PILE CAP DESIGN

PILE CAP:-

A reinforced concrete slab or block which interconnects a group of piles and acts as a medium to transmit the load from wall or column to the Piles is called a **Pile Cap**. The Pile cap should normally be rigid so as to distribute the forces equally on the piles of a group. In general it is designed like a footing on soil but with the difference that instead of uniform reaction from the soil, the reactions in this case are concentrated either point loads or distributed.

As per IS 2911 (Part I/ Sec 3) -2010, the pile cap may be designed by assuming that the load from column is dispersed at 45° from the top of the cap up to the mid depth of the pile cap from the base of the column or pedestal. The reaction from piles may also be taken to be distributed at 45° from the edge of the pile, up to the mid depth of the pile cap. On this basis the maximum bending moment and shear forces should be worked out at critical sections.

ASSUMPTIONS INVOLVED IN THE DESIGN OF PILE CAPS:-

(i) Pile cap is perfectly rigid.

(ii) Pile heads are hinged to the pile cap and hence no bending moment is transmitted to piles from pile caps.

(iii) Since the piles are short and elastic columns, the deformations and stress distribution are planer.

DESIGN PARAMETERS OF PILE CAPS:-

(i) Shape of pile cap.

(ii) Depth of pile cap.

(iii) Amount of steel to be provided.

(iv) Arrangement of reinforcement.

(i) Shape of pile cap:-

Whittle and Beattie have developed through computer program the relationship between dimension of pile cap and the size of the pile.

The minimum spacing of piles permitted from soil mechanics depends on the type and end conditions. CP 2004 requires a minimum centre- to –centre spacing of twice the diameter of the piles for end bearing and three times the diameter for friction piles. IS 2911 part1, sections 1 and 2 recommended a minimum spacing of two and half times the diameter of the pile for both driven cast in situ and bored cast in situ piles.

For accommodating deviations in driving of piles, the size of the pile cap is made 300 mm more than the outer- to outer distance of the exterior piles. (150 mm on either side).

The plan dimension of the pile cap is based on the fact that the actual final position of piles can be in construction up to 100 mm out of line from the theoretical centre lines. Pile caps should be made very large to accommodate these deviations. In practice, pile caps are extended as much as 150 mm beyond the outer face of the piles.

Standard Pile Caps:

s-spacing of pile = F x h_p where

h_p = diameter of pile in mm

$$F = \text{spacing factor} = \frac{\text{centre to centre spacing}}{\text{Pile diameter}}$$

(ii) Depth of Pile Cap :-

The thickness of the Pile Cap is fixed such that it is adequate to resist shear without shear reinforcement and the bars projecting from the piles and the dowel bars for the column can be provided adequate bond length. As per IS 456- 2000, the minimum thickness on top of piles should not be less than 300 mm. Pile cap depth should be kept on the high side to effect economy in the consumption of steel and also to provide adequate rigidity to pile cap. Generally, pile cap thickness should not be less than 500 mm which may be reduced to 300 mm at the free edges. For pile caps to be rigid, pile cap has to be quite deep with 600 mm as the minimum depth. As a guide line the formula given in Reinforced concrete by Reynolds may be followed.

For Pile dia > 550 mm,

Pile cap depth (h) = $(2\ h_p + 100)$mm

For Pile dia ≥ 550 mm,

h= M, x$(8\ h_p + 600)$ mm

Pile Dia h_p (mm)	300	350	400	450	500	550	600	750
Pile Cap depth h(mm)	700	800	900	1000	1100	1200	1400	1800

(i) Amount of steel to be provided :-

The Pile Cap has to be designed either truss theory or beam theory. Although, the pile caps are assumed to act as a simply supported beam and are designed for the usual condition of bending and shear, their tendency is to fail by bursting due to high principal tension and they will therefore always require a cage of reinforcement in three dimensions to resist this tendency.

The main reinforcement is usually bend (full bend) and extended for full depth of pile cap to fulfill the check for development length. Though IS 456-2000 is silent on specifying the minimum reinforcement, a minimum reinforcement of 0.15 % BD for main reinforcement and 0.12 % BD for secondary reinforcement may be provided as per clause 3 .11.4.1 and 2 of CP 110 code). For bursting (horizontal binders) it is suggested that 25 % of the main reinforcement (usually 12 Φ RTS at 150 mm c/c) shall be used.

Cover :- A cover of 75 mm is usually provided for the pile cap surfaces in contact with earth and 60 mm against blinding concrete of 75 to 100 mm thick. In marine situations the cover should be increased to a minimum of 80 mm.

DESIGN OF PILE CAP BASED ON TRUSS THEORY:

The truss theory applied to pile caps with up to 5 piles. In this method the load from the column is transmitted to the piles by inclined thrust and the tie necessary to maintain equilibrium is provided by reinforcement. (Steel acts as tension chord and concrete as diagonal struts).

If the Ultimate load on the column is N and we have two piles the load on each pile is N/2.

From the diagram of forces $\frac{T}{(N/2)} = \frac{l}{d}$

i.e. $T = N\,l/2d$

Area of reinforcement required $= Nl/\,(2d \times 0.87\, f_y)$

In the simple frame described above, the dimensions of the columns have been ignored. If the Column is square of side 2a,

$$T = \frac{N}{6\,ld}\,(3l^2 - a^2)$$

In truss theory, it has usually been the practice to band the reinforcement along the lines joining the piles. The code now suggests that this method of banding is only necessary if the piles are spaced at more than 3 times the pile dia. For the more normal spacing of 3 times the pile dia the total reinforcement forming the tie force in one direction can be distributed uniformly across the cap with a three- pile cap designed on the truss theory, it is difficult to see how this can be done and it is suggested that the reinforcement is banded along the centre lines joining the piles.

In the case of pile caps designed using the truss theory it is suggested that the effective depth is approximately half the distance between the centre of piles. This means the truss has an angle of approximately 45°.

Allowable shear resistance is given by

$N = 2 (d\ h_p)\ 2\ \zeta_c\ (d/a_v) + (b - 2\ h_p)\ \zeta_c\ bd$ where ζ_c = design shear strength of concrete.

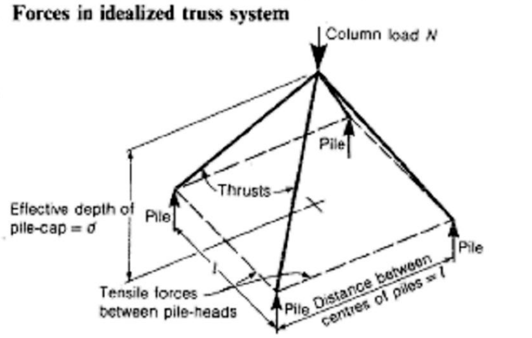
$a_v = 0.5(l - b)$ where l = c/c of piles & b = width of column.

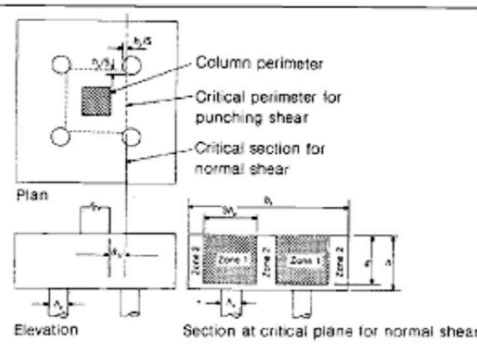
The section should be safe without extra shear reinforcement.

Truss theory design can be done using Table 194 of Reynould's hand book.

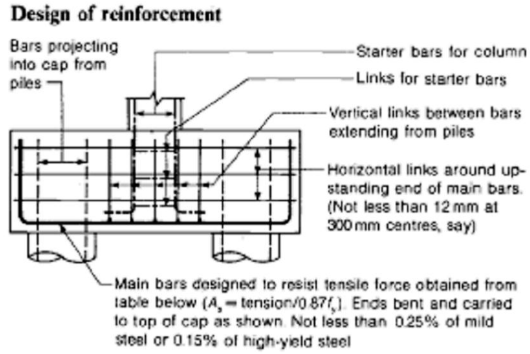
Foundations: pile-cap design

Forces in idealized truss system





Design of reinforcement



Shearing resistance to BS8110

Allowable shearing resistance = $(3nh_p v_{c1} \times 1.5d/a_v) + (b_c - 3nh_p) \times v_{c2} d$, where v_{c1} and v_{c2} are allowable shearing stresses in zones 1 and 2 respectively, read from *Table 142*, and n is number of zones 1. If no longitudinal bars are provided in zone 2, take $v_{c2} = 0$. If centre of any pile is further from column than critical plane, the force in that pile contributes to shear.

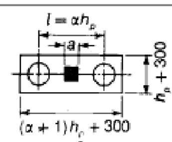
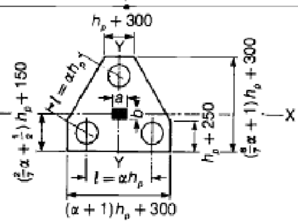
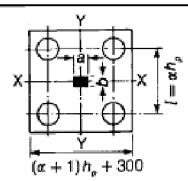
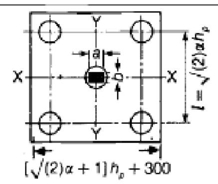
Punching shear

Check punching shear around column perimeter as described on *Table 64*. If pile spacing exceeds $3h_p$ also check punching shear on critical perimeter shown on diagram.

Recommended thickness of pile cap

(Cap thickness must also be sufficient to meet anchorage-bond length requirements of starter bars and normal and punching shear requirements.)

If $h_p \not> 550$ mm: $h = 2h_p + 100$; If $h_p > 550$ mm: $h = \frac{1}{3}(8h_p - 600)$

Number of piles	Dimensions of pile cap	Tensile force to be resisted by reinforcement: Neglecting size of column	Tensile force to be resisted by reinforcement: Taking size of column into consideration
2		$\frac{Nl}{4d}$	$\frac{N}{12ld}(3l^2 - a^2)$
3		$\frac{Nl}{9d}$	Parallel to X-X: $\frac{N}{36ld}(4l^2 + b^2 - 3a^2)$ Parallel to Y-Y: $\frac{N}{18ld}(2l^2 - b^2)$
4		$\frac{Nl}{8d}$	Parallel to X-X: $\frac{N}{24ld}(3l^2 - a^2)$ Parallel to Y-Y: $\frac{N}{24ld}(3l^2 - b^2)$
5		$\frac{Nl}{10d}$	Parallel to X-X: $\frac{N}{30ld}(3l^2 - a^2)$ Parallel to Y-Y: $\frac{N}{30ld}(3l^2 - b^2)$

Notation h_p diameter of pile; a, b dimensions of column; α spacing factor of piles (normally between 2 and 3 depending on ground conditions)

Beam theory :- When (a_V / d) ratio is more than 2 as in shallow pile cap or with the arrangement of 6 or more piles, bending action is more predominant than truss action. In this case the pile cap is designed as a normal beam for bending moment and shear. The pile cap area is divided into a framework of rectangular beam depending on the geometry of the pile group. The width of the beam is taken as equal to the width of the pile. The beam may be simply supported or continuous.

The reinforcement is evenly distributed or concentrated. The reaction from the pile is taken as distributed at 45° from the edge of the pile cap up to the mid- depth of the pile cap. The maximum bending moment and shear force are calculated on this basis. However, it is much easier to consider the loads as concentrated loads and calculate the B.M. and S.F. The depth should be such that no extra shear reinforcement is necessary for the section.

Practical Aspects on Pile cap Design:

The structural design of a pile cap is similar to the design of spread footing. The load acting on the pile cap from the superstructure and piles are resisted by the developments of bending moment and shear force in the pile cap.

Codal provisions made in IS 2911(Part 1/sec3)-2010 :

1. The size of the pile cap is fixed in such way that it has clear overhang beyond the outermost pile not less than 100mm, but preferably 150mm.
2. It should be deep enough to allow the necessary overlap of reinforcements from column and piles.
3. The clear cover to the main reinforcement should not be less than 40mm.
4. The span to thickness ratio of the cap should not be more than 5 so that pile cap is rigid enough to distribute the load uniformly to the piles.
5. Generally, its thickness should not be less than 500mm which may be reduced to 300mm at the free edges.
6. The piles should atleast 50mm into the pile cap.
7. A leveling course of not less 75mm thick concrete should be provided under the pile cap.

Design Aspects :-

The reaction from the piles under the concentric axial load on the cap is assumed equal and is determined by,

$$P_p = Q/n \quad \text{-----} \quad (1)$$

where Q = concentric axial load on the cap

n = Number of Piles

When the Pile cap is eccentrically loaded or subjected to a load and moments then the reactions from the Piles are determined as

$$P_p = Q/n \pm \frac{M_y\, x}{\Sigma x^2} \pm \frac{M_x\, y}{\Sigma y^2} \quad \text{-----} \quad (2)$$

where

Mx, My = moments with respect to x and y axes.

X, y = distances from y and x axes to the Piles.

The critical section for bending moments and bond shall be calculated at the face of column or pedestal.

The critical section for two way shear (Punching shear) will be at a distance d/2 from face of column or pedestal.

One way shear is checked at a distance of d/2 from the face of the column.

The Clause 34.2.4.2 of IS 456 – 2000 states the following :-

"In computing the external shear or any section through a footing supported on Piles, the entire reaction from any pile of diameter Dp whose centre is located Dp/2 or more outside the section shall be assumed as producing shear on the section; the reaction from any Pile whose centre is located Dp/2 or more inside the section shall be assumed as producing no shear on the section. For intermediate positions of the pile centre, the position of pile reaction to be assumed as producing shear on the section shall be based on straight line interpolation between full value at Dp/2 outside the section and zero value at Dp/2 inside the section."

In computing external shear on any section the entire (100%) reaction of the Pile shall be taken if the pile centre is located at 150 mm or more outside the section. The pile reaction will produce no shear (0%) if the pile centre is located at 150 mm or more inside the section. A linear interpolation shall be made for intermediate values of the pile centre.

Let the centre of the pile be located at 'x' from the face of the column. Let 'd' be the effective depth of the pile cap. Then the critical section is located at d/2 from face of the column.

If pile centre is located at (d/2 –x) outside the critical section when x < d/2.

If x > d/2, the expression (d/2-x) yields negative value indicating that the pile centre is located at (x-d/2) inside the section. When (d/2-x), outside is true for other case.

Let the fraction of pile reaction inducing shear be f R where R is the pile reaction.

Rule for checking one way shear,

$$f = \frac{150 + (x - d/2)}{300}$$

where x and d are in millimeters.

DESIGN OF TWO PILE CAP

DATA:-

Pile Diameter : 400 mm

Spacing of piles $2\ h_p = 2 \times 400$: 800 mm

Column Dimension B x D : 300 x 450 mm

Factored Load : 1072.8 KN

Factored Moment Mxu :51.29 KN.m

Safe Load on Single Pile :500KN

Concrete Mix : M_{20}

Steel Grade : Fe 415

DESIGN : -

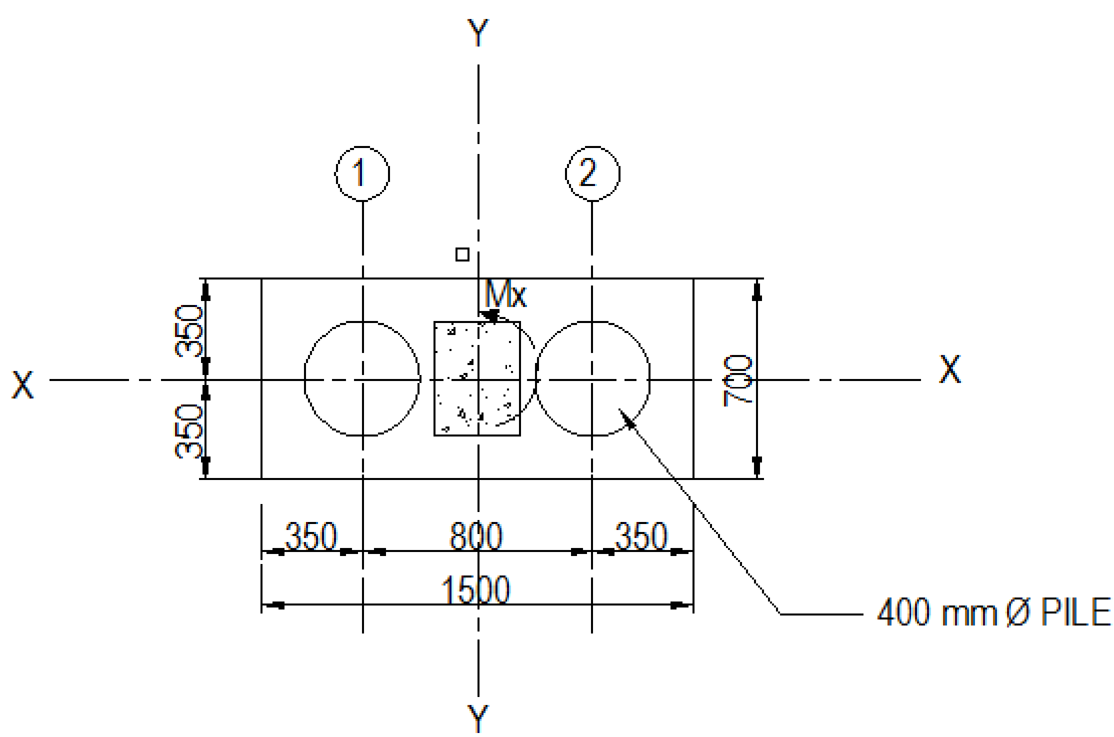
1. **Pile Cap Dimension :**

Breadth of Pile Cap = C/c of Pile + $h_{p\ /2}$ + 150 + $h_{p\ /2}$ + 150

= 800 + 400/2+ 150 +400/2+ 150 =1500 mm

Width of pile cap = h_p + 150 + 150 = 700 mm

Depth of Pile cap = 2 h_p + 100 = 2 x 400 + 100 = 900 mm.



PLAN OF PILE CAP OF TWO PILE GROUP

2. **Check for Pile Load capacity** :-

Total factored axial compressive load

$$= \frac{Pu}{n} +/- \frac{M_x y}{\sum y^2} +/- \frac{M_x x}{\sum x^2}$$

Self weight of Pile Cap = (1.5 x0.7 x 0.9 x 25) x1.5 = 35.45 KN

Factored load from column P_u = 1072.80 KN

Total Factored Load P_u = 1108.25 KN

No. of Piles along one side of axis = 2

y coordinate of Pile cap = 0.4 m

M_x = Moment about x axis = 51.29 KN.m

Compressive load in A1 & A2 about x – x axis

$$= \frac{1108.25}{2} + \frac{51.29 \times 0.4}{2 \times 0.4^2}$$

= 554.13 + 64.11

=618.24 KN

Design working load = 618.24 /1.5 = 412.16 KN < Safe Load on Pile i.e 500KN. O.K.

3. Bending Moment :-

Factored Moment in section Y-Y

$$M_u = 618.24 \times \frac{(0.8-0.3)}{2} = 154.56 \text{ KN.m}$$

4. Check for effective depth :

$M_u = 0.138 f_{ck} b d^2 = 154.56 \times 10^6$

d required = $\sqrt{(154.56 \times 10^6) / 2.76 \times 700}$ =282.84 mm

D provided = 900 mm

d available = 900 – 60 -12- 6 = 822 mm > d required i.e. 282.84 mm

5. Check for Punching Shear (Two way shear) : -

Punching shear at a distance d/2 (i.e.822/2= 411mm) from face of column = 1072.80 KN

The critical section of punching comes the centre of pile.

Hence the net load is to be taken. However the depth is checked for factored axial load from column = 1072.80 KN

b= 700 x 822 mm

d= 822 mm

Perimeter of critical section = 2 (700 + 822) = 3044 mm

Punching shear stress = $\frac{1072.80 \times 10^3}{3044 \times 822}$ = 0. 43 N/mm^2

Allowable shear stress for M_{20}

= $0.25 \sqrt{f_{ck}} = 0.25 \sqrt{20} = 1.12$ N/mm^2

Hence safe.

6. Main Reinforcement : -

M_u = 154.56 x 10^6 KN.m

K = M_u / bd^2 = $\frac{154.56 \times 10^6}{700 \times 822^2}$ = 0.33

Pt from Table 2 of Design Aid=0.11

Minimum Ast = $\frac{0.12}{100}$ x 700 x 822 = 690.48 mm^2

Provide 7 Nos. 12 Φ RTS at bottom on both ways.

(Ast = 791 mm^2 > 690.48 mm^2)

Reinforcement at top :-

Minimum Ast = $\frac{0.12}{100}$ x 700 x 822 = 690.48 mm^2

Provide 7 Nos. 12 mm Dia RTS at top .

(Ast = 791 mm^2 > 690.48 mm^2)

7. Check for one way shear :-

Maximum Shear force at face of column = 618.24 KN

Shear stress = $\frac{618.24 \times 10^3}{700 \times 822}$ = 1.07 N/mm^2

For P_t = 0.20%

ζ_c from Table 61 of Design Aid to IS 456 -1978 = 0.33 N /mm^2

Shear to be carried by stirrups shear

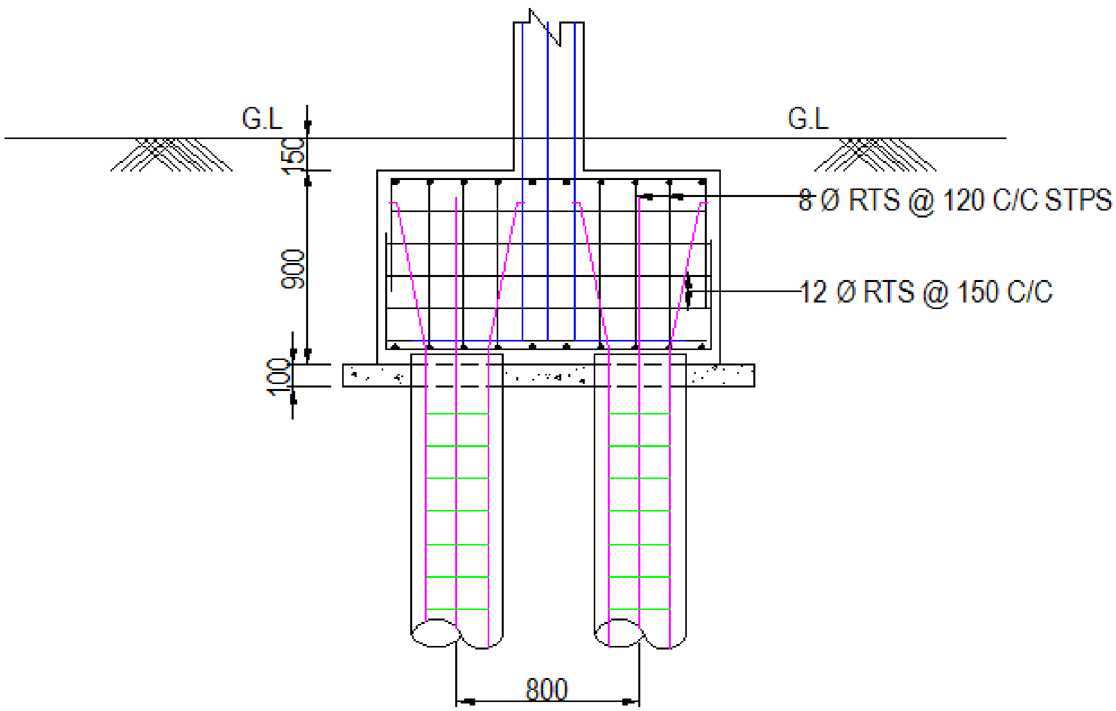
V_{us} =(1.07– 0.33) x700 x822 x 10^{-3}= 425.80 KN.

V_{us} /d = 425.80 / 82.2 = 5.18 KN/cm

Provide 8 Φ RTS 4 legged stirrups @ 120 mm c/c.

(V_{us} /d =5.58 KN/m > 5.18 KN/cm).

8. Sketch :



REINFORCEMENT DETAILS OF TWO PILE GROUP