Module 11

Foundations - Theory and Design

Lesson 28

Foundations - Theory

Instructional Objectives:

At the end of this lesson, the student should be able to:

- explain the two major and other requirements of the design of foundation,
- identify five points indicating the differences between the design of foundation and the design of other elements of the superstructure,
- differentiate between footing and foundation,
- differentiate between shallow and deep foundations,
- identify the situations when a combined footing shall be used,
- explain the safe bearing capacity of soil mentioning the difference between gross and net safe bearing capacities,
- determine the minimum depth of foundation,
- determine the critical sections of bending moment and shear in isolated footings,
- draw the distributions of pressure of soil below the footing for concentric and eccentric loads with $e \leq L/6$ and $e > L/6$,
- determine the soil pressure in a foundation which is unsymmetrical.

11.28.1 Introduction

Till now we discussed the different structural elements viz. beams, slabs, staircases and columns, which are placed above the ground level and are known as superstructure. The superstructure is placed on the top of the foundation structure, designated as substructure as they are placed below the ground level. The elements of the superstructure transfer the loads and moments to its adjacent element below it and finally all loads and moments come to the foundation structure, which in turn, transfers them to the underlying soil or rock. Thus, the foundation structure effectively supports the superstructure. However, all types of soil get compressed significantly and cause the structure to settle. Accordingly, the major requirements of the design of foundation structures are the two as given below (see cl.34.1 of IS 456):

1. Foundation structures should be able to sustain the applied loads, moments, forces and induced reactions without exceeding the safe bearing capacity of the soil.

2. The settlement of the structure should be as uniform as possible and it should be within the tolerable limits. It is well known from the structural analysis that differential settlement of supports causes additional moments in statically indeterminate structures. Therefore, avoiding the differential settlement is considered as more important than maintaining uniform overall settlement of the structure.

In addition to the two major requirements mentioned above, the foundation structure should provide adequate safety for maintaining the stability of structure due to either overturning and/or sliding (see cl.20 of IS 456). It is to be noted that this part of the structure is constructed at the first stage before other components (columns / beams etc.) are taken up. So, in a project, foundation design and details are completed before designs of other components are undertaken.

However, it is worth mentioning that the design of foundation structures is somewhat different from the design of other elements of superstructure due to the reasons given below. Therefore, foundation structures need special attention of the designers.

1. Foundation structures undergo soil-structure interaction. Therefore, the behaviour of foundation structures depends on the properties of structural materials and soil. Determination of properties of soil of different types itself is a specialized topic of geotechnical engineering. Understanding the interacting behaviour is also difficult. Hence, the different assumptions and simplifications adopted for the design need scrutiny. In fact, for the design of foundations of important structures and for difficult soil conditions, geotechnical experts should be consulted for the proper soil investigation to determine the properties of soil, strata wise and its settlement criteria.

2. Accurate estimations of all types of loads, moments and forces are needed for the present as well as for future expansion, if applicable. It is very important as the foundation structure, once completed, is difficult to strengthen in future.

3. Foundation structures, though remain underground involving very little architectural aesthetics, have to be housed within the property line which may cause additional forces and moments due to the eccentricity of foundation.

4. Foundation structures are in direct contact with the soil and may be affected due to harmful chemicals and minerals present in the soil and fluctuations of water table when it is very near to the foundation. Moreover,

periodic inspection and maintenance are practically impossible for the foundation structures.

5. Foundation structures, while constructing, may affect the adjoining structure forming cracks to total collapse, particularly during the driving of piles etc.

However, wide ranges of types of foundation structures are available. It is very important to select the appropriate type depending on the type of structure, condition of the soil at the location of construction, other surrounding structures and several other practical aspects as mentioned above.

11.28.2 Types of Foundation Structures

Foundations are mainly of two types: (i) shallow and (ii) deep foundations. The two different types are explained below:

(A) Shallow foundations

Shallow foundations are used when the soil has sufficient strength within a short depth below the ground level. They need sufficient plan area to transfer the heavy loads to the base soil. These heavy loads are sustained by the reinforced concrete columns or walls (either of bricks or reinforced concrete) of much less areas of cross-section due to high strength of bricks or reinforced concrete when compared to that of soil. The strength of the soil, expressed as the safe bearing capacity of the soil as discussed in sec.11.28.3, is normally supplied by the geotechnical experts to the structural engineer. Shallow foundations are also designated as footings. The different types of shallow foundations or footings are discussed below.

1. Plain concrete pedestal footings

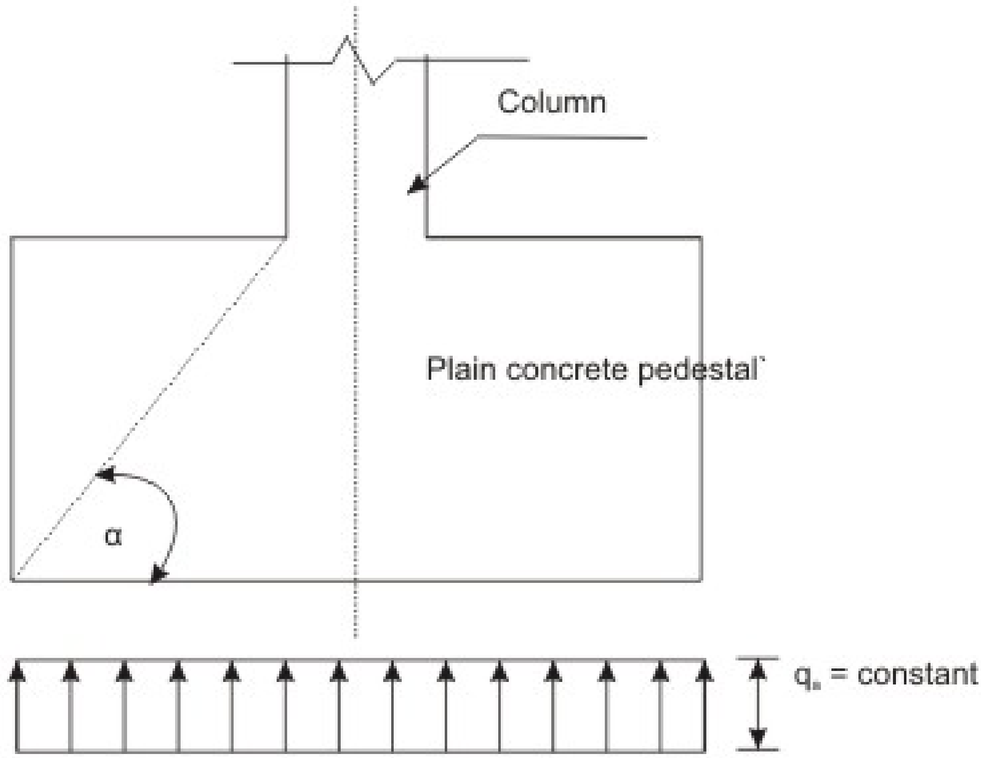

Fig. 11.28.1: Plain concrete pedestal

Plain concrete pedestal footings (Fig.11.28.1) are very economical for columns of small loads or pedestals without any longitudinal tension steel (see cls.34.1.2 and 34.1.3 of IS 456). In Fig.11.28.1, the angle α between the plane passing through the bottom edge of the pedestal and the corresponding junction edge of the column with pedestal and the horizontal plane shall be determined from Eq. 11.3.

2. Isolated footings

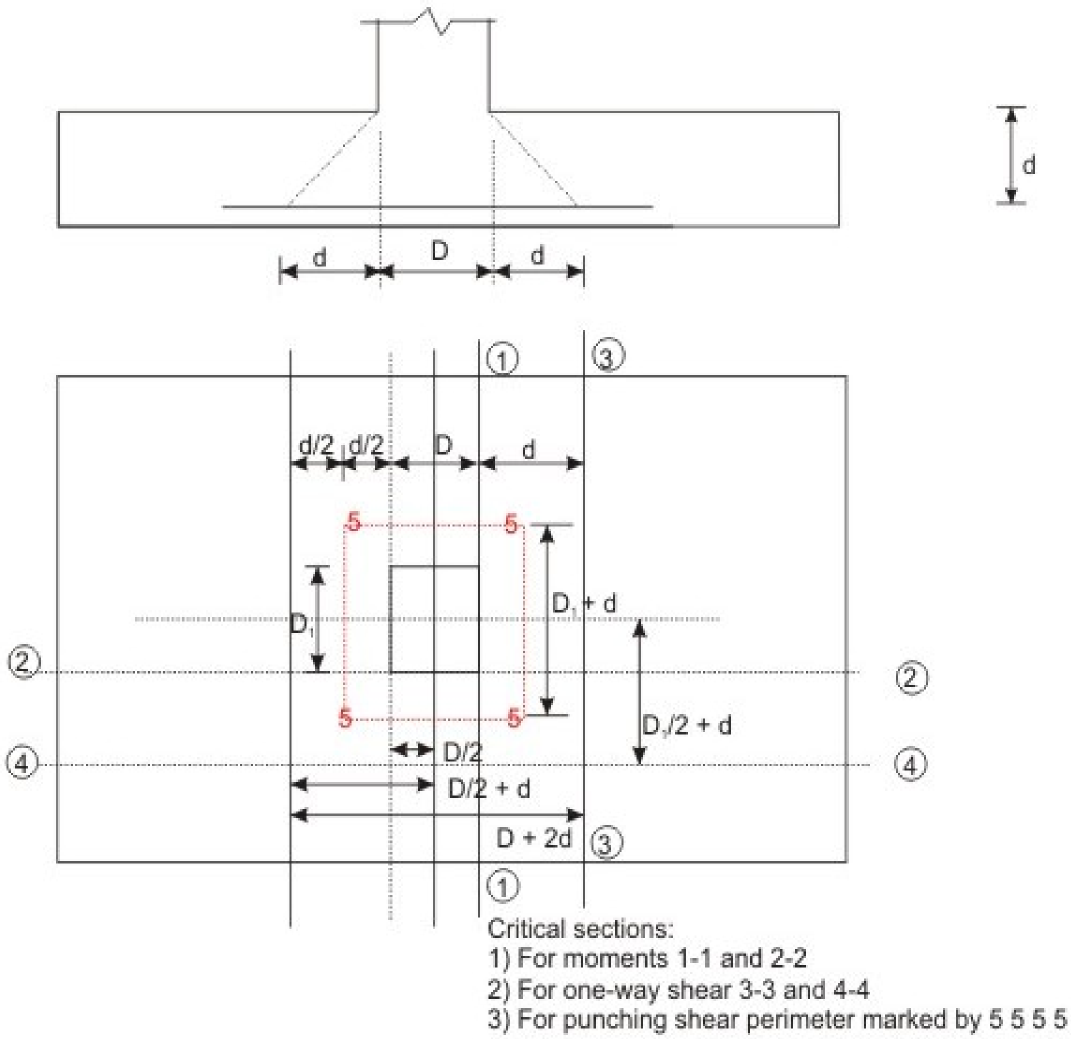

Fig. 11.28.2: Uniform and rectangular footing

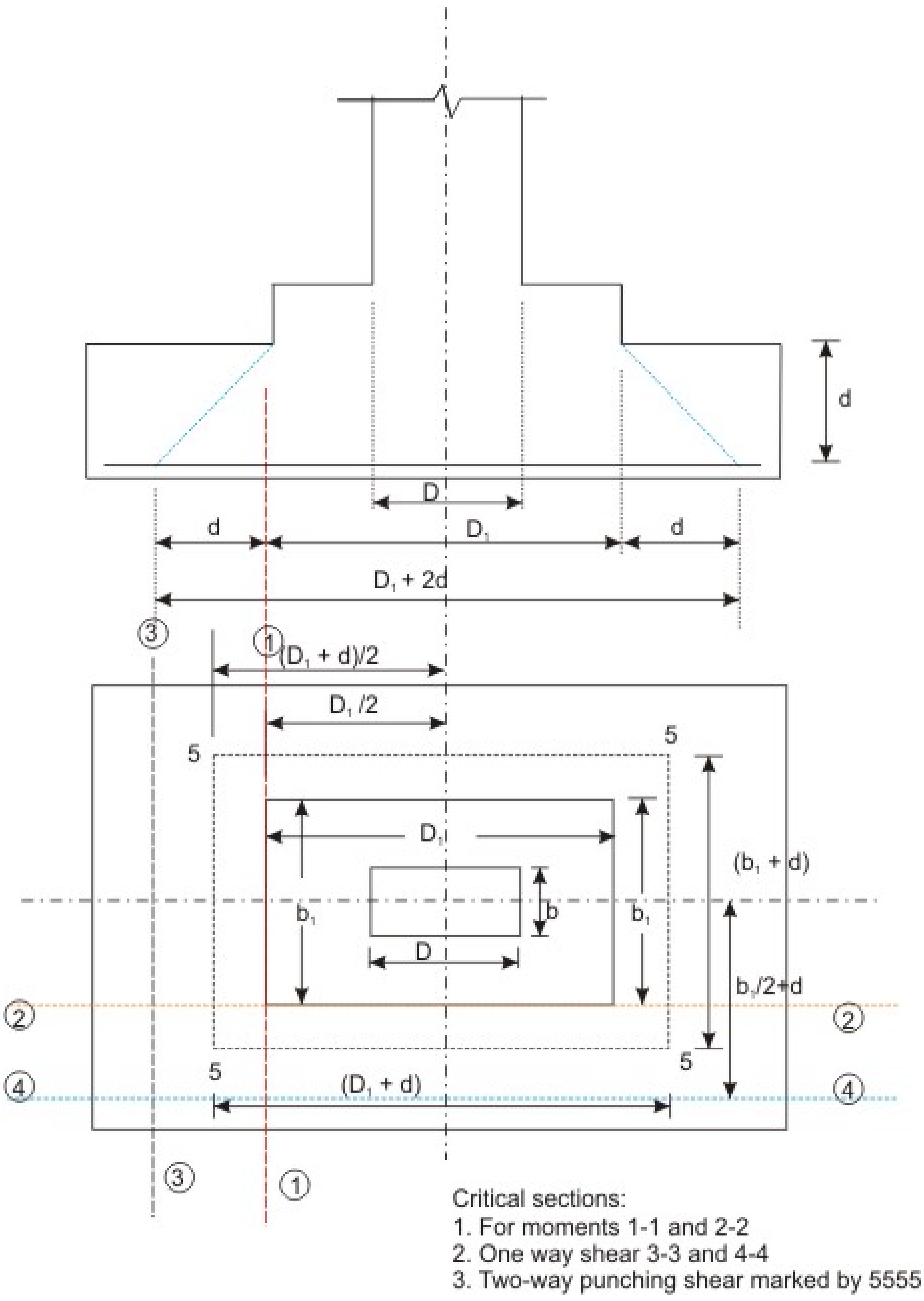

Fig. 11.28.3: Stepped and rectangular footing

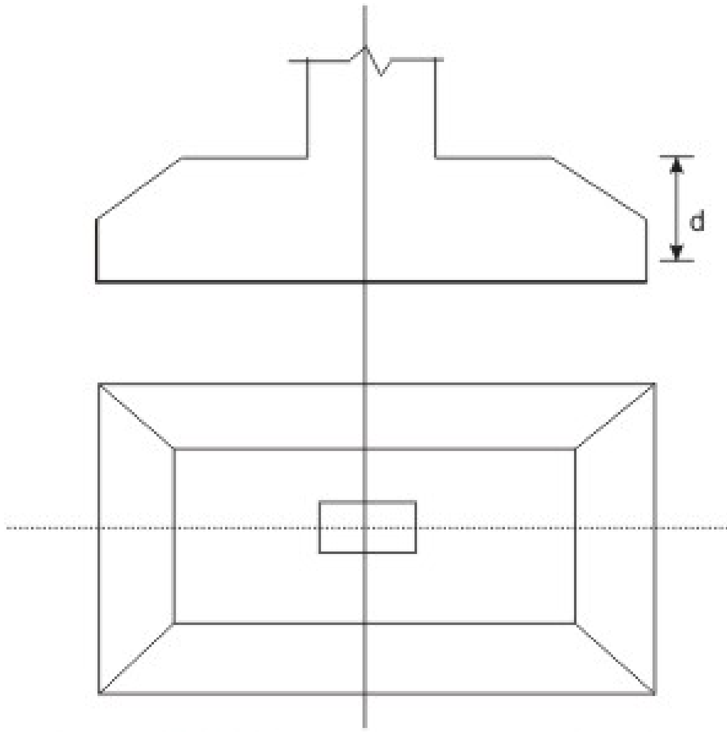

Fig. 11.28.4: Sloped and rectangular footing

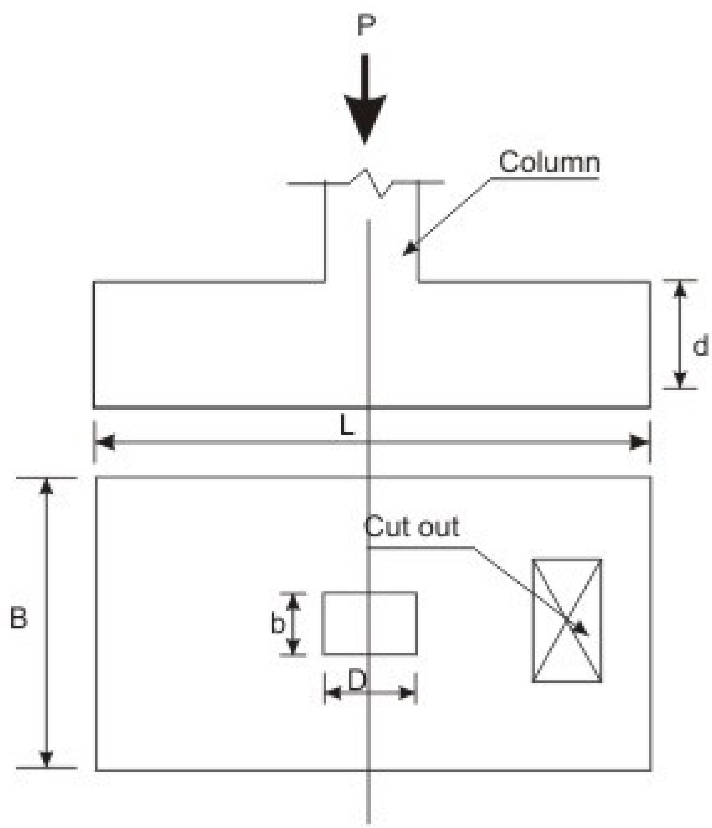

Fig. 11.28.5: Unsymmetrical footing about x axis

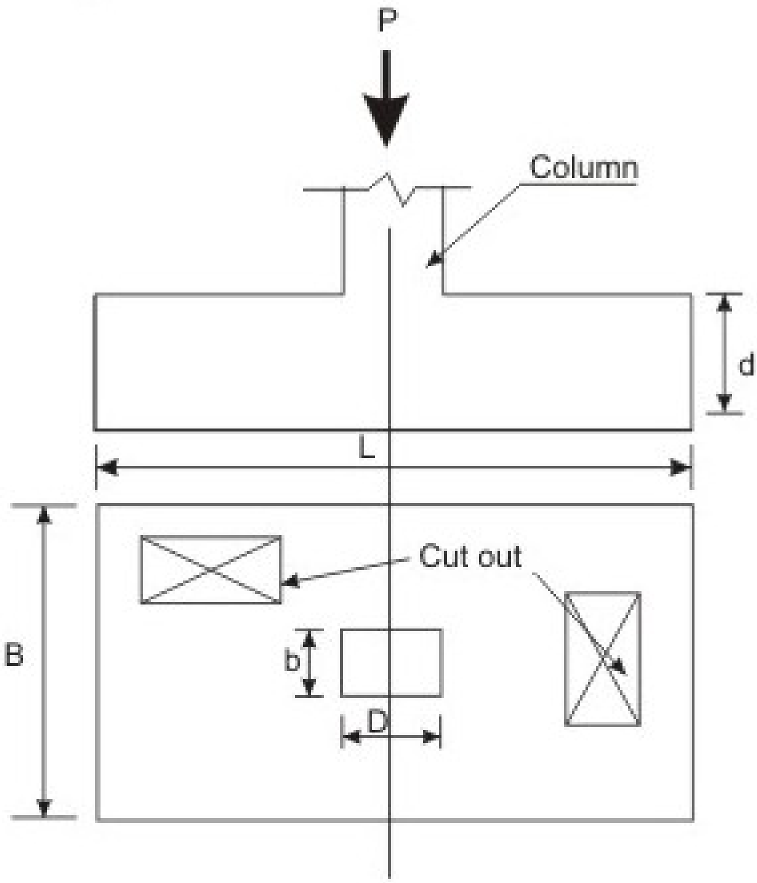

Fig. 11.28.6: Unsymmetrical footing about both axes

These footings are for individual columns having the same plan forms of square, rectangular or circular as that of the column, preferably maintaining the proportions and symmetry so that the resultants of the applied forces and reactions coincide. These footings, shown in Figs.11.27.2 to 11.27.4, consist of a slab of uniform thickness, stepped or sloped. Though sloped footings are economical in respect of the material, the additional cost of formwork does not offset the cost of the saved material. Therefore, stepped footings are more economical than the sloped ones. The adjoining soil below footings generates upward pressure which bends the slab due to cantilever action. Hence, adequate tensile reinforcement should be provided at the bottom of the slab (tension face). Clause 34.1.1 of IS 456 stipulates that the sloped or stepped footings, designed as a unit, should be constructed to ensure the integrated action. Moreover, the effective cross-section in compression of sloped and stepped footings shall be limited by the area above the neutral plane. Though symmetrical footings are desirable, sometimes situation compels for unsymmetrical isolated footings (Eccentric footings or footings with cut outs) either about one or both the axes (Figs.11.28.5 and 6).

3. Combined footings

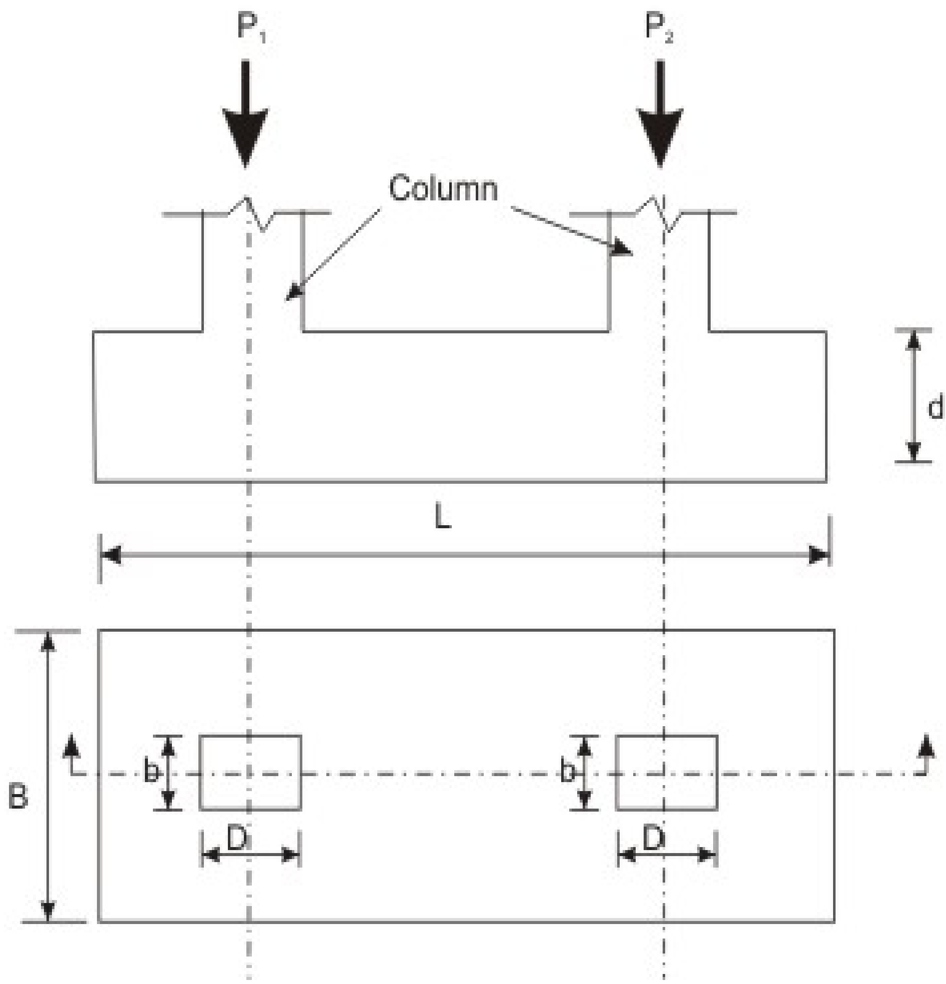

Fig. 11.28.7: Combined footing without a central beam

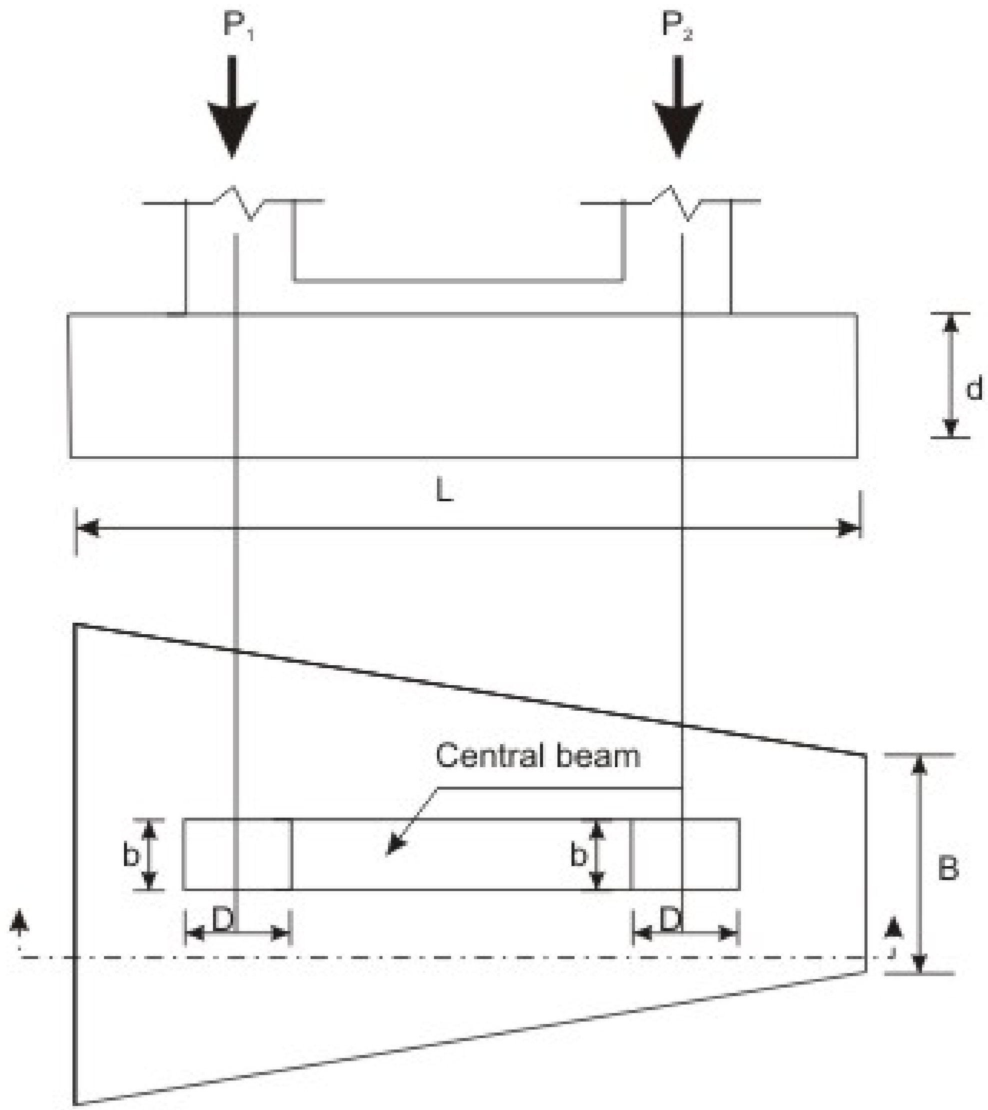

Fig. 11.28.8: Combined footing with a central beam

When the spacing of the adjacent columns is so close that separate isolated footings are not possible due to the overlapping areas of the footings or inadequate clear space between the two areas of the footings, combined footings are the solution combining two or more columns. Combined footing normally means a footing combining two columns. Such footings are either rectangular or trapezoidal in plan forms with or without a beam joining the two columns, as shown in Figs.11.28.7 and 11.28.8.

4. Strap footings

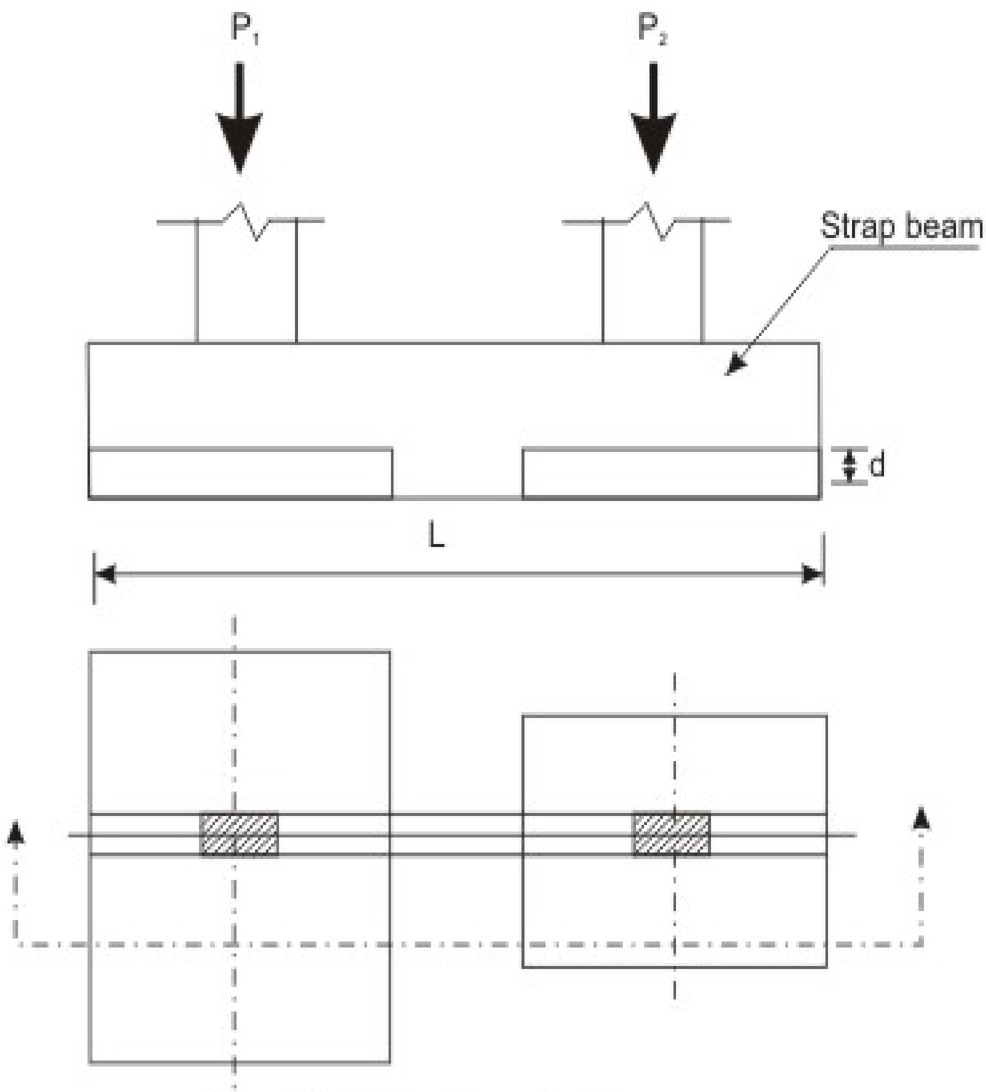

Fig. 11.28.9: Strap footing

When two isolated footings are combined by a beam with a view to sharing the loads of both the columns by the footings, the footing is known as strap footing (Fig.11.28.9). The connecting beam is designated as strap beam. These footings are required if the loads are heavy on columns and the areas of foundation are not overlapping with each other.

5. Strip foundation or wall footings

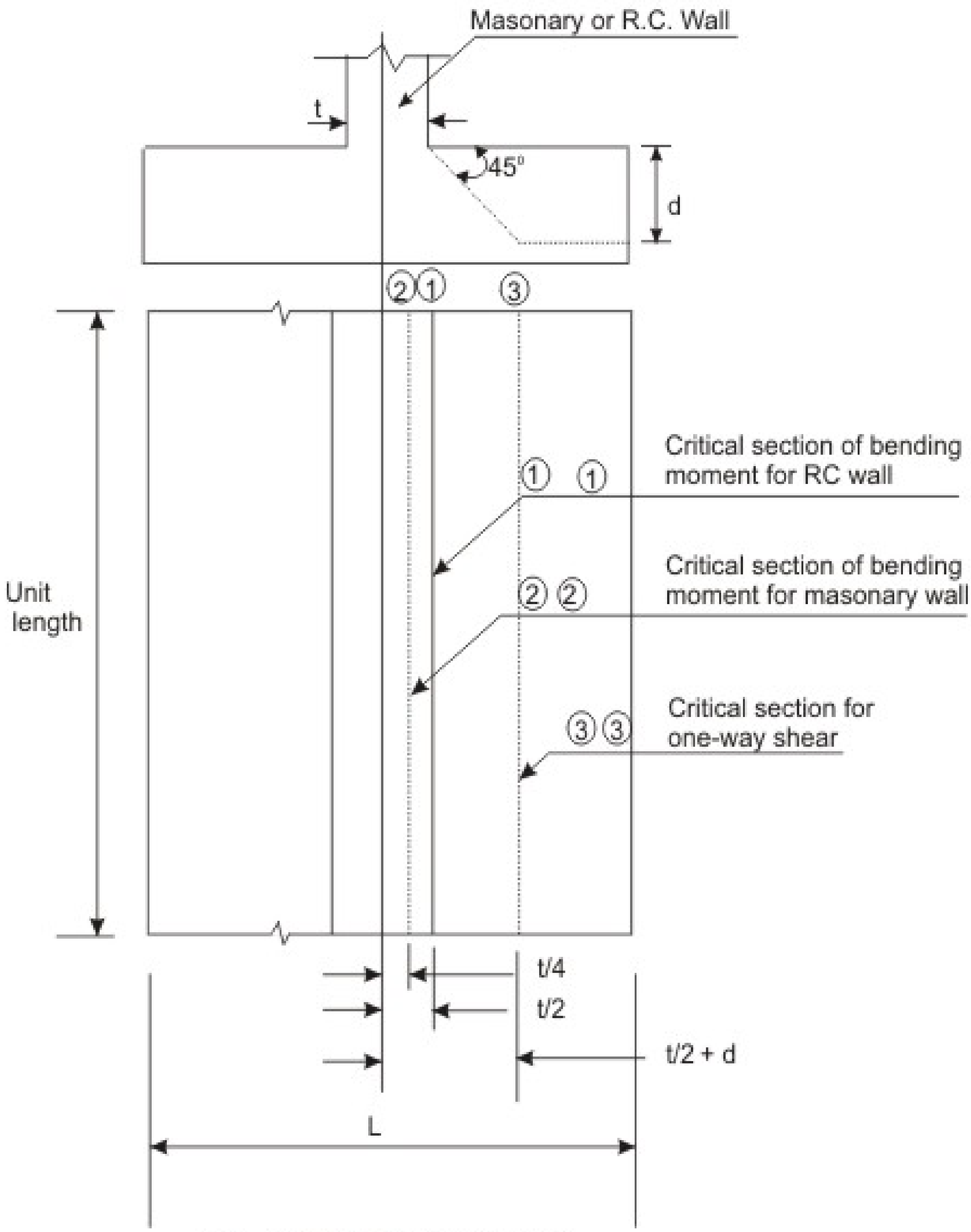

Fig. 11.28.10: Wall footing

These are in long strips especially for load bearing masonry walls or reinforced concrete walls (Figs.11.28.10). However, for load bearing masonry walls, it is common to have stepped masonry foundations. The strip footings distribute the loads from the wall to a wider area and usually bend in transverse direction. Accordingly, they are reinforced in the transverse direction mainly, while nominal distribution steel is provided along the longitudinal direction.

6. Raft or mat foundation

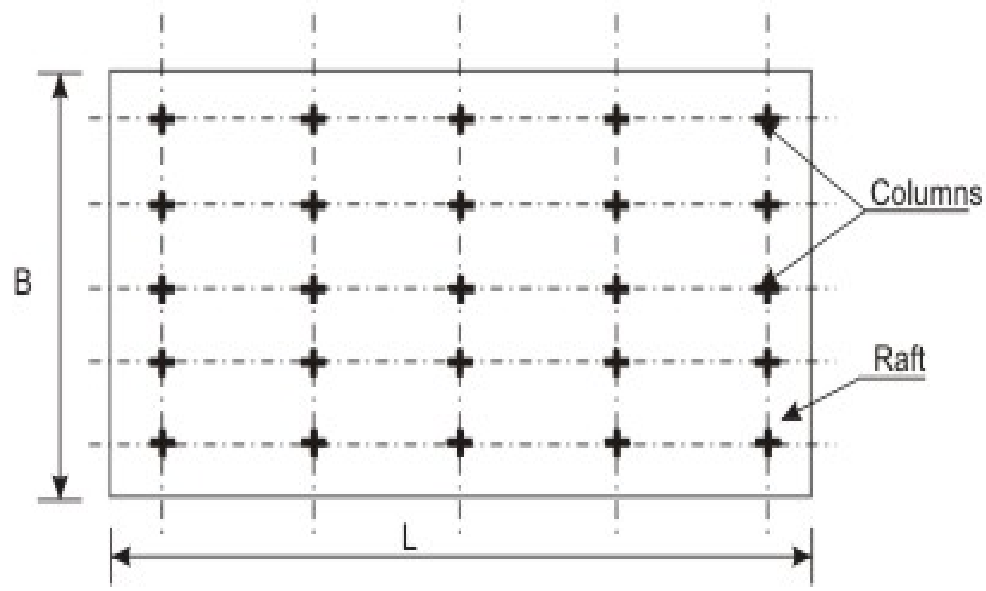

Fig. 11.28.11: Raft footing

These are special cases of combined footing where all the columns of the building are having a common foundation (Fig.11.28.11). Normally, for buildings with heavy loads or when the soil condition is poor, raft foundations are very much useful to control differential settlement and transfer the loads not exceeding the bearing capacity of the soil due to integral action of the raft foundation. This is a threshold situation for shallow footing beyond which deep foundations have to be adopted.

(B) Deep foundations

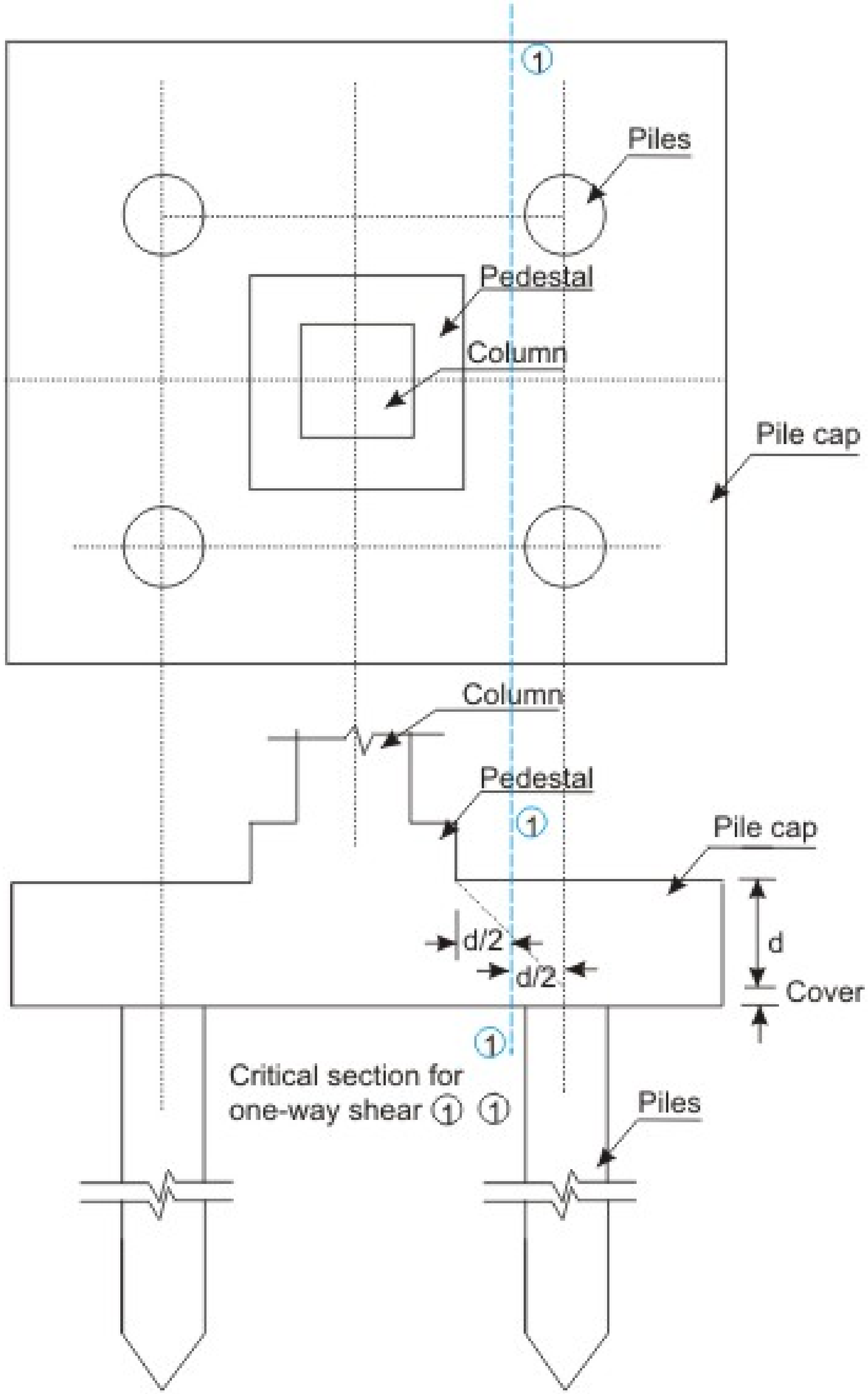

Fig. 11.28.12: Pile foundation

As mentioned earlier, the shallow foundations need more plan areas due to the low strength of soil compared to that of masonry or reinforced concrete. However, shallow foundations are selected when the soil has moderately good strength, except the raft foundation which is good in poor condition of soil also. Raft foundations are under the category of shallow foundation as they have comparatively shallow depth than that of deep foundation. It is worth mentioning that the depth of raft foundation is much larger than those of other types of shallow foundations.

However, for poor condition of soil near to the surface, the bearing capacity is very less and foundation needed in such situation is the pile foundation (Figs.11.28.12). Piles are, in fact, small diameter columns which are driven or cast into the ground by suitable means. Precast piles are driven and cast-in-situ are cast. These piles support the structure by the skin friction between the pile surface and the surrounding soil and end bearing force, if such resistance is available to provide the bearing force. Accordingly, they are designated as frictional and end bearing piles. They are normally provided in a group with a pile cap at the top through which the loads of the superstructure are transferred to the piles.

Piles are very useful in marshy land where other types of foundation are impossible to construct. The length of the pile which is driven into the ground depends on the availability of hard soil/rock or the actual load test. Another advantage of the pile foundations is that they can resist uplift also in the same manner as they take the compression forces just by the skin friction in the opposite direction.

However, driving of pile is not an easy job and needs equipment and specially trained persons or agencies. Moreover, one has to select pile foundation in such a situation where the adjacent buildings are not likely to be damaged due to the driving of piles. The choice of driven or bored piles, in this regard, is critical.

Exhaustive designs of all types of foundations mentioned above are beyond the scope of this course. Accordingly, this module is restricted to the design of some of the shallow footings, frequently used for normal low rise buildings only.

11.28.3 Safe Bearing Capacity of Soil

The safe bearing capacity q_c of soil is the permissible soil pressure considering safety factors in the range of 2 to 6 depending on the type of soil, approximations and assumptions and uncertainties. This is applicable under service load condition and, therefore, the partial safety factors λ_f for different load combinations are to be taken from those under limit state of serviceability (vide Table 18 of IS 456 or Table 2.1 of Lesson 3). Normally, the acceptable value of q_c is supplied by the geotechnical consultant to the structural engineer after proper soil investigations. The safe bearing stress on soil is also related to corresponding permissible displacement / settlement.

Gross and net bearing capacities are the two terms used in the design. Gross bearing capacity is the total safe bearing pressure just below the footing due to the load of the superstructure, self weight of the footing and the weight of earth lying over the footing. On the other hand, net bearing capacity is the net pressure in excess of the existing overburden pressure. Thus, we can write

Net bearing capacity = Gross bearing capacity - Pressure due to overburden soil (11.1)

While calculating the maximum soil pressure q, we should consider all the loads of superstructure along with the weight of foundation and the weight of the backfill. During preliminary calculations, however, the weight of the foundation and backfill may be taken as 10 to 15 per cent of the total axial load on the footing, subjected to verification afterwards.

11.28.4 Depth of Foundation

All types of foundation should have a minimum depth of 50 cm as per IS 1080-1962. This minimum depth is required to ensure the availability of soil having the safe bearing capacity assumed in the design. Moreover, the foundation should be placed well below the level which will not be affected by seasonal change of weather to cause swelling and shrinking of the soil. Further, frost also may endanger the foundation if placed at a very shallow depth. Rankine formula gives a preliminary estimate of the minimum depth of foundation and is expressed as

$$d = (q_c/\lambda)\{(1 - \sin\phi)/(1 + \sin\phi)\}^2$$
(11.2)

where d = minimum depth of foundation
q_c = gross bearing capacity of soil
λ = density of soil
ϕ = angle of repose of soil

Though Rankine formula considers three major soil properties q_c, λ and ϕ, it does not consider the load applied to the foundation. However, this may be a guideline for an initial estimate of the minimum depth which shall be checked subsequently for other requirements of the design.

11.28.5 Design Considerations

(a) Minimum nominal cover (cl. 26.4.2.2 of IS 456)

The minimum nominal cover for the footings should be more than that of other structural elements of the superstructure as the footings are in direct contact with the soil. Clause 26.4.2.2 of IS 456 prescribes a minimum cover of 50 mm for footings. However, the actual cover may be even more depending on the presence of harmful chemicals or minerals, water table etc.

(b) Thickness at the edge of footings (cls. 34.1.2 and 34.1.3 of IS 456)

The minimum thickness at the edge of reinforced and plain concrete footings shall be at least 150 mm for footings on soils and at least 300 mm above the top of piles for footings on piles, as per the stipulation in cl.34.1.2 of IS 456.

For plain concrete pedestals, the angle α (see Fig.11.28.1) between the plane passing through the bottom edge of the pedestal and the corresponding junction edge of the column with pedestal and the horizontal plane shall be determined from the following expression (cl.34.1.3 of IS 456)

$$\tan\alpha \le 0.9\{(100\, q_a/f_{ck}) + 1\}^{1/2} \qquad (11.3)$$

where q_a = calculated maximum bearing pressure at the base of pedestal in N/mm^2, and

f_{ck} = characteristic strength of concrete at 28 days in N/mm^2.

(c) Bending moments (cl. 34.2 of IS 456)

1. It may be necessary to compute the bending moment at several sections of the footing depending on the type of footing, nature of loads and the distribution of pressure at the base of the footing. However, bending moment at any section shall be determined taking all forces acting over the entire area on one side of the section of the footing, which is obtained by passing a vertical plane at that section extending across the footing (cl.34.2.3.1 of IS 456).

2. The critical section of maximum bending moment for the purpose of designing an isolated concrete footing which supports a column, pedestal or wall shall be:

(i) at the face of the column, pedestal or wall for footing supporting a concrete column, pedestal or reinforced concrete wall, (Figs.11.28.2, 3 and 10), and

(ii) halfway between the centre-line and the edge of the wall, for footing under masonry wall (Fig.11.28.10). This is stipulated in cl.34.2.3.2 of IS 456.

The maximum moment at the critical section shall be determined as mentioned in 1 above.

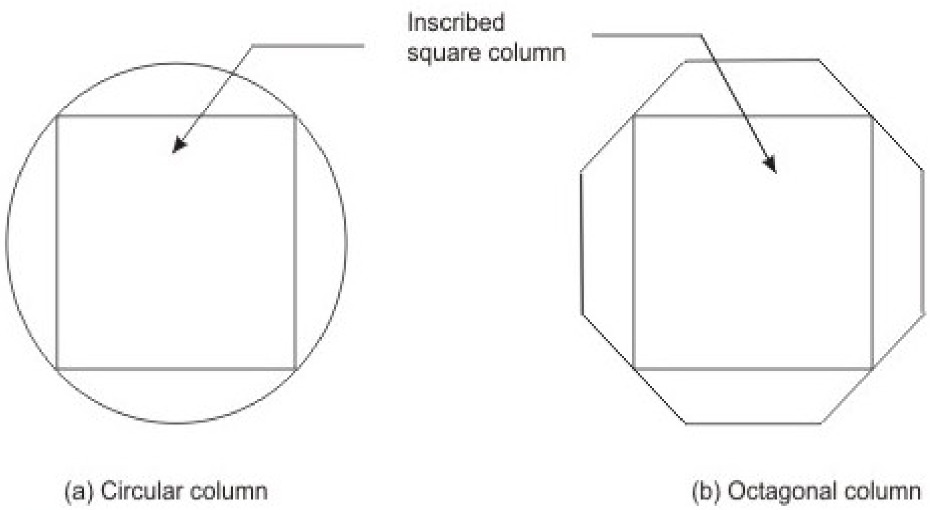

Fig. 11.28.13: Equivalent square columns (cl 34.2.2 of IS 456:2000)

For round or octagonal concrete column or pedestal, the face of the column or pedestal shall be taken as the side of a square inscribed within the perimeter of the round or octagonal column or pedestal (see cl.34.2.2 of IS 456 and Figs.11.28.13a and b).

(d) Shear force (cl. 31.6 and 34.2.4 of IS 456)

Footing slabs shall be checked in one-way or two-way shears depending on the nature of bending. If the slab bends primarily in one-way, the footing slab shall be checked in one-way vertical shear. On the other hand, when the bending is primarily two-way, the footing slab shall be checked in two-way shear or punching shear. The respective critical sections and design shear strengths are given below:

1. One-way shear (cl. 34.2.4 of IS 456)

One-way shear has to be checked across the full width of the base slab on a vertical section located from the face of the column, pedestal or wall at a distance equal to (Figs.11.28.2, 3 and 10):

(i) effective depth of the footing slab in case of footing slab on soil, and

(ii) half the effective depth of the footing slab if the footing slab is on piles (Fig.11.28.12).

The design shear strength of concrete without shear reinforcement is given in Table 19 of cl.40.2 of IS 456.

2. Two-way or punching shear (cls.31.6 and 34.2.4)

Two-way or punching shear shall be checked around the column on a perimeter half the effective depth of the footing slab away from the face of the column or pedestal (Figs.11.28.2 and 3).

The permissible shear stress, when shear reinforcement is not provided, shall not exceed $k_s \tau_c$, where k_s = (0.5 + β_c), but not greater than one, β_c being the ratio of short side to long side of the column, and τ_c = $0.25(f_{ck})^{1/2}$ in limit state method of design, as stipulated in cl.31.6.3 of IS 456.

Normally, the thickness of the base slab is governed by shear. Hence, the necessary thickness of the slab has to be provided to avoid shear reinforcement.

(e) Bond (cl.34.2.4.3 of IS 456)

The critical section for checking the development length in a footing slab shall be the same planes as those of bending moments in part (c) of this section. Moreover, development length shall be checked at all other sections where they change abruptly. The critical sections for checking the development length are given in cl.34.2.4.3 of IS 456, which further recommends to check the anchorage requirements if the reinforcement is curtailed, which shall be done in accordance with cl.26.2.3 of IS 456.

(f) Tensile reinforcement (cl.34.3 of IS 456)

The distribution of the total tensile reinforcement, calculated in accordance with the moment at critical sections, as specified in part (c) of this section, shall be done as given below for one-way and two-way footing slabs separately.

(i) In one-way reinforced footing slabs like wall footings, the reinforcement shall be distributed uniformly across the full width of the footing i.e., perpendicular to the direction of wall. Nominal distribution reinforcement shall be provided as per cl. 34.5 of IS 456 along the length of the wall to take care of the secondary moment, differential settlement, shrinkage and temperature effects.

(ii) In two-way reinforced square footing slabs, the reinforcement extending in each direction shall be distributed uniformly across the full width/length of the footing.

(iii) In two-way reinforced rectangular footing slabs, the reinforcement in the long direction shall be distributed uniformly across the full width of the footing slab. In the short direction, a central band equal to the width of the footing shall be marked along the length of the footing, where the portion of the reinforcement shall be determined as given in the equation below. This portion of the reinforcement shall be distributed across the central band:

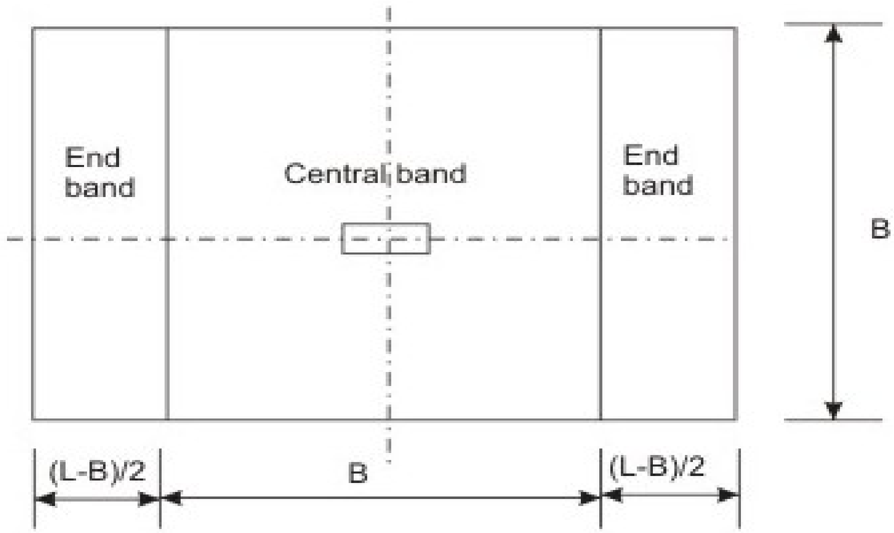

Fig. 11.28.14: Bands for reinforcement in a rectangular footing

Reinforcement in the central band = {2/(β +1)} (Total reinforcement in the short direction)
(11.4)

where β is the ratio of longer dimension to shorter dimension of the footing slab (Fig.11.28.14).

Each of the two end bands shall be provided with half of the remaining reinforcement, distributed uniformly across the respective end band.

(g) Transfer of load at the base of column (cl.34.4 of IS 456)

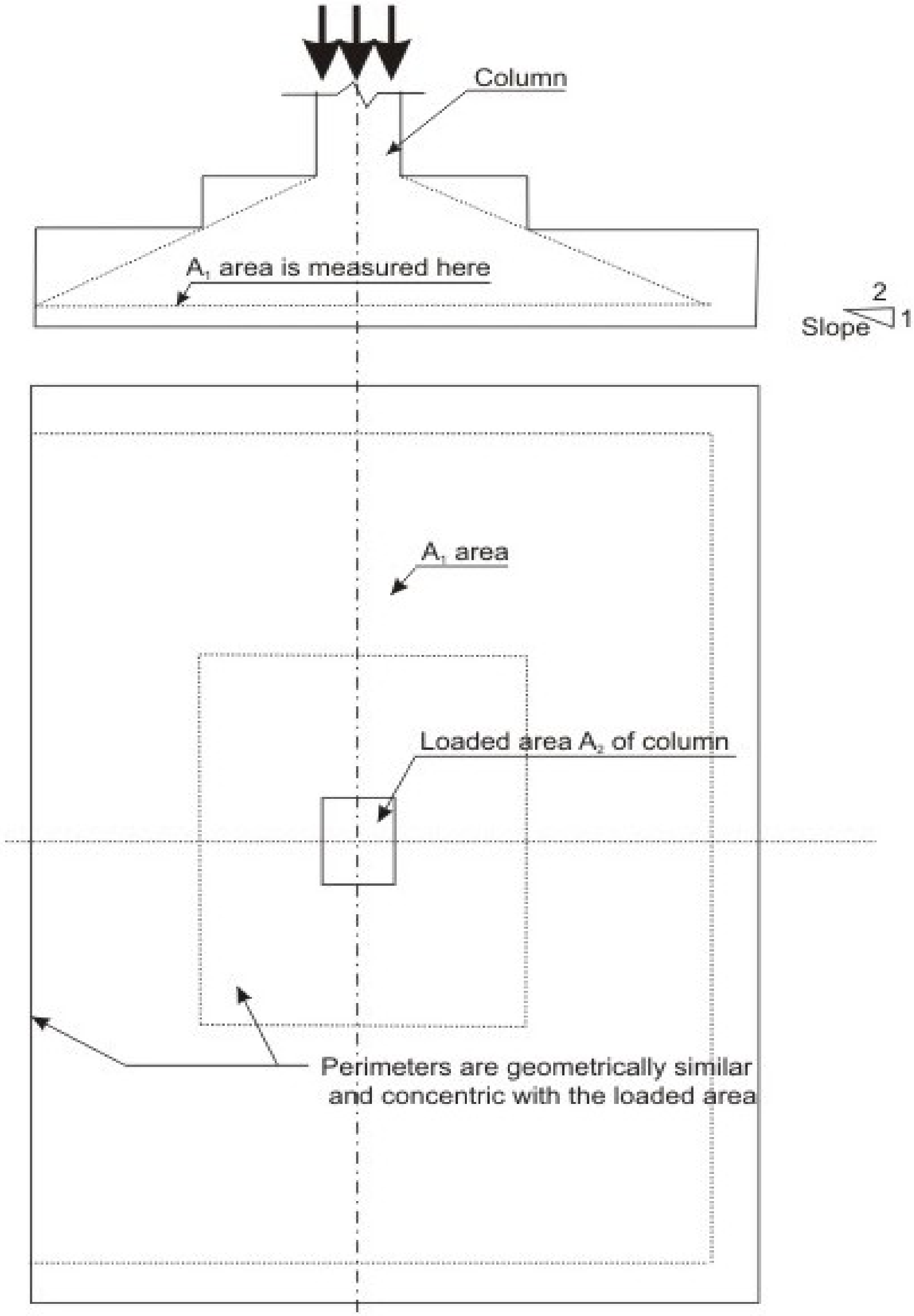

Fig. 11.28.15: Bearing area in sloped or stepped footing

All forces and moments acting at the base of the column must be transferred to the pedestal, if any, and then from the base of the pedestal to the footing, (or directly from the base of the column to the footing if there is no pedestal) by compression in concrete and steel and tension in steel. Compression forces are transferred through direct bearing while tension forces are transferred through developed reinforcement. The permissible bearing stresses on full area of concrete shall be taken as given below from cl.34.4 of IS 456:

$$\sigma_{br} = 0.25 f_{ck}, \text{ in working stress method, and} \quad (11.5)$$

$$\sigma_{br} = 0.45 f_{ck}, \text{ in limit state method} \quad (11.6)$$

It has been mentioned in sec. 10.26.5 of Lesson 26 that the stress of concrete is taken as $0.45f_{ck}$ while designing the column. Since the area of footing is much larger, this bearing stress of concrete in column may be increased considering the dispersion of the concentrated load of column to footing. Accordingly, the permissible bearing stress of concrete in footing is given by (cl.34.4 of IS 456):

$$\sigma_{br} = 0.45 f_{ck} (A_1/A_2)^{1/2} \quad (11.7)$$

with a condition that

$$(A_1/A_2)^{1/2} \leq 2.0 \quad (11.8)$$

where A_1 = maximum supporting area of footing for bearing which is geometrically similar to and concentric with the loaded area A_2, as shown in Fig.11.28.15

A_2 = loaded area at the base of the column.

The above clause further stipulates that in sloped or stepped footings, A_1 may be taken as the area of the lower base of the largest frustum of a pyramid or cone contained wholly within the footing and having for its upper base, the area actually loaded and having side slope of one vertical to two horizontal, as shown in Fig.11.28.15.

If the permissible bearing stress on concrete in column or in footing is exceeded, reinforcement shall be provided for developing the excess force (cl.34.4.1 of IS 456), either by extending the longitudinal bars of columns into the footing (cl.34.4.2 of IS 456) or by providing dowels as stipulated in cl.34.4.3 of IS 456 and given below:

(i) Sufficient development length of the reinforcement shall be provided to transfer the compression or tension to the supporting member in accordance with cl.26.2 of IS 456, when transfer of force is accomplished by reinforcement of column (cl.34.4.2 of IS 456).

(ii) Minimum area of extended longitudinal bars or dowels shall be 0.5 per cent of the cross-sectional area of the supported column or pedestal (cl.34.4.3 of IS 456).

(iii) A minimum of four bars shall be provided (cl.34.4.3 of IS 456).

(iv) The diameter of dowels shall not exceed the diameter of column bars by more than 3 mm.

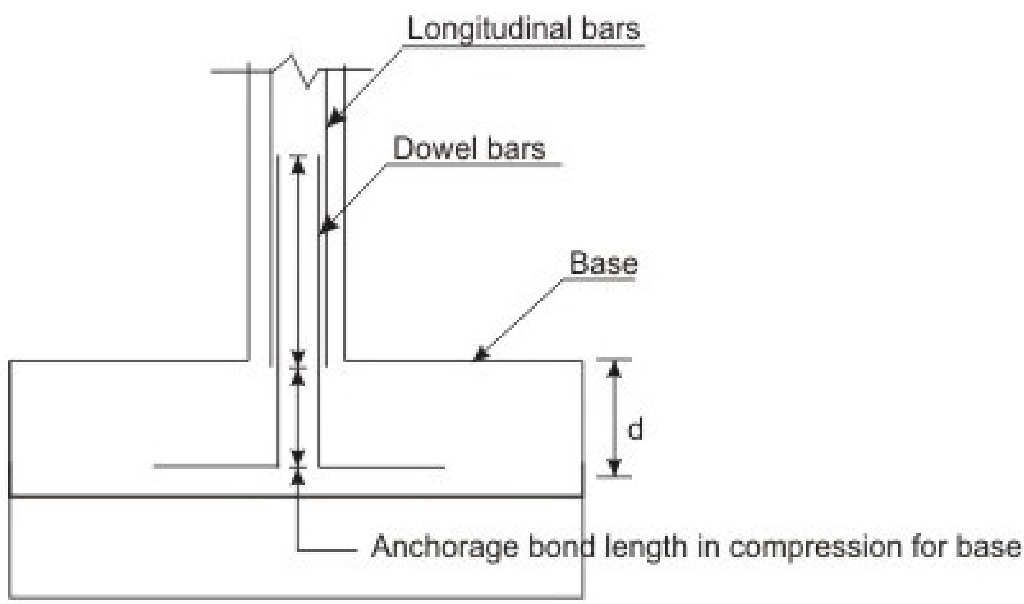

Fig. 11.28.16: Anchorage length of dowels

(v) Column bars of diameter larger than 36 mm, in compression only can be doweled at the footings with bars of smaller size of the necessary area. The dowel shall extend into the column, a distance equal to the development length of the column bar and into the footing, a distance equal to the development length of the dowel, as stipulated in cl.34.4.4 of IS 456 and as shown in Fig.11.28.16.

(h) Nominal reinforcement (cl. 34.5 of IS 456)

1. Clause 34.5.1 of IS 456 stipulates the minimum reinforcement and spacing of the bars in footing slabs as per the requirements of solid slab (cls.26.5.2.1 and 26.3.3b(2) of IS 456, respectively).

2. The nominal reinforcement for concrete sections of thickness greater than 1 m shall be 360 mm^2 per metre length in each direction on each face, as stipulated in cl.34.5.2 of IS 456. The clause further specifies that this provision does not supersede the requirement of minimum tensile reinforcement based on the depth of section.

11.28.6 Distribution of Base Pressure

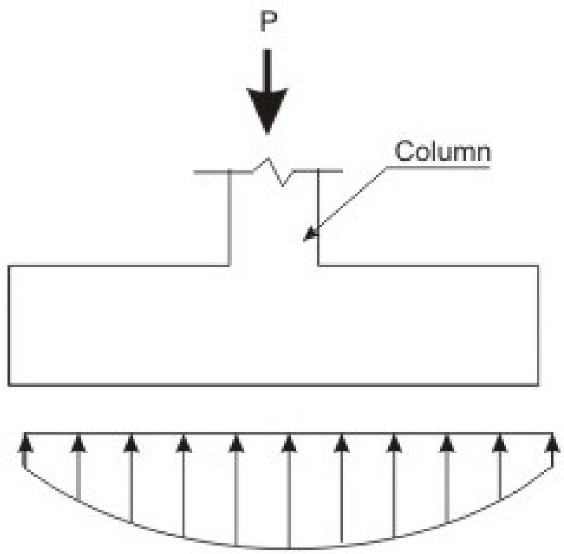

Fig. 11.28.17: Pressure distribution in sandy soil

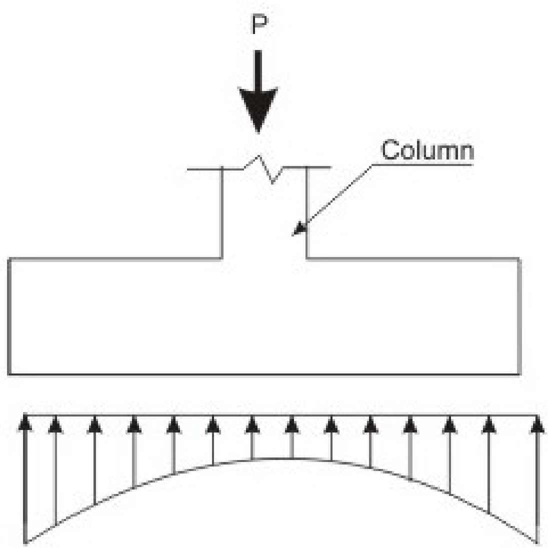

Fig. 11.28.18: Pressure distribution in clayey soil

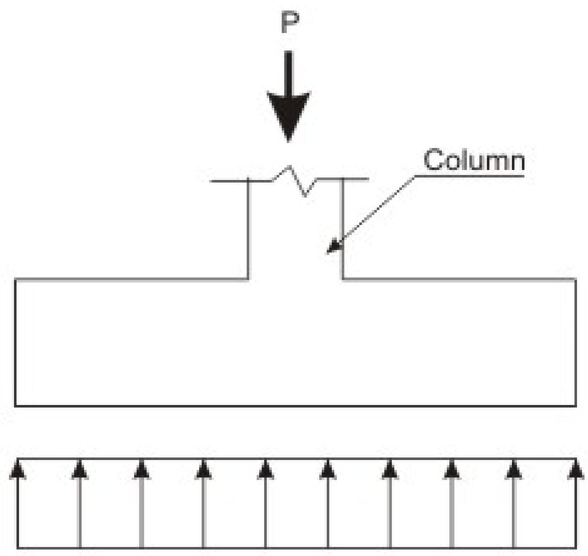

Fig. 11.28.19: Assuming uniform pressure in the design

The foundation, assumed to act as a rigid body, is in equilibrium under the action of applied forces and moments from the superstructure and the reactions from the stresses in the soil. The distribution of base pressure is different for different types of soil. Typical distributions of pressure, for actual foundations, in sandy and clayey soils are shown in Figs.11.28.17 and 18, respectively. However, for the sake of simplicity the footing is assumed to be a perfectly rigid body, the soil is assumed to behave elastically and the distributions of stress and stain are linear in the soil just below the base of the foundation, as shown in Fig.11.28.19. Accordingly, the foundation shall be designed for the applied loads, moments and induced reactions keeping in mind that the safe bearing capacity of the soil is within the prescribed limit. It is worth mentioning that the soil bearing capacity is in the serviceable limit state and the foundation structure shall be designed as per the limit state of collapse, checking for other limit states as well to ensure an adequate degree of safety and serviceability.

In the following, the distributions of base pressure are explained for (i) concentrically loaded footings, (ii) eccentrically loaded footings and (iii) unsymmetrical (about both the axes) footings.

(i) Concentrically loaded footings

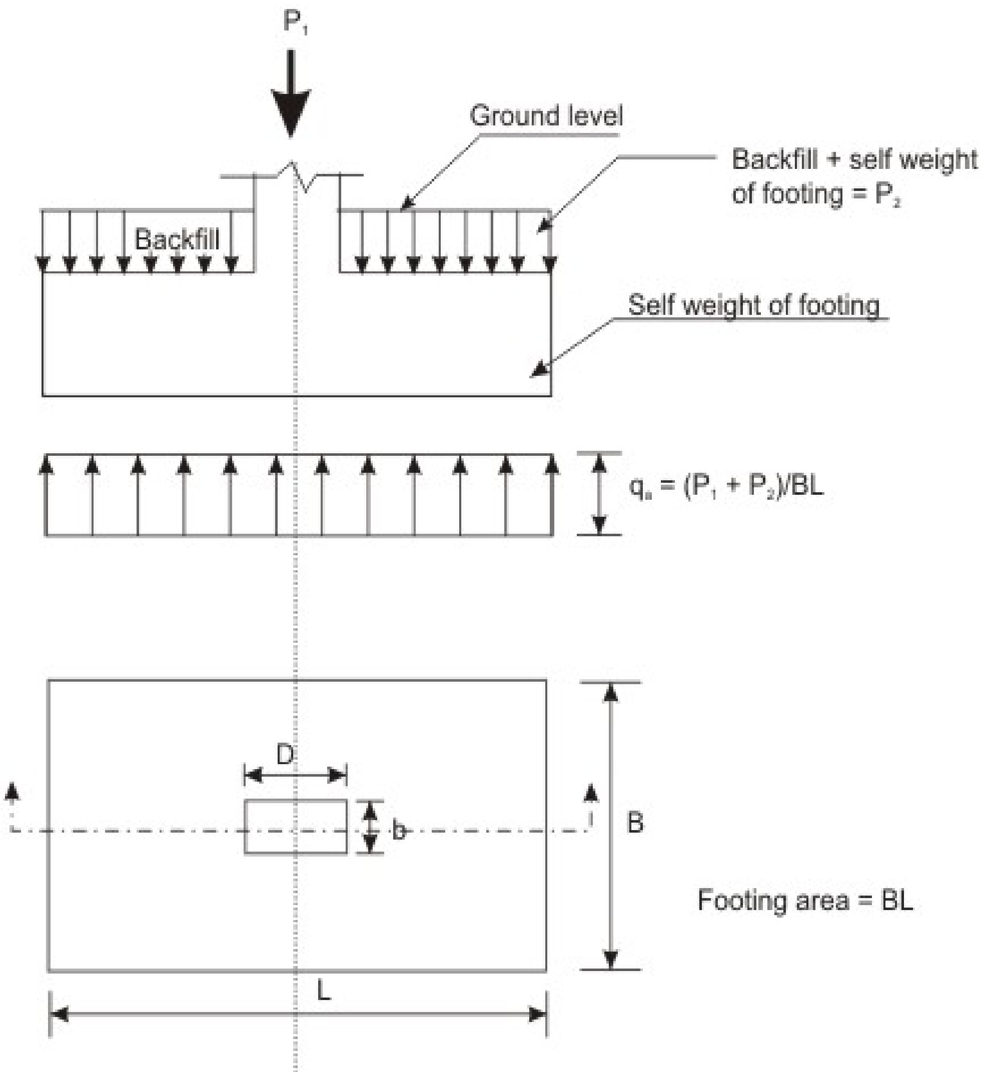

Fig. 11.28.20: Isolated footing subjected to concentric loading

Figure 11.28.20 shows rectangular footing symmetrically loaded with service load P_1 from the superstructure and P_2 from the backfill including the weight of the footing. The assumed uniformly distributed soil pressure at the base of magnitude q is obtained from:

$$q = (P_1 + P_2)/A \qquad (11.9)$$

where A is the area of the base of the footing.

In the design problem, however, A is to be determined from the condition that the actual gross intensity of soil pressure does not exceed q_c, the bearing capacity of the soil, a known given data. Thus, we can write from Eq.11.9:

$$A = (P_1 + P_2)/q_c \qquad (11.10)$$

From the known value of *A*, the dimensions *B* and *L* are determined such that the maximum bending moment in each of the two adjacent projections is equal, i.e., the ratio of the dimensions *B* and *L* of the footing shall be in the same order of the ratio of width *b* and depth *D* of the column.

(ii) Eccentrically loaded footings

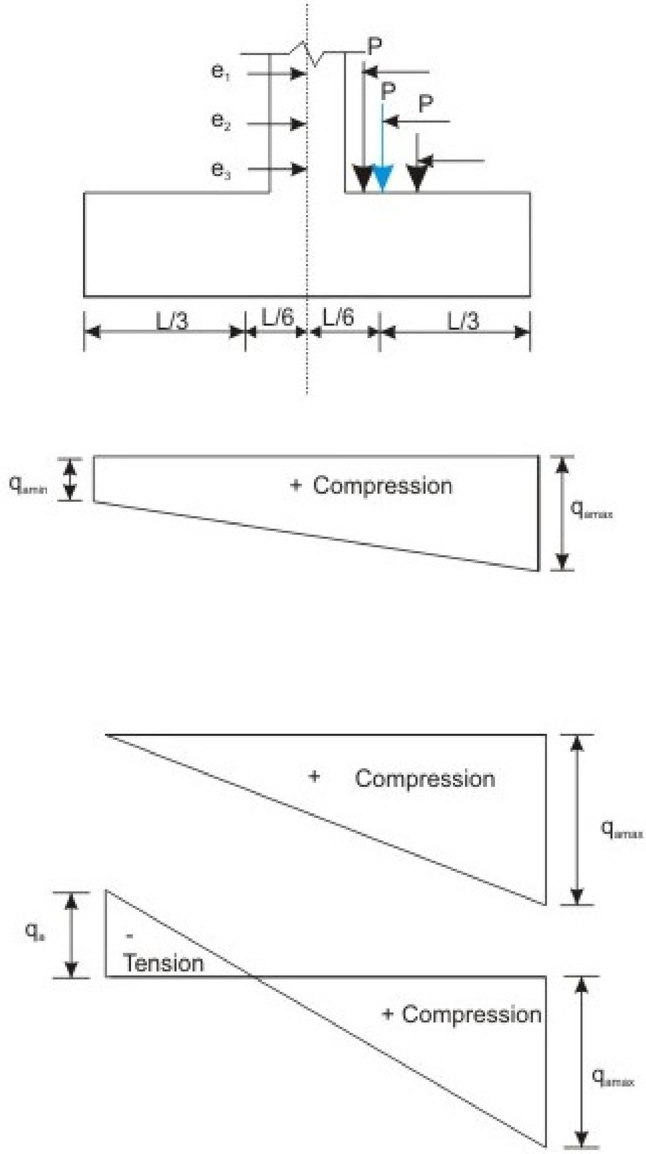

Fig. 11.28.21(a): Isolated footing

Fig. 11.28.21(b:) When e < L/6

Fig. 11.28.21(c): When e = L/6

Fig. 11.28.21(d): When e > L/6

Fig. 11.28.21: Isolated footing subjected to different eccentric loadings

In most of the practical situations, a column transfers axial load *P* and moment *M* to the footing, which can be represented as eccentrically loaded footing when a load *P* is subjected to an eccentricity $e = M/P$. This eccentricity may also be there, either alone or in combined mode, when

- the column transfers a vertical load at a distance of *e* from the centroidal axis of the footing, and

- the column or the pedestal transfers a lateral load above the level of foundation, in addition to vertical loads.

Accordingly, the distribution of pressure may be of any one of the three types, depending on the magnitude of the eccentricity of the load, as shown in Figs.11.28.21b to d. The general expression of q_a, the intensity of soil pressure at a distance of y from the origin is:

$$q_a = P/A \pm (Pe/I_x)y \quad (11.11)$$

We would consider a rectangular footing symmetric to the column. Substituting the values of $A = BL$, $I_x = BL^3/12$ and $y = L/2$, we get the values of q_a at the left edge.

$$q_a \text{ at the left edge} = (P/BL)\{1 - (6e/L)\} \quad (11.12)$$

It is evident from Eq.11.12, that the three cases are possible:

(A) when $e < L/6$, q_a at the left edge is compression (+),

(B) when $e = L/6$, q_a at the left edge is zero, and

(C) when $e > L/6$, q_a at the left edge is tension (-).

The three cases are shown in Figs.11.28.21b to d, respectively. It is to be noted that similar three cases are also possible when eccentricity of the load is negative resulting the values of q_a at the right edge as compression, zero or tension. Evidently, these soil reactions, in compression and tension, should be permissible and attainable.

Case (A): when $|e| \leq L/6$

Figures 11.28.21b and c show these two cases, when $|e| < L/6$ or $|e| = L/6$, respectively. It is seen that the entire area of the footing is in compression having minimum and maximum values of q at the two edges with a linear and non-uniform variation. The values of q are obtained from Eq.11.11.

In the limiting case i.e., when $|e| = L/6$, the value of q_a is zero at one edge and the other edge is having $q_a = 2P/BL$ (compression) with a linear variation. Similarly, when $e = 0$, the footing is subjected to uniform constant pressure of P/BL. Thus, when $|e| = L/6$, the maximum pressure under one edge of the footing is twice of the uniform pressure when $e = 0$.

In a more general case, as in the case of footing for the corner column of a building, the load may have biaxial eccentricities. The general expression of q_a at a location of (x,y) of the footing, when the load is having biaxial eccentricities of e_x and e_y is,

$$q_a = P/A \pm P\, e_x y/I_x \pm P\, e_y x/I_y \qquad (11.13)$$

Similarly, it can be shown that the rectangular footing of width B and length L will have no tension when the two eccentricities are such that

$$6e_x/L + 6e_y/B \leq 1 \qquad (11.14)$$

Case (B): when | *e* | > *L*/6

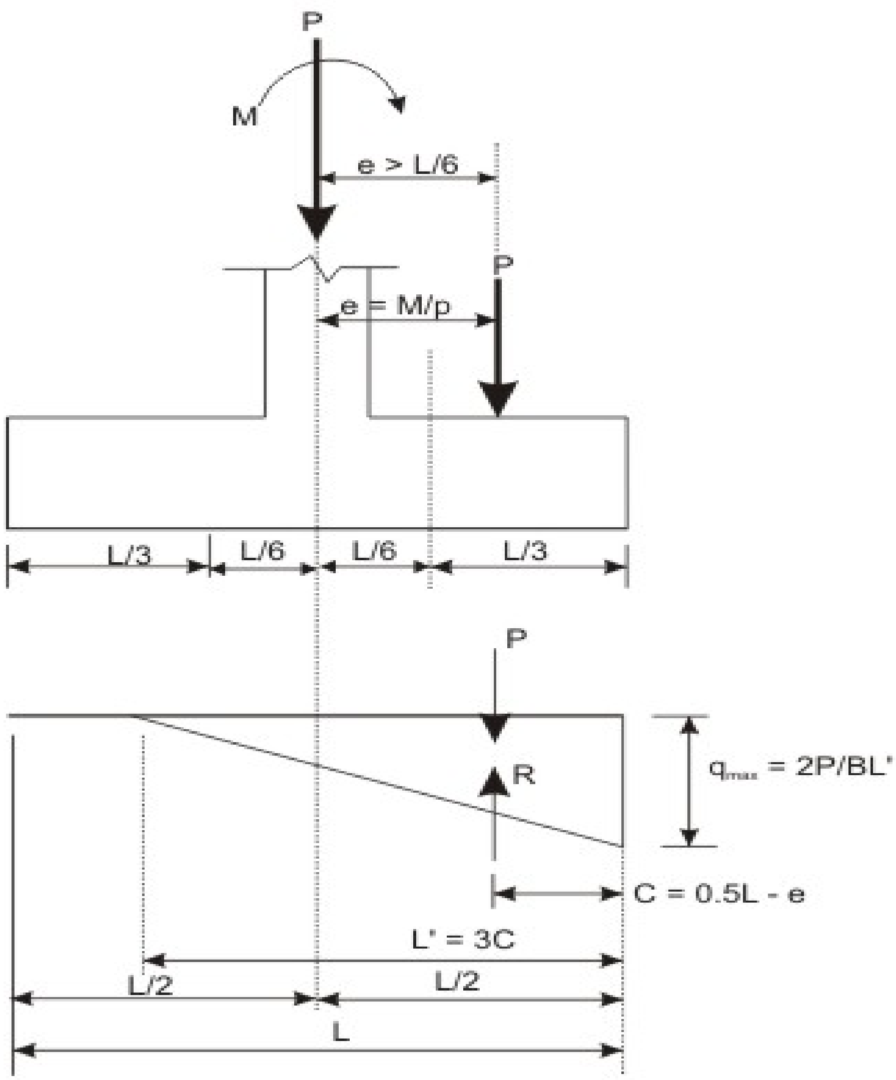

Fig. 11.28.22: Eccentrically loaded isolated footing (e > L/6)

The eccentricity of the load more than *L*/6 results in development of tensile stresses in part of the soil. Stability, in such case, is ensured by either anchoring or weight of overburden preventing uplift. However, it is to ensure that maximum compressive pressure on the other face is within the limit and sufficient factor of safety is available against over turning. Accordingly, the maximum pressure in such a case can be determined considering the soil under compression part only. Further, assuming the line of action of the eccentric load coincides with that of resultant soil pressure (Fig.11.28.22) we have:

$$q_{max} = P/L'B + 12P(0.5\,C)(1.5\,C)/BL' = 2P/L'B \qquad (11.15)$$

where $L' = 3C$ (11.16)

(iii) Unsymmetrical footings

It may be necessary to provide some cutouts in the foundation to reduce the uplift pressure or otherwise. The footing in such cases becomes unsymmetrical about both the axes. It is possible to determine the soil pressure distribution using the structural mechanics principle as given below.

$$q_a(x,y) = P/A \pm \{(M_yI_x - M_xI_{xy})(x)/(I_xI_y - I_{xy}^2)\} + \{(M_xI_y - M_yI_{xy})(y)/(I_xI_y - I_{xy}^2)\} \qquad (11.17)$$

where M_x = moment about *x* axis,

M_y = moment about *y* axis,

I_x = moment of inertia about *x* axis,

I_y = moment of inertia about *y* axis,

I_{xy} = product of inertia

11.28.7 Practice Questions and Problems with Answers

Q.1: **(A)** What are the two essential requirements of the design of foundation?

(B) Mention five points indicating the differences between the design of foundation and the design of other elements of superstructure.

A.1: See sec. 11.28.1.

Q.2: Draw sketches of different shallow foundations.

A.2: Figure Nos. 11.28.1 to 11.

Q.3: Explain the difference between gross and net safe bearing capacities of soil. Which one is used for the design of foundation?

A.3: See sec. 11.28.3.

Q.4: How would you determine the minimum depth of foundation?

A.4: See sec.11.28.4.

Q.5: What are the critical sections of determining the bending moment in isolated footing?

A.5: See part (c)2 of sec.11.28.5.

Q.6: Explain the one-way and two-way shears of foundation slabs.

A.6: See part (d) of sec.11.28.5.

Q.7: Draw the actual distributions of base pressures of soil below the footing in sandy and clayey soils. Draw the assumed distribution of base pressure below the footing.

A.7: Figure Nos. 11.28.17 and 18.

Q.8: Draw the distributions of pressure in a footing for concentric and eccentric loadings ($e \le L/6$ and $e > L/6$).

A.8: Figure Nos. 11.28.20 and 21.

Q.9: How would you determine the pressure at any point (x,y) of a foundation which is unsymmetrical?

A.9: See part (iii) of sec.11.28.6.

11.28.8 References

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11.28.9 Test 28 with Solutions

Maximum Marks = 50,   Maximum Time = 30 minutes

Answer all questions.

TQ.1: (A) What are the two essential requirements of the design of foundation? (5 marks)

(B) Mention five points indicating the differences between the design of foundation and the design of other elements of superstructure. (5 marks)

A.TQ.1: See sec. 11.28.1.

TQ.2: How would you determine the minimum depth of foundation? (10 marks)

A.TQ.2: See sec.11.28.4.

TQ.3: What are the critical sections of determining the bending moment in isolated footing? (10 marks)

A.TQ.3: See part (c)2 of sec.11.28.5.

TQ.4: Explain the one-way and two-way shears of foundation slabs. (10 marks)

A.TQ.4: See part (d) of sec.11.28.5.

TQ.5: Draw the distributions of pressure in a footing for concentric and eccentric loadings ($e \le L/6$ and $e > L/6$). (10 marks)

A.TQ.5: Figure Nos. 11.28.20 and 21.

10.26.11 Summary of this Lesson

This lesson explains the two major and other requirements of the design of foundation structures. Various types of shallow foundations and pile foundation are discussed explaining the distribution of pressure in isolated footings loaded concentrically and eccentrically with $e \le L/6$ and $e > L/6$. The gross and net safe bearing capacities are explained. The equation for determining the minimum depth of the foundation is given. Various design considerations in respect of minimum nominal cover, thickness at the edge of footing, bending moment, shear force, bond, tensile reinforcement, transfer of load at the base of the column, and minimum distribution reinforcement are discussed, mentioning the codal requirements. The actual and the assumed distributions of base pressure are discussed. The distributions of base pressure for concentric and eccentric loads with eccentricity $\le L/6$ and $> L/6$ are explained. Determination of bearing pressure of soil for unsymmetrical footing is also discussed.

All the discussions are relevant in understanding the load carrying mechanism of the foundation and the behaviour of soil. These understandings are essential in designing the foundation structures which is taken up in the next lesson.