Example 13.4
Design of continuous flight auger piles from cone tests
Verification of strength (limit state GEO)

Design situation

Consider the design of continuous flight auger (CFA) piles for a site in Twickenham, London. Ground conditions at the site comprise dense, becoming loose gravelly, SAND. Cone penetration tests have been perfomed at the site to a depth of 8m. (Data courtesy CL Associates.) The limiting average unit shaft resistance p_s and limiting unit base resistance p_b at each cone location are estimated to be:

$$p_s = \begin{pmatrix} 120kPa \\ 120kPa \\ 100kPa \\ 120kPa \end{pmatrix} \quad p_b = \begin{pmatrix} 2800kPa \\ 3000kPa \\ 2000kPa \\ 3000kPa \end{pmatrix}$$ ❶

A group of $N = 6$ piles with diameter $D = 400mm$ and length $L = 6m$ are required to carry between them a permanent action $F_{Gk} = 2100kN$ together with a variable action $F_{Qk} = 750kN$. The weight density of reinforced concrete is $\gamma_{ck} = 25\frac{kN}{m^3}$ (as per EN 1991-1-1 Table A.1).

Design Approach 1

Actions and effects

The self-weight of pile is $W_{Gk} = \left(\frac{\pi \times D^2}{4}\right) \times L \times \gamma_{ck} = 18.8\ kN$

Partial factors from Sets $\begin{pmatrix} A1 \\ A2 \end{pmatrix}$: $\gamma_G = \begin{pmatrix} 1.35 \\ 1 \end{pmatrix}$ and $\gamma_Q = \begin{pmatrix} 1.5 \\ 1.3 \end{pmatrix}$ ❷

Design total action per pile is:

$$F_{cd} = \frac{\gamma_G \times \left(F_{Gk} + W_{Gk}\right) + \gamma_Q \times F_{Qk}}{N} = \begin{pmatrix} 664 \\ 516 \end{pmatrix} kN$$

Calculated shaft resistance

Number of cone penetration tests $n = 4$

Calculated shaft resistance $R_s = \pi \times D \times L \times p_s = \begin{pmatrix} 905 \\ 905 \\ 754 \\ 905 \end{pmatrix}$ kN

Mean calculated shaft resistance $R_{s,mean} = \frac{\sum R_s}{n} = 867$ kN

Minimum calculated shaft resistance $R_{s,min} = \min(R_s) = 754$ kN

Calculated base resistance

Calculated base resistance $R_b = \left(\frac{\pi \times D^2}{4}\right) \times p_b = \begin{pmatrix} 352 \\ 377 \\ 251 \\ 377 \end{pmatrix}$ kN

Mean calculated base resistance $R_{b,mean} = \frac{\sum R_b}{n} = 339$ kN

Minimum calculated base resistance $R_{b,min} = \min(R_b) = 251$ kN

Calculated total resistance

Mean calculated total resistance $R_{t,mean} = R_{s,mean} + R_{b,mean} = 1206$ kN

Minimum calculated total resistance $R_{t,min} = R_{s,min} + R_{b,min} = 1005$ kN

Characteristic resistance

Correlation factor on mean measured resistance $\xi_3 = 1.31$ ❸

Correlation factor on minimum measured resistance $\xi_4 = 1.20$ ❸

For a pile group that can transfer load from weak to strong piles (§7.6.2.2.(9)), ξ may be divided by 1.1 (but ξ_3 cannot fall beneath 1.0).

Thus $\xi_3 = \max\left(\frac{\xi_3}{1.1}, 1.0\right) = 1.19$ and $\xi_4 = \frac{\xi_4}{1.1} = 1.09$

Calculated resistances $\frac{R_{t,mean}}{\xi_3} = 1013$ kN and $\frac{R_{t,min}}{\xi_4} = 922$ kN❹

Characteristic resistance should therefore be based on the minimum value.

Characteristic shaft resistance is $R_{sk} = \frac{R_{s,min}}{\xi_4} = 691\ kN$ ❺

Characteristic base resistance is $R_{bk} = \frac{R_{b,min}}{\xi_4} = 230\ kN$ ❺

Design resistance

Partial factors from Sets $\begin{pmatrix} R1 \\ R4 \end{pmatrix}$: $\gamma_s = \begin{pmatrix} 1 \\ 1.3 \end{pmatrix}$ and $\gamma_b = \begin{pmatrix} 1.1 \\ 1.45 \end{pmatrix}$ ❺

Design resistance is $R_{cd} = \frac{R_{sk}}{\gamma_s} + \frac{R_{bk}}{\gamma_b} = \begin{pmatrix} 901 \\ 691 \end{pmatrix}\ kN$

Verification of compression resistance

Degree of utilization $\boxed{\Lambda_{GEO,1} = \frac{F_{cd}}{R_{cd}} = \begin{pmatrix} 74 \\ 75 \end{pmatrix}\ \%}$ ❻

Design is unacceptable if degree of utilization is > 100%

Design Approach 2

Actions and effects

Partial factors from set A1: $\gamma_G = 1.35$ and $\gamma_Q = 1.5$ ❷

Design total action per pile is $F_{cd} = \frac{\gamma_G \times \left(F_{Gk} + W_{Gk}\right) + \gamma_Q \times F_{Qk}}{N} = 664\ kN$

Design resistance

Characteristic shaft and base resistances are unchanged from DA1

Partial factors from set R2: $\gamma_s = 1.1$ and $\gamma_b = 1.1$ ❼

Design resistance is $R_{cd} = \frac{R_{sk}}{\gamma_s} + \frac{R_{bk}}{\gamma_b} = 838\ kN$

Verification of compression resistance

Degree of utilization $\Lambda_{GEO,2} = \frac{F_{cd}}{R_{cd}} = 79\ \%$ ❻

Design is unacceptable if degree of utilization is > 100%

Design Approach 3

Actions and effects

Partial factors from set A1: $\gamma_G = 1.35$ and $\gamma_Q = 1.5$ ❷

Design total action per pile is $F_{cd} = \frac{\gamma_G \times \left(F_{Gk} + W_{Gk}\right) + \gamma_Q \times F_{Qk}}{N} = 664\ \text{kN}$

Characteristic resistance

Partial factors from set M2 should be applied to material properties... but since there are no material properties to factor, we will factor the resistances instead using $\gamma_\varphi = 1.25$. Since resistances are governed by the minimum calculated resistance (as per DAs 1 and 2)...

Characteristic shaft resistance is $R_{sk} = \frac{R_{s,min}}{\xi_4 \times \gamma_\varphi} = 553\ \text{kN}$

Characteristic base resistance is $R_{bk} = \frac{R_{b,min}}{\xi_4 \times \gamma_\varphi} = 184\ \text{kN}$

Design resistance

Partial factors from set R3: $\gamma_s = 1$ and $\gamma_b = 1$

Design resistance is $R_{cd} = \frac{R_{sk}}{\gamma_s} + \frac{R_{bk}}{\gamma_b} = 737\ \text{kN}$

Verification of compression resistance

Degree of utilization $\Lambda_{GEO,3} = \frac{F_{cd}}{R_{cd}} = 90\ \%$ ❻

Design is unacceptable if degree of utilization is > 100%

Design to UK National Annex to BS EN 1997-1

Characteristic resistance

Correlation factor on mean measured resistance $\xi_3 = 1.38$ ❽

Correlation factor on minimum measured resistance $\xi_4 = 1.29$ ❽

For a pile group that can transfer load from weak to strong piles (§7.6.2.2.(9)), ξ may be divided by 1.1 (but ξ_3 cannot fall beneath 1.0).

Thus $\xi_3 = \max\left(\frac{\xi_3}{1.1}, 1.0\right) = 1.25$ and $\xi_4 = \frac{\xi_4}{1.1} = 1.17$

Calculated resistances $\frac{R_{t,mean}}{\xi_3} = 961.6$ kN and $\frac{R_{t,min}}{\xi_4} = 857$ kN ❹

Characteristic resistance should therefore be based on the minimum value, so...

Characteristic shaft resistance is $R_{sk} = \frac{R_{s,min}}{\xi_4} = 643$ kN

Characteristic base resistance is $R_{bk} = \frac{R_{b,min}}{\xi_4} = 214$ kN

Design resistance

Partial factors from Sets $\begin{pmatrix} R1 \\ R4 \end{pmatrix}$: $\gamma_s = \begin{pmatrix} 1 \\ 1.6 \end{pmatrix}$ and $\gamma_b = \begin{pmatrix} 1 \\ 2 \end{pmatrix}$ ❾

Design resistance is $R_{cd} = \frac{R_{sk}}{\gamma_s} + \frac{R_{bk}}{\gamma_b} = \begin{pmatrix} 857 \\ 509 \end{pmatrix}$ kN

Verification of compression resistance

Degree of utilization $\boxed{\Lambda_{GEO,1} = \frac{F_{cd}}{R_{cd}} = \begin{pmatrix} 77 \\ 101 \end{pmatrix} \%}$ ❿

Design is unacceptable if degree of utilization is > 100%