Example 13.3
Static load tests for the Emirates Stadium load tests in London
Verification of strength (limit state GEO)

Design situation

Consider the design of piles for the Emirates Stadium in London (the new home of Arsenal Football Club) where a large number of bored piles of different diameters are to be installed. Ground conditions at the site comprise 2.9m Made Ground, 2.1m Terrace Gravels, 31.0m London Clay, and at least 5m Lambeth Clay. Assume the top $L_0 = 5m$ of the ground profile provides negligible skin friction to the piles.

Load tests have been perfomed on seven piles, all with the same diameter $D_m = 600mm$ but with different total lengths L_m. (Pile test data courtesy Stent Foundations Ltd.) The peak applied load P and the corresponding settlement at that load is given below for each pile:

$$L_m = \begin{pmatrix} 25.4m \\ 24.9m \\ 23.5m \\ 16.9m \\ 26.3m \\ 24.3m \\ 24.4m \end{pmatrix} \quad P_m = \begin{pmatrix} 6000kN \\ 4956kN \\ 4000kN \\ 2310kN \\ 4300kN \\ 4200kN \\ 4200kN \end{pmatrix} \quad s_m = \begin{pmatrix} 26.2mm \\ 61.9mm \\ 60.5mm \\ 60.7mm \\ 23.2mm \\ 61.5mm \\ 45mm \end{pmatrix}$$

The two piles with less than 30mm settlement at peak load were founded on siltstone within the London Clay, whereas the other piles were founded on London Clay. The settlement reading for the last pile is an underestimate, owing to instrument failure.

A group of piles, with diameter $D = 600mm$ and length $L = 25m$, are each required to carry a permanent action $F_{Gk} = 1500kN$ together with a variable action $F_{Qk} = 700kN$. The weight density of reinforced concrete is

$\gamma_{ck} = 25\frac{kN}{m^3}$ (as per EN 1991-1-1 Table A.1).

Measured resistance

Assume that the majority of the measured resistance from the pile load tests comes from shaft resistance. Regard the results of the first and fifth load tests as unrepresentative because the pile toes are founded on a siltstone layer. The results from the remaining tests on piles with different embedded lengths can then be 'normalized' to the same length as the piles being designed, as follows: ❷

Length of shaft ignored is $L_0 = 5\,m$

Normalized measured resistance $R_m = \overrightarrow{\left[P_m \times \left[\frac{D \times (L - L_0)}{D_m \times (L_m - L_0)}\right]\right]} = \begin{pmatrix} 0 \\ 4981 \\ 4324 \\ 3882 \\ 0 \\ 4352 \\ 4330 \end{pmatrix}$ kN

No of tests considered is $n = 5$

Mean resistance is $R_{m,mean} = \frac{\sum R_m}{n} = 4374$ kN

Minimum resistance is $R_{m,min} = \min\left(R_{m_2}, R_{m_3}, R_{m_4}, R_{m_6}, R_{m_7}\right) = 3882$ kN

Design Approach 1

Actions and effects

Ignore the self-weight of pile

Characteristic total action $F_{ck} = F_{Gk} + F_{Qk} = 2200$ kN ❶

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

Design total action is $F_{cd} = \gamma_G F_{Gk} + \gamma_Q F_{Qk} = \begin{pmatrix} 3075 \\ 2410 \end{pmatrix}$ kN

Characteristic resistance

Correlation factor on mean measured resistance $\xi_1 = 1.0$

Correlation factor on minimum measured resistance $\xi_2 = 1.0$

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 ξ1 cannot fall beneath 1.0). ❸

Thus $\xi_1 = \max\left(\frac{\xi_1}{1.1}, 1.0\right) = 1.0$ and $\xi_2 = \frac{\xi_2}{1.1} = 0.91$

Mean/min measured resistance $\frac{R_{m,mean}}{\xi_1} = 4374$ kN and $\frac{R_{m,min}}{\xi_2} = 4271$ kN

Characteristic resistance is $R_{ck} = \min\left(\frac{R_{m,mean}}{\xi_1}, \frac{R_{m,min}}{\xi_2}\right) = 4271$ kN

Design resistance

Partial factors from Sets $\begin{pmatrix} R1 \\ R4 \end{pmatrix}$: $\gamma_t = \begin{pmatrix} 1.15 \\ 1.5 \end{pmatrix}$

Design resistance is $R_{cd} = \frac{R_{ck}}{\gamma_t} = \begin{pmatrix} 3714 \\ 2847 \end{pmatrix}$ kN

Verification of compression resistance

Degree of utilization $\Lambda_{GEO,1} = \frac{F_{cd}}{R_{cd}} = \begin{pmatrix} 83 \\ 85 \end{pmatrix}$ % ❹

Design is unacceptable if the degree of utilization is > 100%

Design Approach 2

Actions and effects

Ignore the self-weight of pile

Characteristic total action $F_{ck} = F_{Gk} + F_{Qk} = 2200$ kN

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

Design total action is $F_{cd} = \gamma_G F_{Gk} + \gamma_Q F_{Qk} = 3075$ kN

Characteristic resistance

Characteristic resistance is unchanged: $R_{ck} = 4271$ kN

Design resistance

Partial factors from sets R2: $\gamma_t = 1.1$

Design resistance is $R_{cd} = \dfrac{R_{ck}}{\gamma_t} = 3882$ kN

Verification of compression resistance

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

Design is unacceptable if the degree of utilization is > 100%

Design Approach 3

Is not suitable for pile design

Design to UK National Annex to BS EN 1997-1

The UK National Annex changes both the resistance factors and the correlation factors that must be used to verify pile resistance. All other factors remain unchanged from their EN values.

Characteristic resistance

Correlation factor on mean measured resistance is $\xi_1 = 1.35$

Correlation factor on minimum measured resistance is $\xi_2 = 1.08$

For a pile group that can transfer load from weak to strong piles

(§7.6.2.2.(9)): $\xi_1 = \max\left(\frac{\xi_1}{1.1}, 1.0\right) = 1.23$ and $\xi_2 = \frac{\xi_2}{1.1} = 0.98$ ❺

Mean/min measured resistance $\frac{R_{m,mean}}{\xi_1} = 3564$ kN and $\frac{R_{m,min}}{\xi_2} = 3954$ kN

Characteristic resistance is $R_{ck} = \min\left(\frac{R_{m,mean}}{\xi_1}, \frac{R_{m,min}}{\xi_2}\right) = 3564$ kN❻

Design resistance

Partial factors, Sets $\begin{pmatrix} R1 \\ R4 \end{pmatrix}$: $\gamma_t = \begin{pmatrix} 1 \\ 1.7 \end{pmatrix}$, $\gamma_s = \begin{pmatrix} 1 \\ 1.4 \end{pmatrix}$, $\gamma_b = \begin{pmatrix} 1 \\ 1.7 \end{pmatrix}$ ❼

Design resistance is $R_{cd} = \frac{R_{ck}}{\gamma_t} = \begin{pmatrix} 3564 \\ 2096 \end{pmatrix}$ kN❽

Verification of compression resistance

Degree of utilization $\Lambda_{GEO,1} = \frac{F_{cd}}{R_{cd}} = \begin{pmatrix} 86 \\ 115 \end{pmatrix}$ %❾

Design is unacceptable if the degree of utilization is > 100%

Assuming $\chi = 85\%$ of the characteristic resistance comes from shaft friction, design resistance $R_{cd} = \chi\left(\frac{R_{ck}}{\gamma_s}\right) + (1-\chi)\left(\frac{R_{ck}}{\gamma_b}\right) = \begin{pmatrix} 3564 \\ 2478 \end{pmatrix}$ kN

Degree of utilization $\Lambda_{GEO,1} = \frac{F_{cd}}{R_{cd}} = \begin{pmatrix} 86 \\ 97 \end{pmatrix}$ %❿

Design is unacceptable if the degree of utilization is > 100%