RC PILE CAP DESIGN (BS8110:PART1:1997)

Pile Cap Design – Truss Method

Design Input - 4 Piles - With Eccentricity

Number of piles; \(N = 4\)
ULS axial load; \(F_{uls} = 1850.0\) kN
Pile diameter; \(\phi = 350\) mm
Pile spacing, both directions; \(s = 900\) mm
Eccentricity from centroid of pile cap; \(e_x = 75\) mm
Eccentricity from centroid of pile cap; \(e_y = 50\) mm
Characteristic load in pile, φ1:

\[ F_{\text{char}, \text{pile}_1} = F_{\text{char}} \times \frac{(0.5 \times s - e_x)/s \times (0.5 \times s - e_y)/s}{s} = 291.7 \text{ kN} \]

Characteristic load in pile, φ2:

\[ F_{\text{char}, \text{pile}_2} = F_{\text{char}} \times \frac{(0.5 \times s - e_x)/s \times (0.5 \times s + e_y)/s}{s} = 364.6 \text{ kN} \]

Characteristic load in pile, φ3:

\[ F_{\text{char}, \text{pile}_3} = F_{\text{char}} \times \frac{(0.5 \times s + e_x)/s \times (0.5 \times s + e_y)/s}{s} = 510.4 \text{ kN} \]

Characteristic load in pile, φ4:

\[ F_{\text{char}, \text{pile}_4} = F_{\text{char}} \times \frac{(0.5 \times s + e_x)/s \times (0.5 \times s - e_y)/s}{s} = 408.3 \text{ kN} \]

Pile cap overhang; \( e = 200 \text{ mm} \)

Overall length of pile cap; \( L = s + \phi + 2 \times e = 1650 \text{ mm} \)

Overall width of pile cap; \( b = s + \phi + 2 \times e = 1650 \text{ mm} \)

Overall height of pile cap; \( h = 450 \text{ mm} \)

Dimension x of loaded area; \( x = 300 \text{ mm} \)

Dimension y of loaded area; \( y = 300 \text{ mm} \)

Cover

Concrete grade; \( f_{\text{cu}} = 40.0 \text{ N/mm}^2 \)

Nominal cover; \( c_{\text{nom}} = 40 \text{ mm} \)

Tension bar diameter; \( D_t = 16 \text{ mm} \)

Link bar diameter; \( L_{\text{dia}} = 12 \text{ mm} \)

Depth to tension steel; \( d = h - c_{\text{nom}} - L_{\text{dia}} - D_t/2 = 390 \text{ mm} \)

**Pile Cap Forces**

Maximum compression within pile cap; \( F_c = \max(F_{c1}, F_{c2}, F_{c3}, F_{c4}) = 1034.4 \text{ kN} \)

Maximum tension within pile cap; \( F_t = \max(F_{t1}, F_{t2}, F_{t3}, F_{t4}) = 614.9 \text{ kN} \)

**Compression In Pile Cap - Suggested Additional Check**

Check compression diagonal as an unreinforced column, using a core equivalent to pile diameter

Compressive force in pile cap; \( P_{\text{c}} = 0.4 \times f_{\text{cu}} \times \pi \times \phi^2/4 = 1539.4 \text{ kN} \)

**PASS Compression**

Cl. 3.8.4.3

**Tension In One Truss Member**

Characteristic strength of reinforcement; \( f_y = 500 \text{ N/mm}^2 \)

Partial safety factor for strength of steel; \( \gamma_{ms} = 1.15 \)

Required area of reinforcement; \( A_{s, \text{req}} = F_t/(1/\gamma_{ms} \times f_y) = 1414 \text{ mm}^2 \)

Provided area of reinforcement; \( A_{s, \text{prov}} = A_{st} = 1608 \text{ mm}^2 \)

Tension in truss member; \( P_t = (1/\gamma_{ms} \times f_y) \times A_{s, \text{prov}} = 699.3 \text{ kN} \)

**PASS Tension**

Cl. 3.11.4.2

**Max / Min Areas of Reinforcement - Considering A Strip Of Cap**

Minimum required area of steel; \( A_{st, \text{min}} = k_t \times A_c = 439 \text{ mm}^2 \)

Maximum allowable area of steel; \( A_{st, \text{max}} = 4 \% \times A_c = 13500 \text{ mm}^2 \)

*Area of tension steel provided OK*
Beam Shear

Check shear stress on the sections at distance $\phi/5$ inside face of piles.

**Applied shear stress to be checked across each pile pair**

Effective width of pile cap in shear allowing for Clause 3.11.4.4 (b)

\[
\begin{align*}
b_v &= \text{if (} s \leq 3 \times \phi, s + \phi + 2 \times e, 3 \times \phi + 2 \times \min(1.5 \times \phi, \phi/2 + e) \text{)} = 1650 \text{ mm} \\
V_1 &= V_d/(b_v \times d) = 1.68 \text{ N/mm}^2 \\
V_2 &= V_d/(b_v \times d) = 1.20 \text{ N/mm}^2 \\
V_3 &= V_d/(b_v \times d) = 1.60 \text{ N/mm}^2 \\
V_4 &= V_d/(b_v \times d) = 1.28 \text{ N/mm}^2 \\
V_{\text{allowable}} &= \min ((0.8 N^{1/2}/\text{mm}) \times \sqrt{f_{\text{cu}}}, 5 \text{ N/mm}^2) = 5.00 \text{ N/mm}^2
\end{align*}
\]

**Shear stress - OK**

**Design concrete shear strength**

Percentage of reinforcement;

\[r = 100 \times 2 \times A_{v,\text{prov}}/(b_v \times d) = 0.50\]

From BS8110-1:1997 Table 3.8;

\[v_{c,25} = 0.79 \times r^{1/3} \times \max(0.67, (400 \text{ mm/d})^{1/4}) \times 1.0 \text{ N/mm}^2 / 1.25 = 0.50 \text{ N/mm}^2\]

Shear enhancement - Cl. 3.4.5.8 and fig. 3.5;

\[v_c = v_{c,25} \times (\min(f_{\text{cu}}, 40 \text{ N/mm}^2)/25 \text{ N/mm}^2)^{1/3} = 0.59 \text{ N/mm}^2\]

**Case 1:**

\[a_{v,1} = \min(2 \times d, \max((s/2 - \psi/2 + \psi/5 - e - x/2), 0.1 \text{ mm}) = 120 \text{ mm}\]

\[v_{c,\text{enh},1} = 2 \times d \times v_c/a_{v,1} = 3.84 \text{ N/mm}^2\]

**Concrete shear strength - OK, no links reqd. for Case 1**

**Case 2:**

\[a_{v,2} = \min(2 \times d, \max((s/2 - \psi/2 + \psi/5 + e - x/2), 0.1 \text{ mm}) = 270 \text{ mm}\]

\[v_{c,\text{enh},2} = 2 \times d \times v_c/a_{v,2} = 1.71 \text{ N/mm}^2\]

**Concrete shear strength - OK, no links reqd. for Case 2**

**Case 3:**

\[a_{v,3} = \min(2 \times d, \max((s/2 - \psi/2 + \psi/5 + e - y/2), 0.1 \text{ mm}) = 145 \text{ mm}\]

\[v_{c,\text{enh},3} = 2 \times d \times v_c/a_{v,3} = 3.18 \text{ N/mm}^2\]

**Concrete shear strength - OK, no links reqd. for Case 3**

**Case 4:**

\[a_{v,4} = \min(2 \times d, \max((s/2 - \psi/2 + \psi/5 + e - y/2), 0.1 \text{ mm}) = 245 \text{ mm}\]

\[v_{c,\text{enh},4} = 2 \times d \times v_c/a_{v,4} = 1.88 \text{ N/mm}^2\]

**Concrete shear strength - OK, no links reqd. for Case 4**

Note: If no links are provided, the bond strengths for PLAIN bars must be used in calculations for anchorage and lap lengths.
Local Shear At Concentrated Loads (Cl 3.7.7)

Total length of inner perim. at edge of loaded area; \( u_0 = 2 \times (x + y) = 1200 \) mm

Assumed average depth to tension steel; \( d_{av} = d - D_t = 374 \) mm

Max shear effective across perimeter; \( V_p = F_{uls} = 1850.0 \) kN

Stress around loaded area;

\[
V_{\text{allowable}} = \min((0.8 N^{1/2}/\text{mm}) \times \sqrt{f_{cu}}, 5 N/\text{mm}^2) = 5.00 \text{ N/mm}^2
\]

Shear stress - OK

Clear Distance Between Bars In Tension (Cl 3.12.11.2.4)

Maximum / Minimum allowable clear distances between tension bars considering a strip of cap

Actual bar spacing;

\[
\text{spacing}_{\text{bars}} = \max(0 \text{mm}, (b_{cs} - n_{surfaces} \times (c_{\text{adopt}} + L_{\text{dia}}) - D_t)/(\text{Nt} - 1) - D_t) = 75 \text{ mm}
\]

Maximum allowable spacing of bars; \( \text{spacing}_{\text{max}} = \min(47000 \text{ N/mm}/f_s, 300 \text{ mm}) = 160 \text{ mm} \)

Minimum required spacing of bars; \( \text{spacing}_{\text{min}} = h_{agg} + 5 \text{ mm} = 25 \text{ mm} \)

Bar spacing OK

Clear Distance Between Face Of Beam And Tension Bars (Cl 3.12.11.2.5)

Distance to face of beam;

\[
\text{Dist}_{\text{edge}} = c_{\text{adopt}} + L_{\text{dia}} + D_t/2 = 60 \text{ mm}
\]

Max allowable clear spacing;

\[
\text{Spacing}_{\text{max}} = \min(47000 \text{ N/mm}/f_s, 300 \text{ mm}) = 160 \text{ mm}
\]

Max distance to face of beam;

\[
\text{Dist}_{\text{max}} = \text{Spacing}_{\text{max}}/2 = 80 \text{ mm}
\]

Max distance to beam edge check - OK

Anchorage Of Tension Steel

Anchorage factor; \( \phi_{\text{factor}} = 35 \)

Type of lap length; \( \text{lap} \text{ } \text{type} = "\text{tens} \text{ _lap}" \)

Type of reinforcement; \( \text{reft} \text{ } \text{type} = "\text{def2} \text{ _fy500}" \)

Minimum radius; \( r_{\text{bar}} = 32 \text{ mm} \)

Minimum end projection; \( P_{\text{bar}} = 130 \text{ mm} \)

Minimum anchorage length or lap length req’d;

\[
L_{\text{table} \text{ } 3.27} = \phi_{\text{factor}} \times D_t = 560 \text{ mm}
\]

Check anchorage length to cl. 3.12.9.4 (b);

\[
L_{\text{cl} \text{. } 3.12.9.4} = 12 \times D_t + D_t/2 = 387 \text{ mm}
\]

Required minimum effective anchorage length;

\[
L_a = \max(L_{\text{table} \text{ } 3.27}, L_{\text{cl} \text{. } 3.12.9.4}) = 560 \text{ mm}
\]

Check bearing stress on minimum radius bend

Note that the bars must extend at least 4D past the bend

Force per bar at bend; \( F_{\text{bt}} = F_t / L_{\text{nt}} = 76.9 \text{ kN} \)

Bearing stress; \( f_{\text{bt}} = F_{\text{bt}} / (r_{\text{bar}} \times D_t) = 150.12 \text{ N/mm}^2 \)

Edge bar centres; \( s_{\text{ext}} = c_{\text{adopt}} + D_t = 56 \text{ mm} \)
Edge maximum allowable bearing stress; 
\[ f_{bt_{\text{max\_ext}}} = 2 \times f_{cu} / (1 + 2 \times (D_t / s_{\text{ext}})) = 50.91 \text{ N/mm}^2 \]

Internal bar centres; 
\[ s_{\text{int}} = \text{spacing bars} + D_t = 91 \text{ mm} \]

Internal maximum allowable bearing stress; 
\[ f_{bt_{\text{max\_int}}} = 2 \times f_{cu} / (1 + 2 \times (D_t / s_{\text{int}})) = 59.19 \text{ N/mm}^2 \]

**FAIL - Bearing stress on minimum radius bend exceeds maximum allowable**

**Deflection Check (CI 3.4.6)**

Redistribution ratio; 
\[ \beta_b = 1.0 \]

Design service stress in tension reinforcement; 
\[ f_s = 2 \times f_y \times A_{s_{\text{req}}} / (3 \times A_{s_{\text{prov}}} \times \beta_b) = 293.1 \text{ N/mm}^2 \]

Modification for tension reinforcement; 
\[ \text{factor}_{\text{tens}} = \min(2, 0.55 + (477 \text{ N/mm}^2 - f_s) / (120 \times (0.9 \text{ N/mm}^2 + F_t / (b \times d)))) = 1.376 \]

Modified span to depth ratio; 
\[ \text{mod}_{\text{span\_depth}} = \text{factor}_{\text{tens}} \times \text{basic}_{\text{span\_depth}} = 27.5 \]

Span of pile cap for deflection check; 
\[ L_s = 900 \text{ mm} \]

Actual span to depth ratio; 
\[ \text{actual}_{\text{span\_depth}} = L_s / d = 2.31 \]

**PASS - Deflection**