - Characteristic permanent vertical load G_k = 300 kN
    - Characteristic variable vertical load Q_k = 150 kN
- The ground consists of dense sand beneath loose sand with soft clay and peat to 16.5m as shown in figure on next slide
- It has been decided to use 0.45m diameter bored piles
- The pile foundation design involves determining the length of the piles

B'hole log/CPT profile

- 1 CPT was carried out
- Soil has upper 11m layer of loose sand, soft clay and some peat over 5.5m of clay with peat seams

  Cautious average q_c = 2.5 MPa
- Stronger layer of medium to dense sand starts at depth of 16.5m

  Cautious average q_c = 12.5 MPa
- Assume the soil above 16.5m provides no shaft resistance



Unit pile resistances

- The base and shaft pile resistances are calculated using Tables D.3 and D.4 of EN 1997-2 relating a single cautious average q_c value in 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

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
> 15	0,120

NOTE Intermediate values may be interpolated linearly

Worked example 2 –
design of pile foundations from test profiles
SOLUTION

Characteristic pile resistance

Pile diameter $D = 0.45m$

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 stronger layer providing shaft resistance $= L_s$

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

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

$$= (0.159 \times 2.5 + 1.414 \times L_s \times 0.10) \times 10^3\ kN$$

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

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 $\xi_4 = \xi = 1.4$ and the characteristic base and shaft compressive pile resistances are:

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

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

Design Approach 1 partial factors

- Combinations of sets of partial factors:

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

  DA1.C2 A2 "+" M1 or M2 "+" R4

- Partial actions factors:

  A1 $\gamma_G = 1.35$ $\gamma_Q = 1.5$

  A2 $\gamma_G = 1.0$ $\gamma_Q = 1.3$

- Partial material factors:

  M1 and M2 not relevant ($\gamma_{\phi'} = 1.0$)

- Partial resistance factors:

  R1 $\gamma_b = 1.25$ $\gamma_s = 1.0$

  R4 $\gamma_b = 1.6$ $\gamma_s = 1.3$

Design Approach 1 - pile design

Design equation $\mathbf{F_{c,d} \leq R_{c,d}}$

Design actions

DA1.C1 $F_{c,d} = 1.35\ G_k + 1.5\ Q_k = 1.35x300 + 1.5x150$ = **630 kN**

DA1.C1 $F_{c,d} = 1.0\ G_k + 1.3\ Q_k = 1.0x300 + 1.3x150$ = **495 MN**

Design resistances

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

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

Equating actions and resistances

DA1.C1 $630 = 284/1.25 + 101 \text{ x } L_s / 1.0 \rightarrow$ $L_s = 3.99$ m

DA1.C2 $495 = 284/1.6 + 101 \text{ x } L_s / 1.3 \rightarrow$ $L_s = 4.08$ m

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

Design Approach 2 - pile design

Partial action factors same as for Example 1

Partial resistance factors:

R2 $\gamma_b = 1.1$ $\gamma_s = 1.1$

Design equation $\mathbf{F_{c,d} \leq R_{c,d}}$

Design action

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

Design resistance

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

Equating actions and resistances

$630 = 284/1.1 + 101 \times L_s / 1.1 \rightarrow L_s = 4.05$ m

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

Design Approach 3 - pile design

- Combination of sets of partial factors:

  DA3 A1 "+" M1 "+" R3

- Partial resistance factors:

  R3 $\gamma_b = \gamma_s = 1.0$

- Since the R3 recommended partial resistance factors are both equal to 1.0, no safety margin is provided if these factors are used in DA3 to calculated the design pile resistance from a CPT test profile

- Hence piles should not be designed using the DA3 recommended partial resistance factors applied to the characteristic pile resistance obtained from a CPT test profile

Conclusions from pile worked 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

European Commission

Worked example 3 –
design of pile foundations from soil parameters
DESIGN SITUATION

Design situation for a pile designed from soil parameters

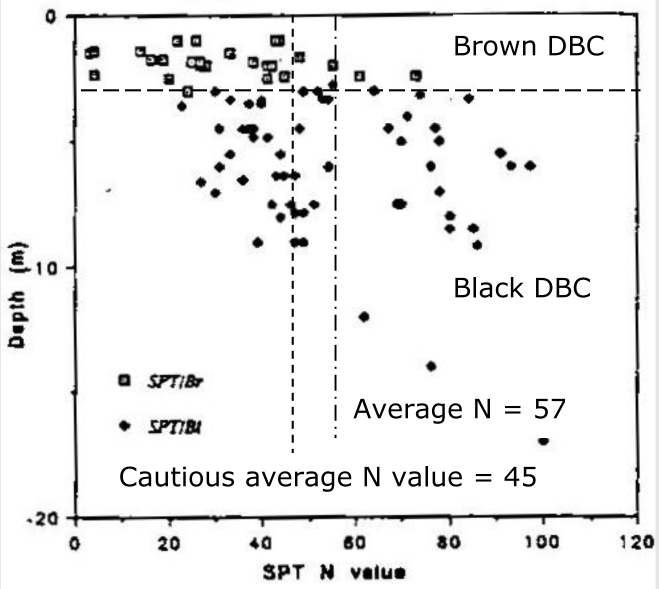
- The piles for a proposed building in Dublin are each required to support the following loads:
  - Characteristic permanent vertical load G_k = 600 kN
  - Characteristic variable vertical load Q_k = 300 kN
- The ground consists of about 3m Brown Dublin Boulder Clay over Black Dublin Clay to great depth
- It has been decided to use 0.45m diameter driven piles
- The pile foundation design involves determining the length of the piles

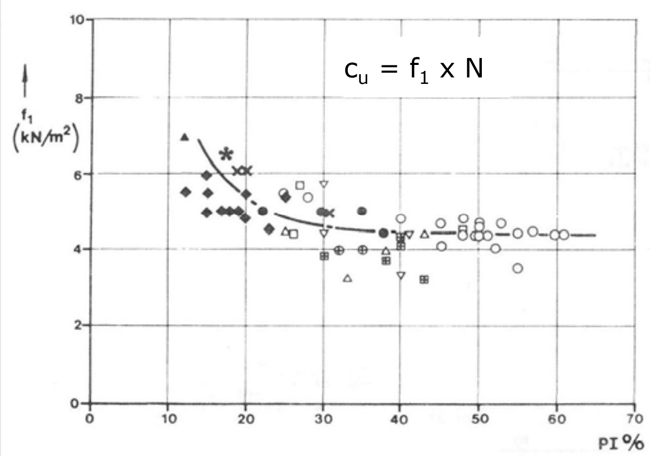
Characteristic undrained shear strength

- Figure shows plot of SPT N values obtained plotted against depth
- Shaft resistance in Brown Dublin Boulder Clay is ignored
- Average N value in Black Dublin Boulder Clay = 57
- A cautious average N value = 45
- PI of the Dublin Boulder Clay = 14%
- From Stroud and Butler plot of f_1 vs. N

  Adopt $f_1 = 6$

- Hence characteristic undrained shear strength $\mathbf{c_{u;k}} = f_1 \times N = 6 \times 45 =$ **270 kPa**





Pile resistances

Pile diameter $D = 0.45\text{m}$

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 Black Dublin Clay providing shaft resistance = L_s

The characteristic unit pile base and shaft resistances, $q_{b;k}$ and $q_{s;k}$ are obtained as follows:

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

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

Characteristic base resistance

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

Characteristic shaft resistance

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

Design Approach 1 partial and model factors

- Combinations of sets of partial factors:

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

  DA1.C2 A2 "+" M1 or M2 "+" R4

- Partial actions factors:

  A1 $\gamma_G = 1.35$ $\gamma_Q = 1.5$

  A2 $\gamma_G = 1.0$ $\gamma_Q = 1.3$

- Partial material factors:

  M1 and M2 not relevant (resistances factored not soil parameters)

- Partial resistance factors:

  R1 $\gamma_b = 1.0$ $\gamma_s = 1.0$

  R4 $\gamma_b = 1.3$ $\gamma_s = 1.3$

- Model factors:

  $\gamma_{R;d} = 1.75$ (In Irish NA and applied to γ_b, γ_s and γ_t)

Design Approach 1 - pile design to Irish NA

Design equation $\mathbf{F_{c,d} \leq R_{c,d}}$

Design actions

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

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

Design resistances

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

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

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

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

Equating actions and resistances

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

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

Hence DA1.C2 controls and the DA1 design pile length $L = 3.0 + L_s =$ **15.5m**

Design Approach 2 partial and model factors

- Combination of sets of partial factors

  DA2 A1 "+" M1 "+" R2

- Partial actions factors

  A1 $\gamma_G = 1.35$ $\gamma_Q = 1.5$

- Partial material factors

  M1 not relevant ($\gamma_{\phi'} = 1.0$)

- Partial resistance factor

  R2 $\gamma_b = 1.1$ $\gamma_s = 1.1$

- Model factors:

  $\gamma_{R;d} = 1.75$ (In Irish NA and applied to γ_b, γ_s and γ_t)

  $\gamma_{R;d} = 1.27$ (In German NA giving $\gamma_b = 1.1\text{x}1.27 = 1.4$, $\gamma_s = 1.1\text{x}1.27 = 1.4$

Design Approach 2 - pile design to Irish NA

Design equation $\mathbf{F_{c;d} \leq R_{c;d}}$

Design action

$$F_{c;d} = 1.35\ G_k + 1.5\ Q_k = 1.35 \times 600 + 1.5 \times 300 = \mathbf{1260\ kN}$$

Design resistance

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

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

Equating design action and resistance

$$1260 = 201 + 79.5\ L_s \quad \rightarrow \quad L_s = 13.3\ \text{m}$$

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

Design Approach 2 - pile design to German NA

Design equation $\mathbf{F_{c;d} \leq R_{c;d}}$

Design action

$$F_{c;d} = 1.35\ G_k + 1.5\ Q_k = 1.35 \times 600 + 1.5 \times 300 = \mathbf{1260\ kN}$$

Design resistance

$$R_{c;d} = R_{b,k}/\gamma_b + R_{s,k}/\gamma_s$$

Note: R1 partial factors of 1.1 have been increased to 1.4, i.e. a model factor of 1.4/1.1 = 1.27 has been applied

$$= 386/1.4 + 153 \times L_s/1.4 = \mathbf{276 + 109\ L_s\ kN}$$

Equating design action and resistance

$$1260 = 276 + 109\ L_s \quad \rightarrow \quad L_s = 9.0\ \text{m}$$

Hence DA2 design pile length $L = 3.0 + L_s =$ **12.0m**

Design Approach 3 partial and model factors

- Combination of sets of partial factors:

  DA3 A1* or A2† "+" M2 "+" R3

  * on structural actions

  † on geotechnical actions

- Partial actions factors:

  A1 $\gamma_G = 1.35$ $\gamma_Q = 1.5$

  A2 $\gamma_G = 1.0$ $\gamma_Q = 1.3$

- Partial material factor:

  M2 $\gamma_{cu} = 1.4$

- Partial resistance factors:

  R3 $\gamma_b = 1.0$ $\gamma_s = 1.0$

- Model factor:

  $\gamma_{R;d} = 1.75$ (applied to γ_b, γ_s and γ_t)

Design Approach 3 - pile design

Design equation $\mathbf{F_{c,d} \leq R_{c,d}}$

Design action

$$F_{c,d} = 1.35\ G_k + 1.5\ Q_k = 1.35 \times 600 + 1.5 \times 300 = \mathbf{1260\ kN}$$

Design resistance

$$R_{c,d} = R_{b,d} + R_{s,d}$$
$$= A_b \times q_{b;d} + A_s \times L_s \times q_{s;d}$$
$$= (A_b x N_q x c_{u;k}/\gamma_{cu})/(\gamma_{R;d} x \gamma_b) + (A_s x L_s x \alpha x c_{u;k}/\gamma_{cu})/(\gamma_{R;d} x \gamma_s)$$
$$= (0.159x9x270/1.4)/(1.75x1.0) + (1.414xL_s x0.4x270/1.4)/(1.75x1.0)$$
$$= \mathbf{158 + 62.3\ L_s}$$

Equating design action and resistance

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

Hence the DA3 design pile length $L = 3.0 + L_s = \mathbf{21\ m}$

Conclusions from pile worked example 3

- The design pile lengths obtained from ground strength parameters using the alternative procedure and the model factor in the Irish and German National Annexes are:
  - DA1 (Irish NA) L = 15.5 m
  - DA2 (Irish NA) L = 16.5 m
  - DA3 (Irish NA) L = 21.0 m
  - DA2 (German NA) L = 12.0 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
- The longer design pile length of 16.5 m when using the Irish NA with DA2 compared to 12.0 m when using the German NA is because of the model factor of 1.75 in the Irish NA and 1.27 in the German NA

Geotechnical design with worked examples

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