CHAPTER Four

DESIGN OF SHALLOW FOUNDATIONS

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4.1 General

4.1.1. General Requirements of Foundations

For a satisfactory performance, a foundation must satisfy the following three basic criteria:

1. Location and depth criterion.
2. Shear failure criterion or bearing capacity.
3. Settlement.

Location and Depth Criterion:

As a general rule, any foundation should be placed at a depth where the soil stratum is adequate from the point of view of bearing capacity and settlement criteria.

Minimum Requirements:

F A foundation should be located at a minimum depth of 50cm below natural ground surface.

F The foundation must be placed below the zone of volume change, where volume change is expected. For example, in areas where there is expansive soil the foundation should be taken below the active zone.

F Foundations for structures in a river have to be protected from the scouring action of the flowing-stream. The depth of foundation for a bridge pier or any similar structure must be sufficiently below the deepest scour level.

Foundations Near Existing Structures:

When footings are to be placed adjacent to existing structure, as indicated in figure 4.1.1, the line from the base of the new footing to the bottom edge of the existing footing should be 45?Or less with the horizontal plane. The distance m should be greater than Z_f (fig.4.1.1(a)).

Conversely, Fig.4.1.1 (b) indicates that if the new footing is lower than the existing footing, there is a possibility that the soil may flow laterally from beneath the existing footing.

This may increase the amount of excavation somewhat but, more importantly, may result in settlement cracks in the existing building. This problem is difficult to analyze; however, an approximation of the safe depth Z_f may be made for C-? soil.

$$\sigma_1 \approx \gamma z_f + q_o$$

$$\sigma_3 = 0 = \sigma_1 K - 2c\sqrt{K}$$

$$= \gamma z_f K + q_o K - 2c\sqrt{K}$$

$$z_f = \frac{2c}{(\mathrm{SF})\gamma\sqrt{K}} - \frac{q_o}{(\mathrm{SF})\gamma}$$

Note:

- The vertical pressure s_1 would include the pressure from the existing footing.
- The K in these equation is a lateral pressure coefficient of $K_a = K = K_p$.
- If the soil is sand (does not have cohesion) one cannot excavate to a depth greater than that of the existing foundation.

Figure 4.1.2 Illustrate how a problem can develop if the excavation for the foundation of the new structure is too close to the existing building. In this case the qN_q term of the bearing capacity equation is lost, for most foundations below the ground surface this is a major component of the bearing capacity.

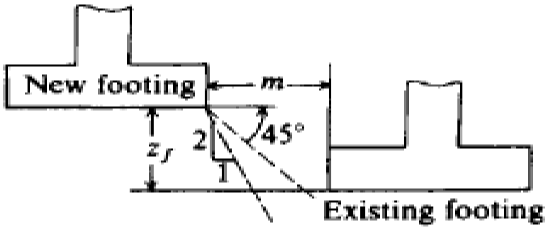


Fig. 4.1.1(a)

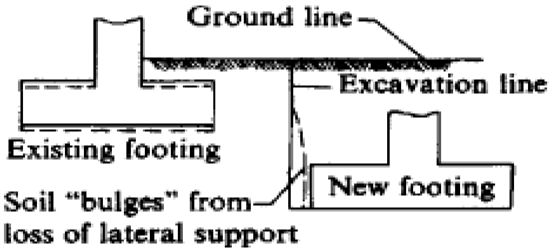


Fig.4.1.1(b)

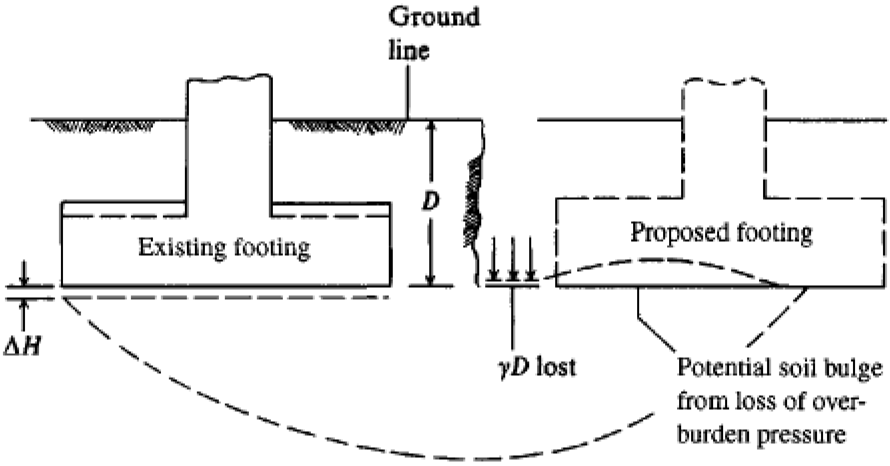


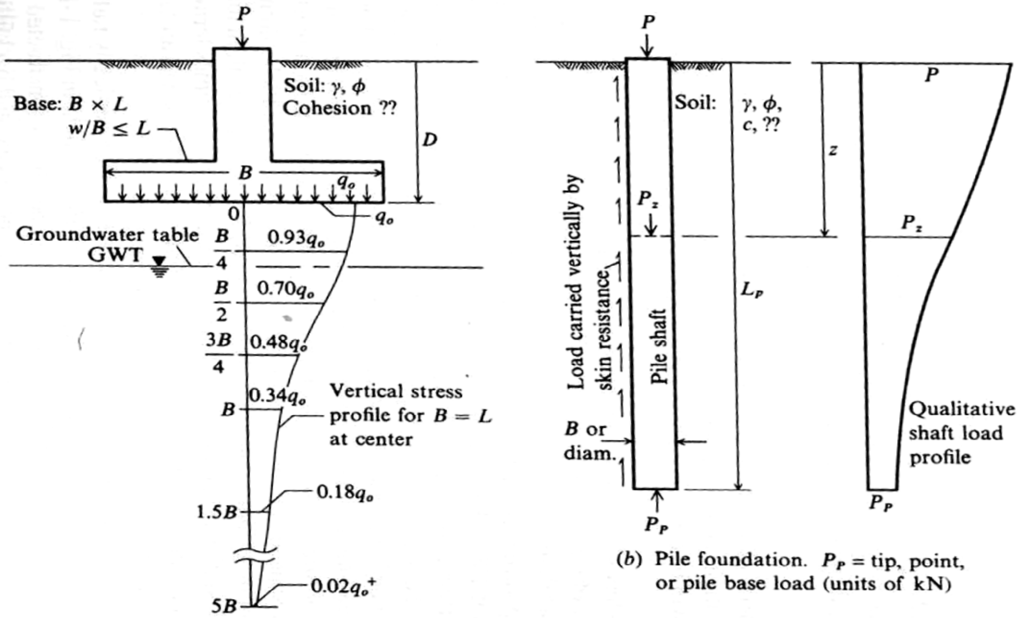
Fig.4.1.2

4.1.2. Foundation Classifications:

Foundations may be classified based on where the load is carried by the ground, according to Terzaghi: *Shallow foundations*: termed bases, footings, spread footings, or mats. The depth is generally $D/B \leq 1$ but may be somewhat more (fig. 4.1.3a)

Deep foundations: piles, drilled piers, or drilled caissons. $L_p/B \geq 4$ With a pile illustrated in figure 4.1.3b

As the column type members, transferring the superstructure load to the foundation soil, have higher strength than the soil the foundation will spread the load in a manner such that the soil limiting strength is not exceeded and the resulting deformations are tolerable.



(*b*) Pile foundation. P_p = tip, point, or pile base load (units of kN)

(*a*) Spread foundation. Base contact pressure $q_o = \frac{P}{BL}$ (units of kPa, usually)

Figure 4.1.3 Definition of select terms used in foundation engineering

The choice of the appropriate type of foundation is affected by:

- Type of superstructure to be supported: function and load that it transfers to the foundation.
- Subsurface condition and/or type of soil.
- Cost of foundation.

A safe foundation design provides for a suitable factor against,

- Shear failure of the soil: by not exceeding the bearing capacity of the soil.
- Excessive settlement (both uniform and differential settlement)

A) Shallow Foundations:

Shallow/spread footings are the most widely used type among all foundations because they are usually more economical. Construction of footings requires a least amount of equipment and skill and no heavy or special equipment is necessary.

Shallow foundations are usually used when the soil at a shallow depth has adequate capacity to support the load of the superstructure. For reasons of economy, shallow foundations are the first choice unless they are considered inadequate.

1. Wall or Continuous Footings:

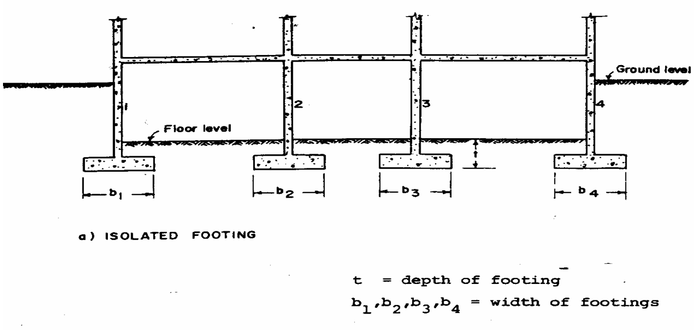
As the name implies, a wall footing supports a load-bearing wall. Continuous footings are those footings that carry a series of closely spaced column loads along a row. The width, B, of such foundations is much less than their length (L).

2. Footings:

Footings belong to shallow foundation and their purpose is to transmit the load from the structure to soil or rock. Included in the category of footings are those that support a single column, referred to as: Isolated or spread footings: can be a square, rectangular or circular in shape depending on the relative magnitude of the moments Mx and My from the superstructure (square or rectangular footings), and the shape of the superstructure to be supported.

Footings that support two or more columns are classified as *combined footings. Rectangular*, *Trapezoidal* and *strap combined footings* are special versions of combined footings, patterned to meet certain conditions or restrictions; so are mat foundations.

Pile caps are special footings needed to transmit the column load to a group or cluster of piles.



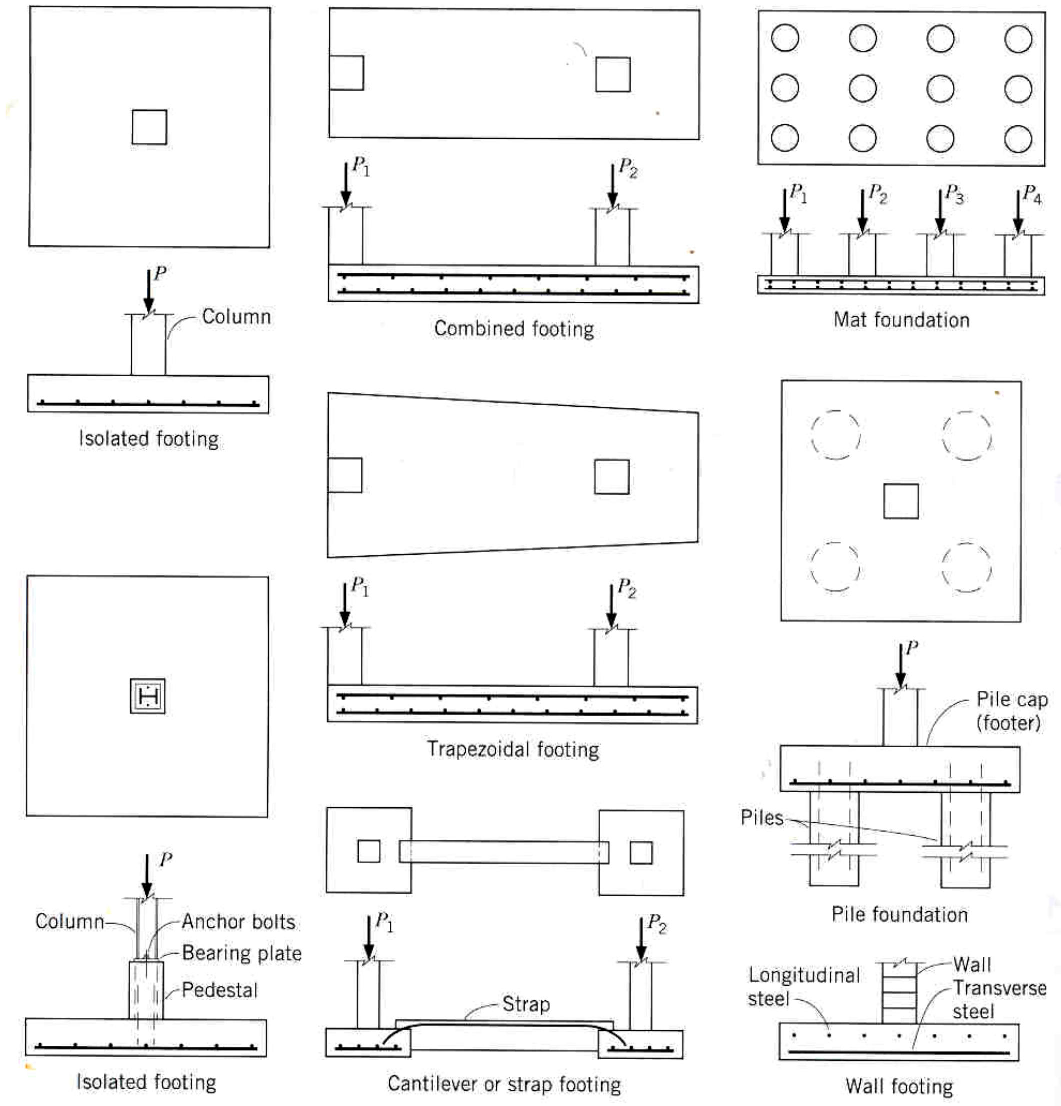


Figure 4.1.4 Typical configurations for various types of footings

Concrete is almost always the material used in footings. It is strong, durable, and is a convenient, economical construction material, workable and adaptable to field construction and requirements. Concrete footings may be plain or reinforced, with reinforcement running in one (one way) or two (two way) directions, depending on the direction of flexure.

Footing shapes usually vary with specific requirements and design needs. For spread or isolated footings, square shapes are common and usually most economical, but rectangular shapes are used if space is limited in one direction, or when loads are eccentric in one direction. The typically desired objective is to select the footing shape that makes the soil pressure (bearing pressure) as uniform as possible. Furthermore, footings may be of uniform thickness or may be sloped or stepped. Stepped or sloped footings are most commonly used to reduce the quantity of concrete away from the column where the bending moments are small and when the footing is not reinforced.

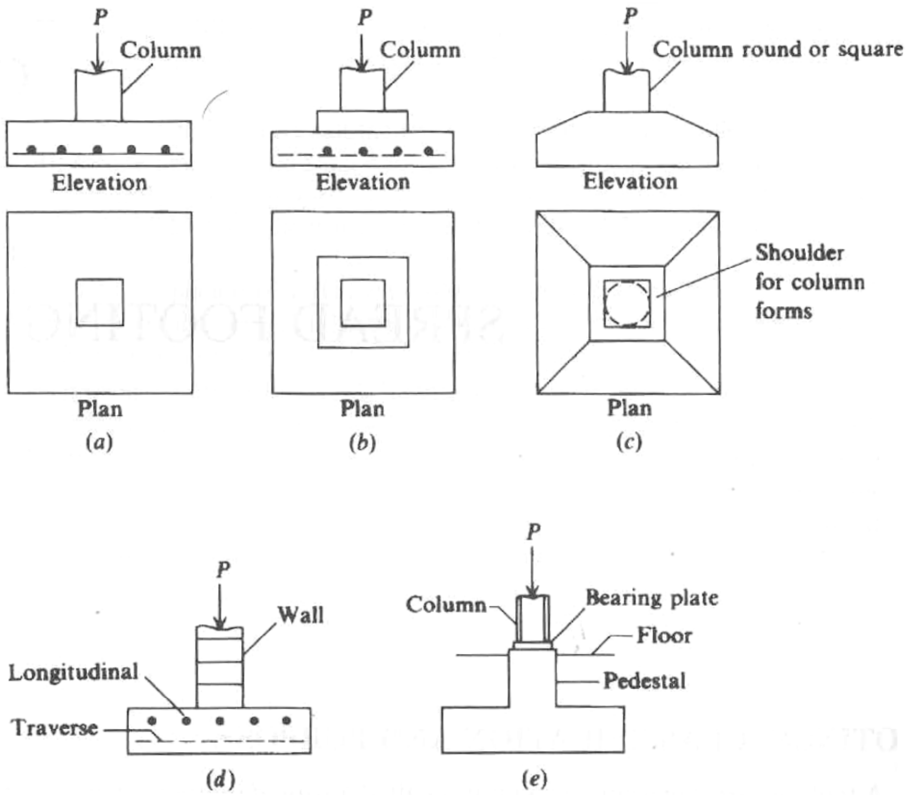


Figure 4.1.5 Typical footings. (a) Single or spread footings; (b) stepped footing; (c) sloped footing; (d) Wall footing; (e) footing with pedestal.

A steel base plate is used to spread the load from the steel column to the concrete, and thus ensure against crushing of the concrete. Pedestals are short concrete columns used to interface steel columns with spread or wall footings that are located at the depth in the ground. This prevents possible corrosion of steel through direct contact with the soil (fig. 4.1.5e).

Spread footings are designed to satisfy a combination of flexure, shear, and bearing. The safety factor for allowable bearing capacity ranges from 2 to 5 for cohesionless materials depending on density, effects of failure and consultant caution. The value may range from 3 to 6 for cohesive materials, with the higher values used where consolidation settlements might occur over a long period of time.

The pressure distribution under a footing depends, among other things, on footing rigidity, shape, footing depth, and soil properties. Generally, for ordinary spread footings resting on cohesionless formations, the pressure distribution is as shown in fig. 4.1.4a. For combined and larger footings, the distribution may vary toward a more uniform shape near the middle two-thirds of the footing. On the other hand, for cohesive soils, the distribution appears to be opposite that for cohesionless; for this condition, the shape may approach that shown in fig. 4.1.4b. It is seldom that the engineer deals with a soil stratum that is totally cohesive or totally cohesionless; the more likely case is a mixture of cohesive and cohesionless material. Thus, it is a widely accepted practice to assume a uniform pressure distribution rather than a variable one.

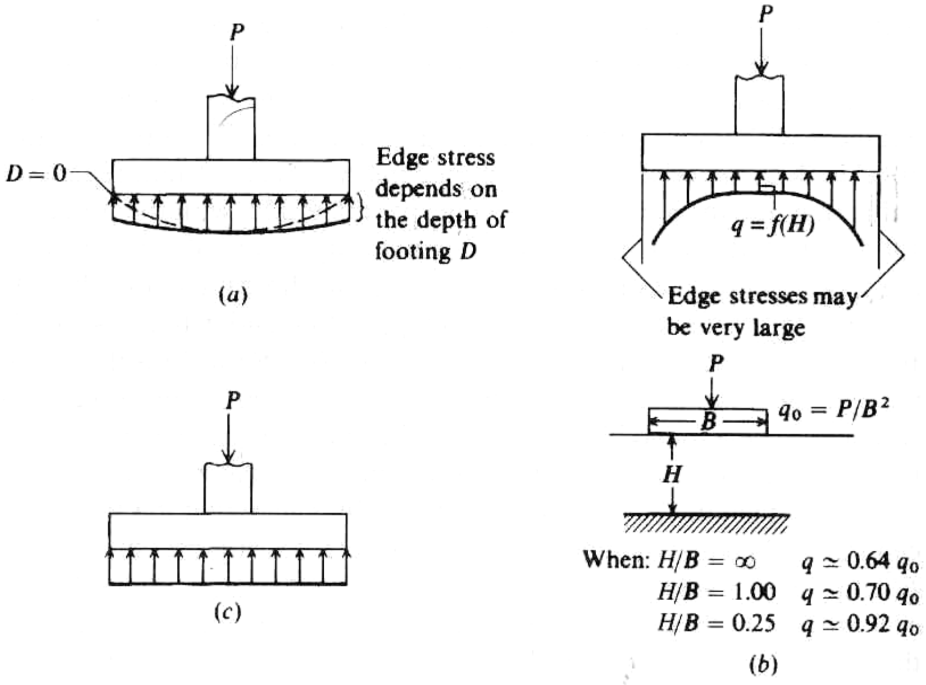


Figure 4.1.6 Probable pressure distribution beneath a rigid footing. (a) On a cohesionless soil; (b) Generally for cohesive soils; (c) usual assumed linear distribution.

Combined footings are used when:

a) Columns are closely spaced and design/proportioning of isolated footings results in an overlap of footing areas and/or,
b) When there is a property line/boundary line/restriction and there exists a column along the boundary line and use of isolated footing is not possible.

Rectangular Combined footings are used:

F When case(a) is encountered and the spacing between the columns is less than 6m-7m and/or,

F When case (b) is encountered and the outer column, which is the one along the boundary line, carries a larger load as compared to the inner column (the one to be combined with the outer column).

Trapezoidal combined footings: are used when case (b) is encountered and the inner column carries a larger load as compared to the load carried by the column along the boundary line.

Strap Footings:

Strap (Cantilever) footings may be used in lieu of a combined rectangular or trapezoidal footing when either case (a) or case (b) is encountered and the spacing between the columns is large (say greater than 6m-7m, for in this range it may be economical) and/ or the allowable soil pressure is relatively large so that the additional footing area is not needed. A strap footing should be considered only after a carefully analysis shows that rectangular or trapezoidal combined footings- even if oversize- will not work. The extra labor and forming costs for this type of footing make it one use as a last resort. The strap serves the same purpose as the interior portion of a combined rectangular and trapezoidal footing but much narrower to save materials.

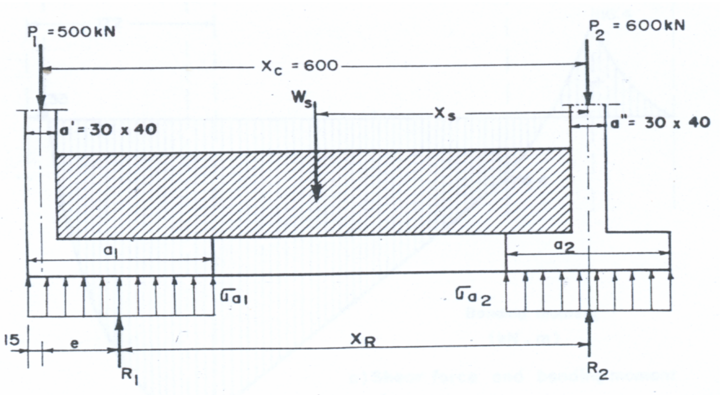


Figure: Sample problem on strap footings.

3. Mat Foundations:

On grounds with very low bearing capacity or where excessive variations in ground conditions would lead to unacceptable differential settlement, mat foundations are used as an alternative to the other types of shallow foundations.

In the majority of the cases, mat foundations are used where the subsoil has low-bearing capacity. By combining all individual footings into one big mat, not only the unit pressures on the subsoil are reduced but also the bearing capacity is often increased (since bearing capacity increases with increasing width of foundation).

A mat foundation may be used where the base soil has a low bearing capacity and/or the column loads are so large that more than 50% of the area is covered by the conventional spread footings. It is common to use mat foundations for deep basements both to spread the column loads to a more uniform pressure distribution and to provide the floor slab for the basement. A particular advantage for basements at or below the GWT is to provide a water barrier. Depending on local costs, and noting that a mat foundation requires both positive and negative reinforcing steel, one may find it more economical to use spread footings-even if the entire area is covered. Spread footings avoid the use of negative reinforcing steel.

Mat foundations may be supported by piles in the situations such as high ground water (to control buoyancy) or where the base soil is susceptible to large settlements.

Note that the mat contact stress will penetrate the ground to a greater depth or have greater relative intensity at a shallower depth. Both factors tend to increase settlements unless there is stress compensation from excavated soil so that the net increase in pressure is controlled. In localities where the subsoil is very compressible and extends to a great depth, the so-called compensated design is used to the best advantage. In this design, a deeper basement is made so that the net pressure (the total building load minus the weight of the soil replaced by basement) at any depth in the subsoil is negligible.

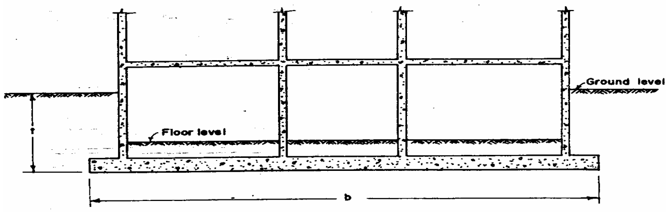


Figure: sample problem on mat foundation

B) Deep Foundations:

The most common used deep foundations are pile foundations. The following list identifies some of the conditions that require pile foundations:

- When the upper soil layer(s) is (are) highly compressible and too weak to support the load transmitted by the superstructure, piles are used to transmitted the load the underlying bedrock or a stronger soil layer. When bedrock is not encountered at a reasonable depth below the ground surface, piles are used to transmit the structural load to the soil gradually. The resistance to the applied structural load is derived mainly from the frictional resistance developed at the soil-pile interface.
- When subjected to horizontal forces, pile foundations resist by bending while still supporting the vertical load transmitted by the superstructure. This type of situation is generally encountered in the design and construction of the earth retaining structures and foundations of tall structures that are subjected to high wind and/or earthquake forces.
- In many cases, expansive soils may be present at the site of proposed structure; these soils may extend to a great depth below the ground surface. Expansive soils swell and shrink as the moisture content increases and decreases, and swelling pressure of such soils can be considerable damage. However, pile foundations may be considered as an alternative when piles are extended beyond the active zone, which swells and shrinks.
- Foundations of some structures, such as transmission towers, offshore platforms, and basement mats below the water table, are subjected to uplifting forces. Piles are sometimes used for these foundations to resist the uplifting force.
- Bridge abutments and piers are usually constructed over pile-foundations to avoid the possible loss of bearing capacity that a shallow foundation might suffer because of soil erosion at the ground surface.

4.1.3. Shear in Footings:

- Design of footings for shear shall be in accordance with provisions for slabs.
- The location of the critical section for shear shall be measured from face of column, pedestal or wall for footings supporting a column, pedestal, or wall.
- For footings supporting a column or pedestal with steel base plates, the critical section shall be measured from halfway between face of column and edge of steel base.

4.1.4. Moment in Footings:

The critical section for moment shall be taken as follows:

(a) At the face of column, pedestal, or wall, for footings supporting a concrete column pedestal or wall.

(b) Halfway between middle and edge of wall, for footing supporting a masonry wall.

(c) Halfway between face of column and edge of steel base for footings supporting a column with steel base plates.

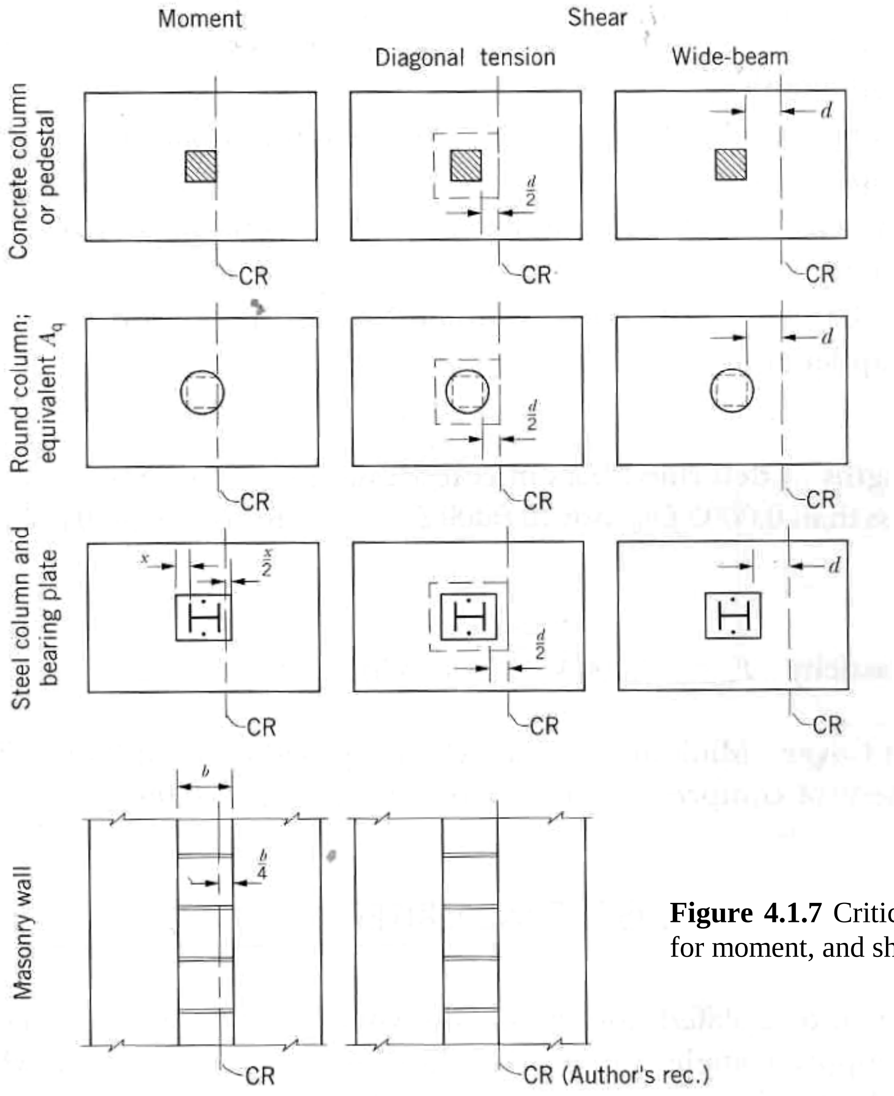


Figure 4.1.7 Critical footing sections for moment, and shear.

4.2. Elements of Reinforced Concrete Design

4.2.1. General:

The design of a structure for a specific function is usually a two-stage process, involving first the selection of an appropriate type or form of structure and secondly the detailed design of the various parts of the chosen structure. In selecting the type or form of structure the question of the relative costs of different types of structures and of different methods of construction of the same structure will be of great importance. In this selection the designer must rely to a large extent on his experience judgment and intuition. A preliminary study of several types of structure may be necessary.

Having selected the type of structure the designer then has to proceed with the detailed design of the chosen one, always bearing in mind the factors of safety considerations and cost. In most cases the aesthetic requirements will have been substantially met in the selection of the type of structure and will now be completely satisfied by the specification of surface finishes, colour, etc. Fundamentally, then, the design process consists of finding and detailing the most economical structure consistent with the safety and serviceability requirements.

In design the following points have to be taken into consideration:

(i). variations in materials in the structure and in test specimens

(ii). variations in loading

(iii). constructional inaccuracies

(iv). accuracy of design calculations

(v). safety and serviceability

For (i) we know that the cube test is a reliable guide as regards quality of concrete from the mixer but does not guarantee that the concrete in the structure is the same. This is why we took a higher proportion of the cube strength as a permissible stress when we have quality control. i.e. a design mix. The same applies to reinforcement, as tests are carried out on small samples which may or may not be truly representative of the whole. For (ii) we must enquire how true the loading is. Constructional inaccuracies (iii) are probably accidental. For (iv) designers can and do make mistakes in calculations but very often in analysis they assume a structure will behave in a certain way or that certain conditions exist. Item (v) is dealt with quite arbitrarily in previous codes -if the structure does not collapse it is deemed to be satisfactory.

4.2.2 Design Methods:

Based on design load determination and the corresponding design strength of materials, different methods of design have been introduced.

- *Permissible stress method:* The ultimate strength of the material is divided by a factor of safety to give safe design stresses, which are usually within the elastic range. Stresses caused by the working loads must not exceed the permissible stresses.
- *Load factor method:* The working loads are multiplied by a factor of safety to obtain design loads. Stresses caused by the design load must not exceed the ultimate strength of the material.
- *Limit state method:* The working loads are multiplied by partial factors of safety to obtain design loads and ultimate strengths of materials are divided by further partial factors of safety to obtain design strengths. Stresses caused by the design loads must not exceed the design strength of the material.

The permissible stress method has proved to be a simple and useful method. However, there are certain shortcomings: Because it is based on an elastic stress distribution, it is not entirely applicable to concrete which is a semi-plastic material. Neither is it suitable when deformations are not proportional to the load, as in the case of slender columns.

In the load factor method, the ultimate strengths of the materials are used in the calculations. Because this method does not apply factors of safety to the materials, the variability of the materials cannot directly be taken into account. Furthermore, it cannot be used to calculate deflections and cracking under working loads.

The limit state method overcomes most of the shortcomings of the previous two methods. This is achieved by applying partial factors of safety to both the material strengths and the working loads, and also by varying the magnitude of the factors, depending on whether plastic conditions at the ultimate limit state are being considered, or whether elastic conditions under working loads are being considered.

4.2.3. Limit State Principles:

When dealing with the most economical structure associated with safety and serviceability requirements, the variability exists between construction materials and the construction process itself. We should be able to state a design philosophy to cope with the various criteria required to define the serviceability or usefulness of any structure in a rational manner.

The various criteria required to define the serviceability or usefulness of any structure can be described under the following headlines. The effects listed may lead to the structure being considered 'unfit for use'.

(i). *Collapse:* failure of one or more critical sections; overturning or buckling.

(ii). *Deflection:* the deflection of the structure or any part of the structure adversely affects the appearance or efficiency of the structure.

(iii). *Cracking:* cracking of the concrete which may adversely affect the appearance or efficiency of the structure.

(iv). *Vibration:* vibration from forces due to wind or machinery may cause discomfort or alarm, damage the structure or interfere with its proper function.

(v). *Durability:* porosity of concrete.

(vi). *Fatigue:* where loading is predominantly cyclic in character the effects have to be considered.

(vii). *Fire resistance:* insufficient resistance to fire leading to 1, 2 and 3 above.

When any structure is rendered unfit for use for its designed function by one or more of the above causes, it is said to have entered a *limit state.* The Code defines the limit states as:

(i). *Ultimate limit state:* the ultimate limit state is preferred to collapse.

(ii). *Serviceability limit states:* deflection, cracking, vibration, durability, fatigue, fire resistance and lightning.

The purpose of design then is to ensure that the structure being designed will not become unfit for the use for which it is required, i.e. that it will not reach a limit state. The essential basis for the design method, therefore, is to consider each limit state and to provide a suitable margin of safety. To obtain values for this margin of safety it was proposed that probability considerations should be used and the design process should aim at providing acceptable probabilities so that the structure would not become unfit for use throughout its specified life.

Accepting the fact that the strengths of construction materials vary, as do also the loads on the structure, two partial safety factors will now be used. One will be for materials and is designated γ_m; the other, for loading, is termed γ_f. These factors will vary for the various limit states and different materials. As new knowledge on either materials or loading becomes available the factors can be amended quit easily without the complicated procedures to amend one overall factor used in previous Codes.

The normal procedure is to design for a critical limit state and then to check for the other limit states are satisfied. The critical state for reinforced concrete structures is usually the ultimate limit state. However, water-retaining structures and prestressed concrete is usually designed at the serviceability limit state with checks on the ultimate limit state.

The limit states failure criteria can be summarized as follows:

(Design load effects Q_d) ≤ (Deisgn resistance R_d)

$$\gamma_f Q_n \leq \frac{f_k}{\gamma_m}$$

Where
Q_d = design load effects = $\gamma_f Q_n$
Q_n = nominal load
γ_f = partial safety factor for loads
R_d = design resistance = f_k/γ_m
f_k = characteristic material strength
γ_m = partial safety factor for materials

Each of these terms are discussed in the following sections.

N.B. Limit state is adopted throughout the design of reinforced concrete foundations.

Grades of Concrete

Grades of concrete	C15	C20	C25	C30	C40	C50	C60
f_{ck}	12	16	20	24	32	40	48

$$f_{ck} = \frac{Grade}{1.25}$$

Where: f_{ck} = Characteristic cylinder compressive strength of concrete.

Safety Factors

Partial Safety Factors for Materials at ULS

Design Situations	Concrete, γ_c		Reinforcing Steel, γ_s	
	Class I	Class II	Class I	Class II
Persistent and Transient	1.50	1.65	1.15	1.20
Accidental	1.30	1.45	1.00	1.10

Partial Safety Factors for Actions in Building Structures at ULS

Design Situation	Action	Factor, γ	Favorable	Unfavorable
Persistent and Transient	Permanent	γ_G	1.00	1.30
	Variable	γ_Q	0.00	1.60
Accidental	Permanent	γ_G	1.00	1.00

Design values for actions for use in combination with other actions at ULS.

Design Situation		Permanent actions	Accidental actions	Variable actions	
				Principal action	All other actions
Fundamental	Favorable	$1.0G_k$	-	0	0
	Unfavorable	$1.3G_k$	-	$1.6Q_k$	$1.6\psi_0 Q_k$
Accidental		$1.0G_k$	A_d	$1.0\psi_1 Q_k$	$1.0\psi_2 Q_k$

Combination values: $Q_r = \psi_0 Q_k$

Frequent values: $Q_r = \psi_1 Q_k$

Qausi-permanent values: $Q_r = \psi_2 Q_k$

Where,

Q_r = representative value

Q_k = characteristic value

Representative load factors, ψ_0, ψ_1, ψ_2

Action	ψ_0	ψ_1	ψ_2
Imposed Category A, B	0.7	0.5	0.3
Category C, D	0.7	0.7	0.6
Category E	1.0	0.9	0.8
Wind	0.6^*	0.5^*	0^*
Snow	0.6^*	0.2^*	0^*

* Values may have to be modified for specific locations.

Category A – Domestic, Residential.

Category B – Offices

Category C – Congregation areas

Category D – Shopping areas.

Category E – Storage areas

Design Strength for Concrete

(a) In compression: $$f_{cd} = \frac{0.85 f_{ck}}{\gamma_c}$$

(b) In tension: $$f_{ctk} = \frac{f_{ctk}}{\gamma_c}$$

Design Strength for Steel

In tension and compression: $$f_{yd} = \frac{f_{yk}}{\gamma_s}$$

Stress-Strain Relationships in RC Flexural Elements

- The maximum compressive strain in the concrete is taken to be:
  - 0.0035 in bending (simple or compound).
  - 0.002 in axial compression.
- The maximum tensile strain in the reinforcement is taken to be 0.01.
- The strain diagram (fig. 4.2.1) shall be assumed to pass through one of the three points A,B or C.

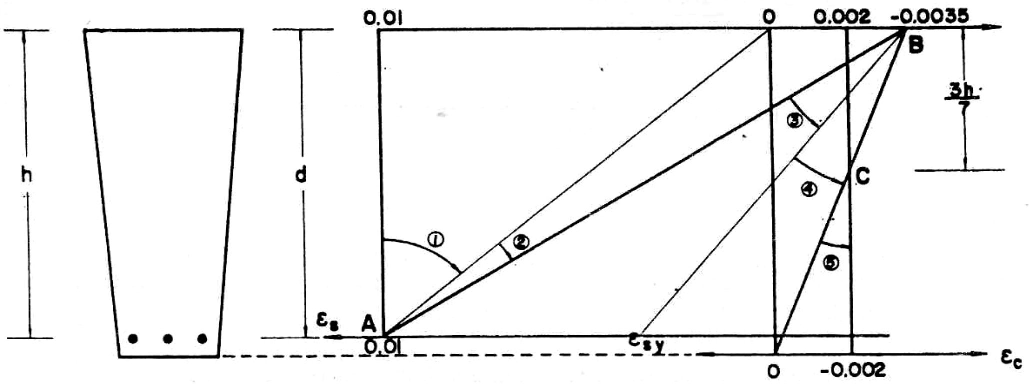


Figure 4.2.1 Strain diagram in the Ultimate Limit State

- The parabolic-rectangular stress distribution may be used for calculation of section capacity.

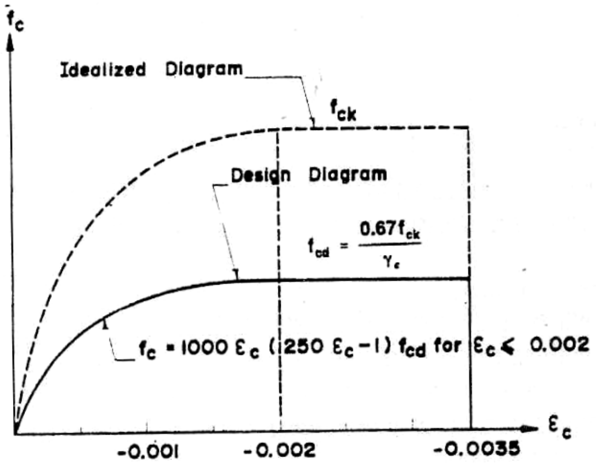


Figure 4.2.2 Parabolic-rectangular stress-strain diagram for concrete in compression

- For sections which are partly in tension (beams or columns with large eccentricity), the simplified rectangular stress block shown in fig. 4.2.3 may be used.

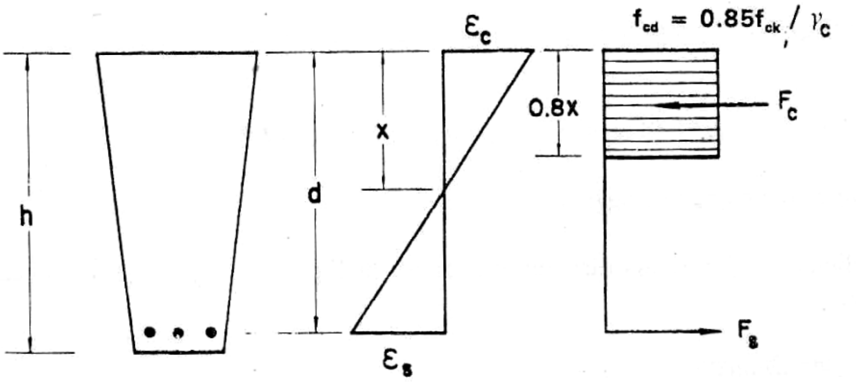


Figure 3.2.3 Rectangular stress diagram

- The elasto-plastic diagram shown in fig. 4.2.4 may be used for ordinary steel.

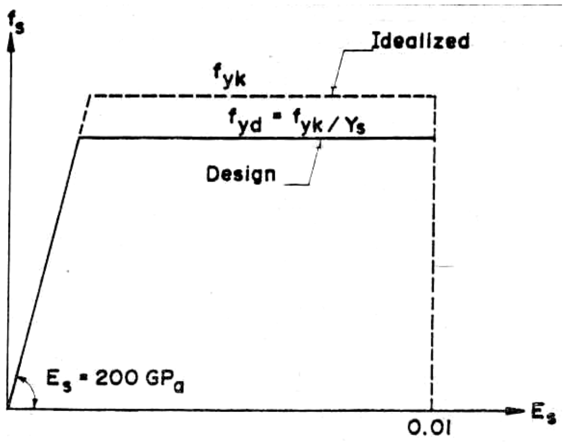


Figure 4.2.4 Stress-strain diagram for reinforcing steel

Reinforcement Required to Resist Moment.

Formula for A_s required in a rectangular section.

- It is assumed that the reinforcement has yielded. Steps are taken to ensure that the beam is under-reinforced.
- For a singly reinforced rectangular section (referring to the stress block diagram (fig. 4.2.3))

$$F_c = \left(\frac{\alpha f_{ck}}{\gamma_c}\right)(0.8x)b \quad \text{Tφ / Φ9 15.8633 Tφ 0.745 0 0 1 269.16 602.2498 Tμ}$$

- Summing moment about the reinforcement level.

$$\left(\quad M_s \qquad F_c(d \qquad x \qquad F_cZ \qquad Z \qquad Lever\,arm\right.$$

$$x \quad \frac{d \quad z}{}$$

$$M_{ult} = \left(\frac{f_{ck}}{c}\right)(\ )\ \text{Tφ}\ xb\ z\ \text{Φ9}\left(\frac{f_{ck}}{c}\right)\left(\frac{d \quad z}{}\right) \quad \text{[illegible]}$$

Where: $f_{ctd} = 0.21 f_{ck}^{2/3} / \gamma_c$

$k_1 = 1 + 50\rho_e \leq 2.0$

$k_2 = 1.6 - d_{av} \geq 1.0$ (d in meter). For members where more than 50% of the bottom reinforcement is curtailed, k_2 = 1.0

$d_{av} = (d_x + d_y)/2$

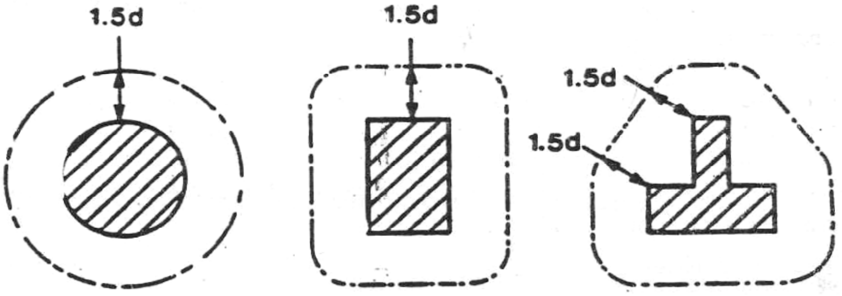
$\rho_e = (\rho_{ex} + \rho_{ey})^{1/2} \leq 0.015$

ρ_{ex} and ρ_{ey} correspond to the geometric ratios of longitudinal reinforcement parallel to x and y, respectively.

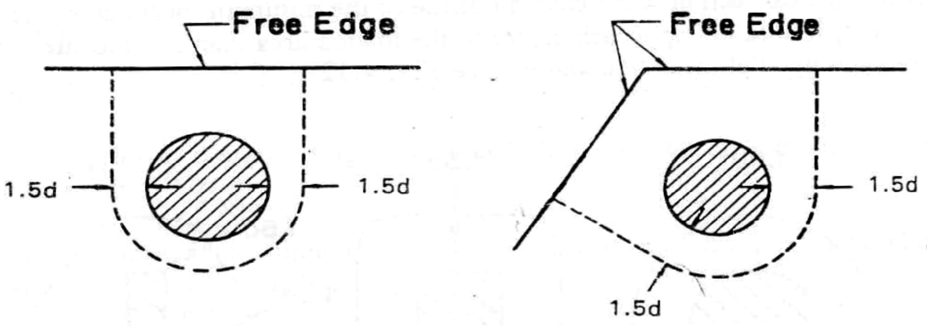
u = periphery of critical section.

d_{av} = the average effective depth in x and y directions.

The shear stresses usually govern the thickness of reinforced footings. Flexure may control the thickness of plain footings. Punching shear dominates in reinforced square footings subjected to concentric loads; this is frequently true for combined footings as well. Wide beam shear must also be checked in these footings. As a matter of fact, wide beam shear may govern the footing thickness for long footings, generally when the length to width ratio exceeds about 2:1. The provision in EBCS-2 has been included in fig. 4.2.5 for the critical section of punching shear. Wide beam can be taken conservatively at d distance from the face of the column.(Include fig. 4.12 and fig. 4.14 of EBCS-2)



(a) Critical section remote from a free



(a) Critical sections near free

Figure 4.2.5 Critical sections for punching shear

Equation of Punching Shear

Observing figure 4.2.5:

$$P_u = v_c du + A_p q_u$$

$$u = 2(x+y)+3\pi d \,;\; A_p = xy + 2(1.5d)x + 2(1.5d)y + \pi(1.5d)^2$$

$$P_u = BLq_u \; - \; \textit{from equilibrium of entire footing.}$$

Expanding and rearranging terms, it becomes.

$$3\pi(v_c + 0.75q_u \; d^2 + (2v_c + 3q_u \; (x+y \; d - (BL - xy \; q_u = 0$$

$$v_c = 0.25 f_{ctd} k_1 k_2$$

Equation for wide beam shear

$$v_c db = q_u l_1 b \quad \Rightarrow \quad d = \frac{q_u l_1}{v_c}$$

Where, l_1 is the distance from d distance to the periphery of footing.

For v_c determination ρ_e is replaced by ρ_x and d_{av} replaced by d_x.

Hence, one proceeds to solve for d using either of the above shear equations, then check for the other shear stress, and subsequently to complete the design.

Flexural Reinforcement Distribution

- In one-way footings and two way square footings reinforcement shall be distributed uniformly across the entire width of footing.
- In two-way rectangular footings, reinforcement shall be distributed as follows:
  - Reinforcement in longer direction shall be distributed uniformly across the entire width of footing.
  - For reinforcement in the short direction, a portion of the total reinforcement given by equation below shall be distributed uniformly over a band width (centered on center line of column or pedestal) equal to the length of the short side of footing. The remainder of the reinforcement required in the short direction shall be distributed uniformly outside the center band width of the footing.

$$\frac{\text{Reinforcement in band width}}{\text{Total reinforcement in short direction}} = \frac{2}{\beta + 1}$$

Where, β is the ratio of long side to short side of footing.

Flexural Reinforcement Anchorage

- If the projection of the footing from the critical section for moment does not exceed the effective depth d at that section, the bottom reinforcement shall be provided with full anchorage length measured from the end of the straight portion of the bars.
- If the projection exceeds d, the anchorage length may be measured from a section situated at a distance d from the defined critical section for moment.

Basic anchorage length: $l_b = \frac{\phi}{4}\frac{f_{yd}}{f_{bd}}$

Required anchorage length: $l_{b,net} = a l_b \frac{A_{s,cal}}{A_{s,ef}} \geq l_{b,\min}$

Where, f_{yd} and f_{bd} are design yield strength and bond strength respectively.

a = 1.0 for straight bar anchorage in tension or compression.

= 0.7 for anchorage in tension with the standard hook

For bars in tension: $l_{b,\min} = 0.3 l_b \geq 10\phi \ (or \geq 200mm)$

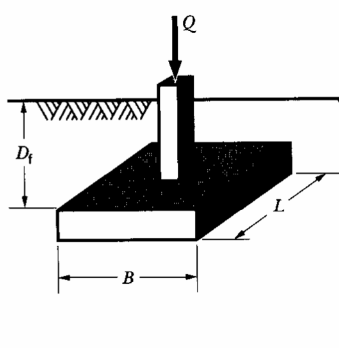
For bars in compression: $l_{b,\min} = 0.6 l_b \geq 10\phi \ (or \geq 200mm)$

Hooking is at 90^0 or 150^0 and in both cases hook length $\geq 5\phi$.

Figure: sample picture of placement of reinforcement.

4.3. The General Procedure for the Design of Concentrically Loaded Isolated Footing

Given: Column dimensions and reinforcement; column loads (LL, DL); f_{ck} for footing and column; f_{yk} for footing and column; allowable bearing capacity, q_a.



Solution:

a) Find P_u = *1.3DL* + *1.6LL* (Self wt. and backfill usually absent).

b) Determine B and L of footing; $A=\frac{(DL+LL}{q_a}$. For a unique solution, B or L is fixed.

c) Find $q_u=\frac{P_u}{BL}$ (Ultimate bearing pressure beneath footing).

d) Assume trial effective depth, d, of footing for determination of flexural reinforcement.

e) Check d for punching shear and wide beam shear.

f) If step (v) is not fulfilled increase d and repeat starting from step (iv).

g) Calculate the anchorage length and reinforcement distribution.

h) Select the appropriate dowels based on the anchorage length and lap length.

i) Complete a design drawing showing all details (footing dimensions, reinforcement size, spacing cover, etc..)

4.4. Eccentrically Loaded Spread Footings

The ensuing "load" on the column, and subsequently on the footing, due to supported beams from several spans, can be a combination of a vertical load and moments as shown in figure 4.4.1.

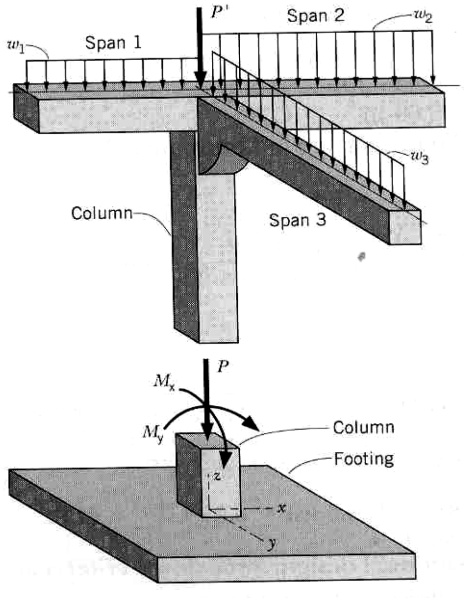


Figure 4.4.1 Example of a loading condition that may induce eccentric loading in two directions.

The source for the effects of eccentricity on the footing may be either a concentric vertical load and moment combination (fig. 4.4.2a) or a column located eccentrically to the centroid of the footing (fig. 4.4.2b). In order not to overstress the soil under some points of the footing, and to eliminate tilting of column and footing, a footing is proportioned in such a way that a uniform soil pressure distribution is attained.

The difficulty in establishing a fixed location of the load centerline relative to the footing centroid lies on the change of magnitude and direction of the variable loads (such as the live and wind load). Hence, if the column is not centrally located for the sake of having uniform bearing pressure (fig. 4.4.2c), our design is perhaps somewhat hypothetical in a strict sense.

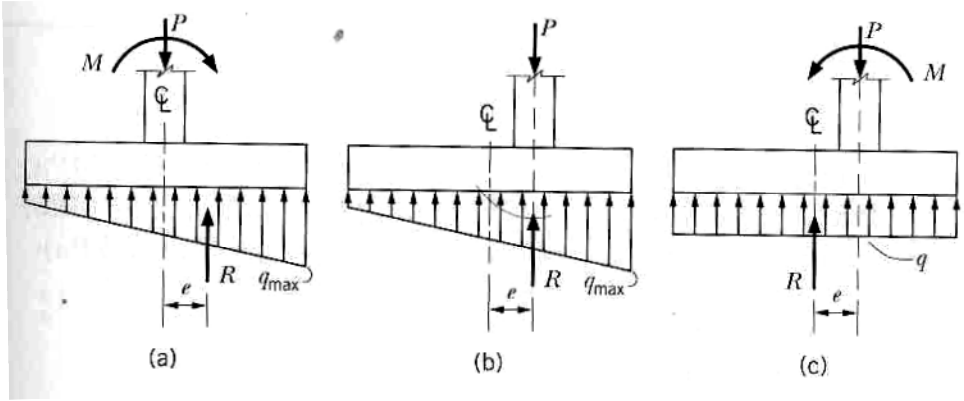


Figure 4.4.2 Soil pressures resulting from eccentric loading

Superimposing the pressures resulting from the direct vertical load to those from moment:

$$q = \frac{P}{A} \pm \frac{M_x c_1}{I_x} \pm \frac{M_y c_2}{I_y}$$

$$M_x = Pe_y \quad and \quad M_y = Pe_x$$

$$I_x = \frac{LB^3}{12} \quad and \quad I_y = \frac{BL^3}{12}$$

$$= \frac{}{}\left[\pm \frac{}{} \pm \frac{}{} \right]$$

This procedure ensures four items of considerable concern:

(i) The resultant soil pressure R (fig. 4.4.3) is never out of the middle one-third of the base so that the overturning stability is always satisfied. This R always gives:

$$SF = \frac{M_{resist}}{M_{overturn}} = \frac{PL}{2M}$$

(ii) The toe pressure will always be such that $q_{toe} \le q_a$.

(iii) The design is more easily done when a uniform soil pressure is used to compute design moments.

(iv) Approximately the same amount of steel is required as in the design using the triangular stress distribution.

$$L' = L - 2e_x \quad ; \quad B' = B - 2e_y$$

$$e_x = \frac{M_y}{P} \quad ; \quad e_y = \frac{M_x}{P}$$

The amount of steel computed for a unit width is used across the full base dimensions of B and L. For the punching shear and wide beam shear compute an “average” $q_{u,av} = \frac{P_u}{BL}$ and use this $q_{u,av}$ value.

4.5. Combined Footings

When a footing supports a line of two or more columns, it is called a combined footing. A combined footing may have either rectangular or trapezoidal shape or be a series of pads connected by narrow rigid beams called a strap footing.

Isolated and wall footings are usually economical and practical, but are generally limited to relatively light to moderate loads, and for building sites of good soil bearing. Special considerations and design features or schemes are sometimes adopted to overcome or accommodate imposed limitation by perhaps space, soil formations, loads or functional concerns. Combined footings are adopted where there is:

(i) Property line restriction.
(ii) Closed spacing of isolated footings.

Rectangular Combined Footing

An isolated footing is likely to result in an uneven soil-pressure distribution for a column very close to a property line. In order to achieve uniform soil pressure, one alternative may be a rectangular-shaped, combined footing. The footing near the property line is connected with an adjacent one.

Generally, it is assumed that the rectangular footing is a rigid member, thus, the pressure is linear. The approach yields a rather conservative design; the moments are somewhat larger than those obtained by treating the footing as a beam on an elastic foundation.

The following is a summary of the procedure:

Given: Typically included in the given part of the problem are column data (loads, sizes, reinforcement, location, and spacing), soil bearing, concrete strength (f_{ck}), and grade of reinforcement (f_{yk}).

Objective: The goal is to determine footing dimensions (width, length, thickness), steel reinforcement (bar sizes, spacing, placement, details, dowels), and relevant details for construction.

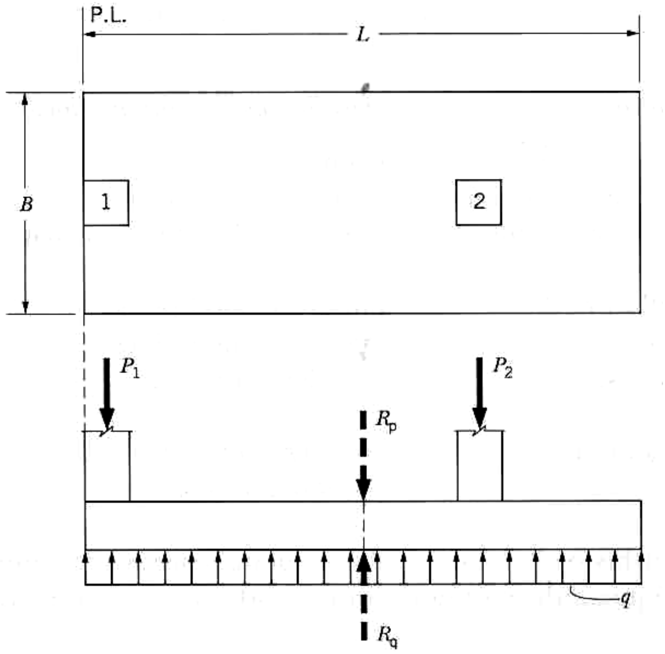


Figure 4.5.1 Rectangular shaped combined footing. For uniform *q*, the resultant of the applied load is collinear with that of the soil pressure *q*.

Procedure: The design is predicated on the assumption that the footing is rigid and that the soil pressure is uniform. The following explanation may illustrate the procedure:

Step 1: Convert the column loads to ULS loads via P_u = 1.3(D.L.) + 1.6(L.L.). Then convert the allowable soil pressure to ULS pressure via $q_u = (P_{lu} + P_{2u})\, q_a / (P_1 + P_2)$.

Step 2: Determine the footing length *(L)* and width *(B).* First determine the location of the load resultant distance ($\bar{x}$). This point coincides with the midpoint of *L*, thus yielding the value for *L*. *B* is then determined from $B = \sum P_u / Lq_u$.

Step 3: Draw shear and moment diagrams. The footing is treated as a beam, loaded with a uniform soil pressure (upward) and column loads (downward), which are treated as concentrated loads.

Step 4: Determine the flexural reinforcing steel based on reasonable assumption of footing depth. The longitudinal (flexural) steel is designed using the critical moments (negative and positive) from the moment diagram. Thus, typically, combined footings will have longitudinal steel at both top and bottom of the footing.

Step 5: Check footing depth based on shear. Critical sections are at *1.5d* for diagonal tension (or punching shear) and at the *d* for a wide beam, the same as for spread footings. The critical section for wide-beam shear is investigated only at one point (max. shear). For punching shear, however, an investigation of a three- or four-sided zone for each column may have to be done.

Step 6: Determine the steel in the short direction. The steel in the transverse direction is-determined based on an equivalent soil pressure q' and subsequent moment, for each column. Even for stiff footings, it is widely accepted that the soil pressure in the proximity of the columns is larger than that in the zone between columns. Thus, for design, we account for this phenomenon by assuming an empirical effective column zone width of s. The soil pressure in this zone, q', is calculated as $q' = P_u / B_s$, where P_u is the ULS column load, B the footing width and s an equivalent width of footer strip for the column in question. Commonly, the value of s is taken as the width of the column (in the longitudinal direction) plus about *0.75d* on each side of that column.

Step 7: Evaluate dowel steel. The requirements are the same as for spread footings.

Step 8: Provide a drawing showing final design. This drawing is to show sufficient detail from which one may construct.

4.6. Trapezoid-shaped Footings

A combined footing will be trapezoid-shaped if the column that has too limited a space for a spread footing carries the larger load. In such a case, the resultant of the column loads (including moments) will be closer to the larger column load, and doubling the centroid distance as done for the rectangular footing will not provide sufficient length to reach the interior column. Correspondingly, the soil pressure would not be uniform (recall that our typical objective is uniform soil pressure). For very large column spacings (e.g., say greater than 7m), a strap (cantilever) footing may be a somewhat more economical (i.e., less material) solution to such a problem For smaller column spacings, a trapezoid-shaped footing, as shown in fig. 4.6.1 for a two-column arrangement, is usually deemed suitable.

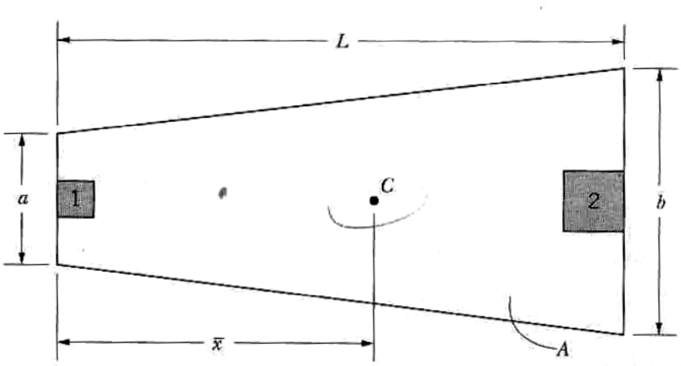


Figure 4.6.1 Trapezoid-shaped footing

Referring to fig. 4.6.1, the area, A, is

$$A = (a+b)L/2$$

From $\bar{x} = \sum Ax / \sum A$, *we get*

$$\bar{x} = \frac{(aL)(L/2) + [(b-a)(L/2)]2L/3}{aL + (b-a)L/2}$$

$$\bar{x} = (L/3)(a+2b)/(a+b)$$

For the pressure to be uniform, the resultant of the column loads coincides (is collinear) with the resultant of pressure at the centroid *(C)* as shown

The following is a summary of the procedure for the design of trapezoid-shaped footings:

Given: Included in the given data are column information (loads, sizes, location, and spacing), length of footing *(L)*, soil bearing values *(q_a)*, concrete strength *(f_{ck})*, and grade of reinforcement *(f_{yk})*

Objective: The goal is to determine footing dimensions (width, thickness), steel reinforcement (bar sizes, spacing, placement, details, dowels), and relevant details for construction.

Procedure: The design is predicated on the assumption that the footing is rigid and that the soil pressure is uniform. The basic steps are:

Step 1: Convert the column loads to ultimate loads via P_u = 1.3(DL) + 1.6(LL); then convert the allowable soil pressure to ultimate; that is, $q_u = (P_{ul} + P_{u2})\, q_a/(P_l + P_2)$.

Step 2: Determine dimensions *a* and *b* via simultaneous solutions of two independent equations.

$$A = (a+b)L/2$$

$$\bar{x} = (L/3)(a+2b)/(a+b)$$

Thus, we solve for *a* and *b.*

Step 3: Draw the shear and moment diagrams. The footing is treated as a beam, loaded with a uniform soil pressure (upward) and column loads (downward), which are treated as concentrated loads. Note that while the pressure is uniform, the pressure force for-unit length varies with the width [e.g., at the narrow end, the load is $a(q_u)$; and $b(q_u)$ at the wide end, etc.].

Step 4: Determine footing depth based on shear (Use ρ_{min} and ρ_e = 0.015 for k_1 in wide beam shear and punching shear respectively). Critical sections are usually checked for wide-beam shear at the narrow end and punching shear at the wide end.

Step 5: Determine the flexural reinforcing steel. Because the width varies, it is advisable to determine $-A_s$ at several points; the same is now required for $+A_s$ since it is typically governed by ρ_{min}.

Step 6: Determine the steel in the short direction. Assume an average length for the cantilever length; determine the equivalent lengths as for rectangular footings.

Step 7: Determine dowel steel, as for rectangular combined or spread footings.

Step 8: Provide a drawing with details for construction. Here some judgment is necessary to accommodate the steel arrangement in view of the variable width along the footing.

4.7. Strap Footings

A strap footing (cantilever footing) is a composite of two spread (isolated) footings connected by a rigid beam or strap, as shown in fig. 4.6.1. The strap connects an eccentrically loaded footing (e.g., footing 1) with an interior footing, subsequently resulting in a uniform soil pressure and minimum differential settlement.

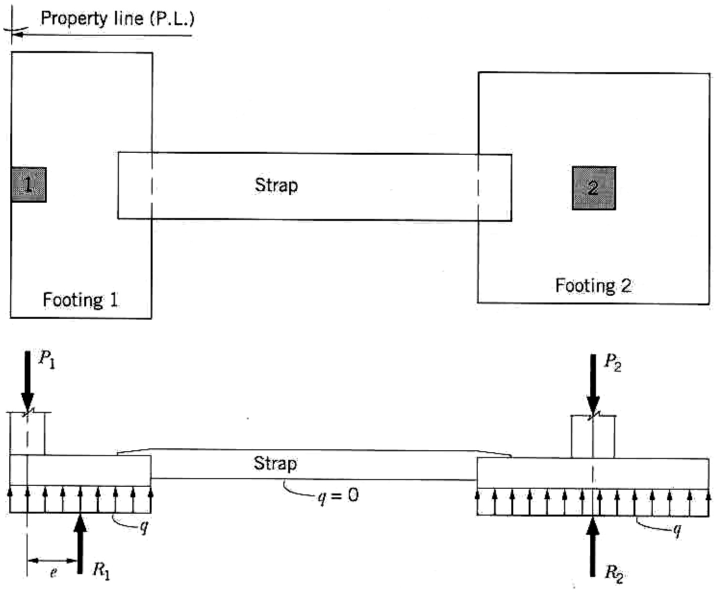


Figure 4.6.1 Typical configuration of a strap footing

A strap footing may be somewhat more economical than a combined footing if distances between columns are large (say greater than 7m). It may also serve a special need of bridging over areas that cannot be loaded, such as pits, shallow culverts, tunnels, and the like.

The strap is designed as a rigid beam connected to the footings such that it overcomes rotational effects on eccentrically loaded footings; it is assumed to experience no soil pressure. This is accomplished by either forming the strap above the ground or by pouring the strap over a compressible formation, such as loose or spaded soil or semi-rigid Styrofoam. Hence, the shear is a constant between the footings; the moment varies linearly.

The footings are treated as isolated footings. The interior footing (e.g., footing 2) is generally square-shaped and is designed as a spread footing, with appropriate negative (top) longitudinal steel provided to resist the negative moment transmitted via the strap. While this spread-footing approach also applies to footing 1, one carefully scrutinizes the zone near column 1 for some additional transverse steel requirements, as typically included for rectangular or trapezoid-shaped footings discussed in the preceding sections. .

The following procedural summary to illustrate the recommended approach for a strap footing design.

Given Typically, included in the given part of the problem are column data (loads, sizes, reinforcement, location, and spacing), allowable soil bearing, q., concrete strength (f_c), and grade of reinforcement (f_y).

Objective The goal is to (a) determine the footing dimensions (length, width, and thickness) proportioned such that the soil pressure is reasonably uniform and differential settlement is minimal, (b) design the strap, (c) design the footings, and (d) show a drawing with pertinent details for construction purposes.

Procedure: The design assumes no soil pressure under the strap (other than that necessary to support the weight of the strap; hence, the weight of the strap is negated). The footings are designed as isolated footings subjected to column loads and strap reactions.

Step 1 (a) Convert to P_u and q_u, as previously described. (b) Try a value for e. This establishes the position of R_1; subsequently, this influences the ratio of *LI* and ~. An adjustment in e may be warranted if L_l/ B_l appear unreasonable. (c) From equilibrium (i.e., ?M = 0 and ?F_y = 0), determine the values for R_l and R_2.

Step 2 Determine footing dimensions, L and B. Note that q will be uniform when R coincides with the centroid of that footing. Also, for minimum differential settlement, q should be the same for both footings.

Step 3 Draw the shear (V) and moment (M) diagrams. *Step* 4 Design the strap as a beam. Use maximum, M in the section between footings. Affix the strap to the footings to effectively prevent footing rotation.

Step 5 Design the footings as spread (isolated) footings with reinforcement in both directions including -A_s steel to accommodate the negative moment. Some special assessment for the transverse steel near column 1 is recommended.

Step 6 Provide the final drawing showing details for construction.

Example 4.1:

Determine the Dimensions of a square footing necessary to sustain an axial column load of 850KN as shown in the figure below, given that $D_f=2m$, $\gamma=19.1$ KN/m^3,if

a) An allowable presumptive bearing pressure of $150KN/m^2$ is used.

b) $C_u=40KN/m^2$;$C'=7.5KN/m^2$;?'=22.50.

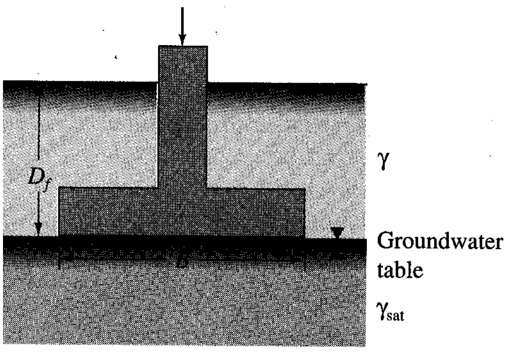


Figure: Proportioning of a square footing.

Example 4.2:

Using the data given below, design a rectangular footing with side a/b=2 for the loading condition in the figure below.

Allowable soil pressure=100KN/m^2

Use concrete C-25 and steel S-300.

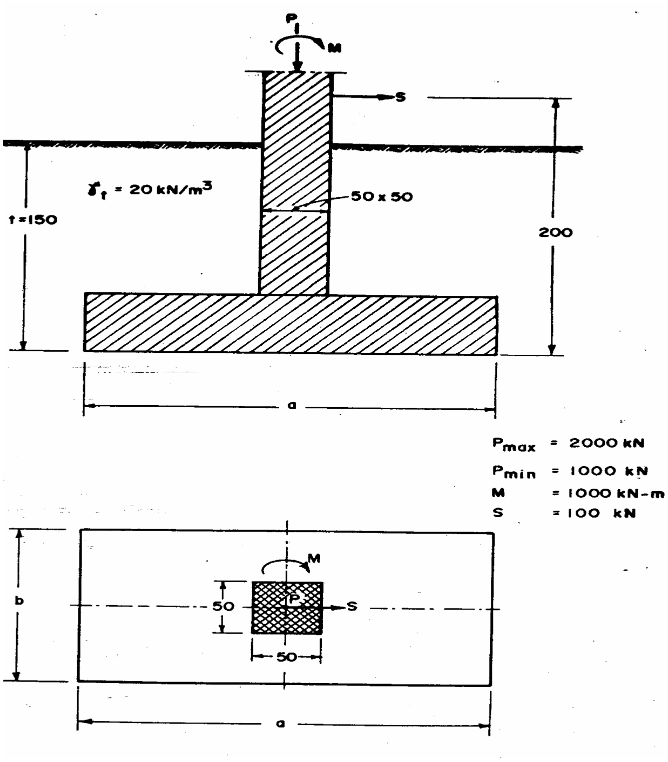


Figure: plan and section of footing.

Example 4.3:

A Building is to be constructed over a site that has the soil stratification shown in figure below.

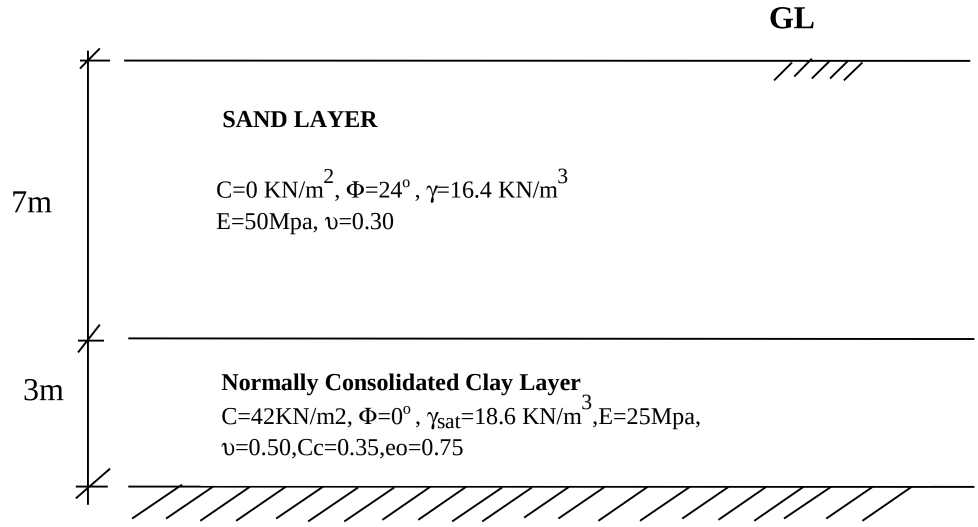
A. Determine the area of a square footing that can safely transfer the load from the superstructure without shear failure, i.e. bearing capacity failure.

B. Determine the corresponding total settlement for the footing area proportioned above. Check if the load can be transferred without excessive settlement. Is an isolated footing the right choice for this condition? Why?

C. If the load from a superstructure transferred through a column are to be supported by an isolated footing, Determine the depth of the footing and provide the necessary reinforcements and show the reinforcement details/sketches. Assume $M_x = M_y = 0$.

Use the following data:-

- The load from the superstructure; P=2645KN.
- The footing is to be placed at a depth of 2.0m below the ground surface.
- The allowable total settlement is 75mm.
- Maximum center-to-center spacing between columns is 5.0m.
- Assume the foundation to be a rigid foundation.
- Assume also that the shear failure zone is limited within the sand layer.
- Ground water table exists at a depth of 7.0m below the ground surface. Assume that the ground water table does not have an effect on the bearing capacity.
- Use concrete C-25 and steel S-300.
- Column size: 400mm by 400mm.
- Use Meyerhof's Bearing Capacity equation. Use F.S=2.5.

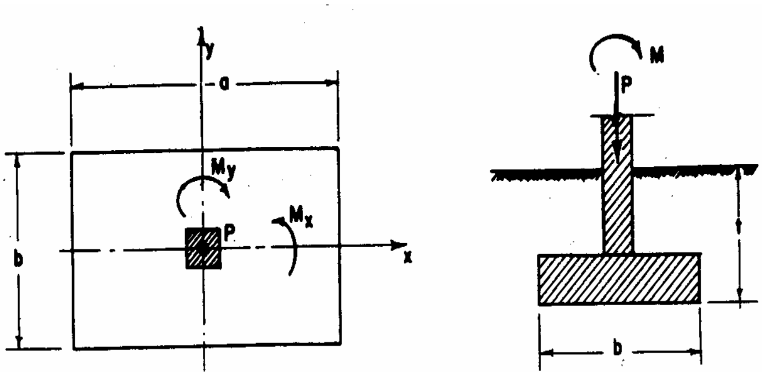


Example 4.4:

The Loads from a superstructure transferred through a column are to be supported by an isolated footing.

A. Proportion the area of the footing.

B. Determine the depth of the footing.



Use the following Data:

Loads: P=800KN, M_x=80KN-m, M_y=70KN-m

Soil Data: $s_{all,\ soil}$ =250Kpa

Column size: 400mm*400mm

Use concrete C-30 and steel S-300

Example 4.5:

A Building is to be constructed over a site that has the soil stratification shown in Figure below.

A. Determine the area of a square footing that can safely transfer the load from the superstructure without shear failure, i.e. bearing capacity failure.

B. Determine the corresponding total settlement for the footing area proportioned above. Check if the load can be transferred without excessive settlement. Is an isolated footing the right choice for this condition? Why?

Use the following data:-

- The load from the superstructure, P=2645KN.
- The footing is to be placed at a depth of 2.0m below the ground surface.
- The allowable total settlement is 75mm.
- Maximum center-to-center spacing between columns is 5.0m.
- Assume the foundation to be a rigid foundation.
- Ground water table exists at a depth of 5.0m below the ground surface.
- Use Meyerhof's Bearing Capacity equation. Use F.S=3.0.

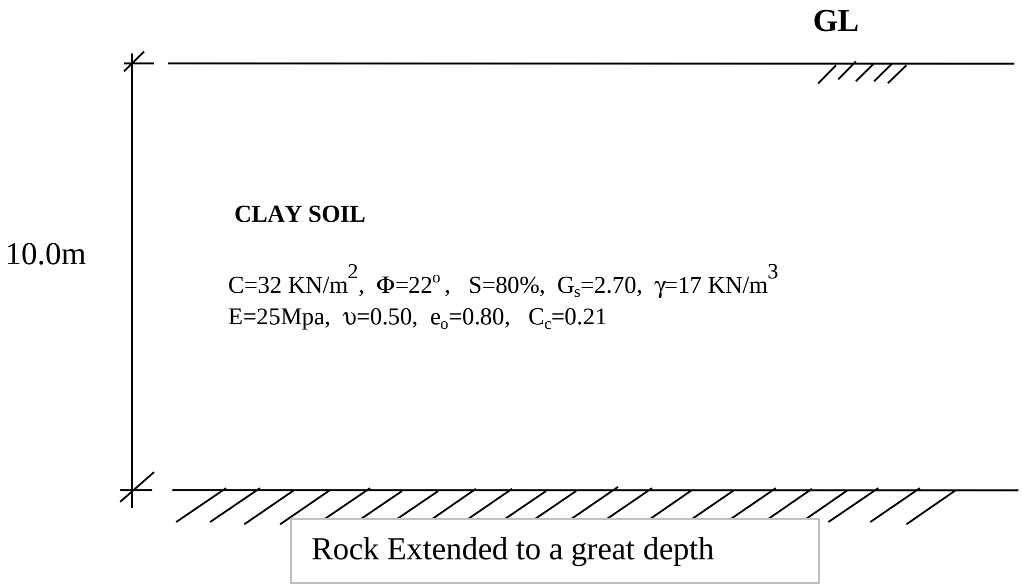


Figure: Subsurface profile

Example 4.6:

Design a rectangular combined footing shown in the figure below using the following data:

Column 1: 30cm X 30cm with 4∅20.

Column 2: 35cm X 35cm with 4∅25.

Soil Data: $s_{all,\ soil}$ =250Kpa

Use concrete C-30 and steel S-300

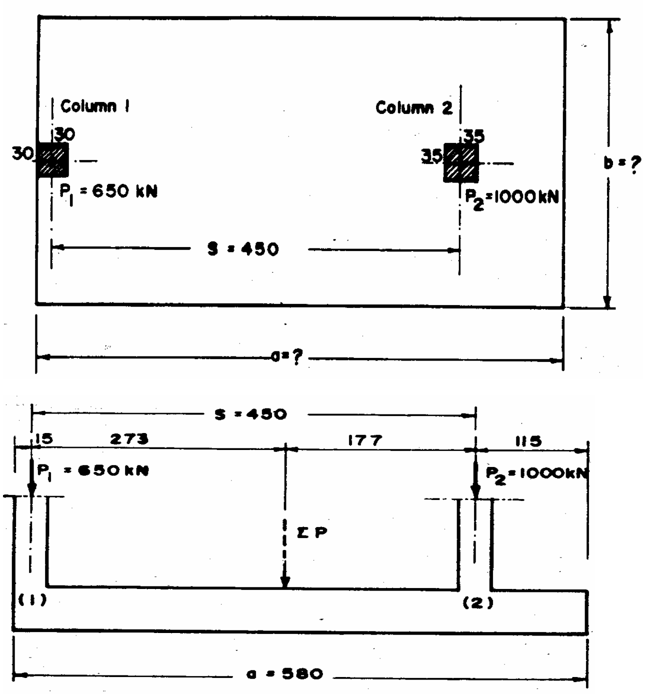


Figure: Plan and section of rectangular combined footing.

Example 4.7:

Design a rectangular combined footing for the loading conditions shown below:

Use concrete C-30 and steel S-300

Soil Data: Allowable soil pressure, $s_{all,\ soil}$ =250KN/m^2.

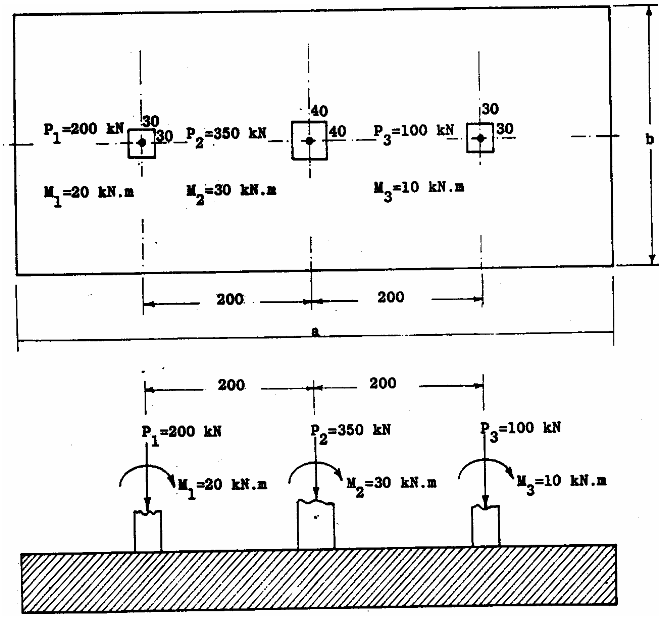


Figure: Plan and section of rectangular combined footing.

Example 4.8:

Design a strap foundation for the given loads in the figure below.

Given that:

Soil Data: $s_{all,\ soil}$ =50Kpa

Use concrete C-30 and steel S-300

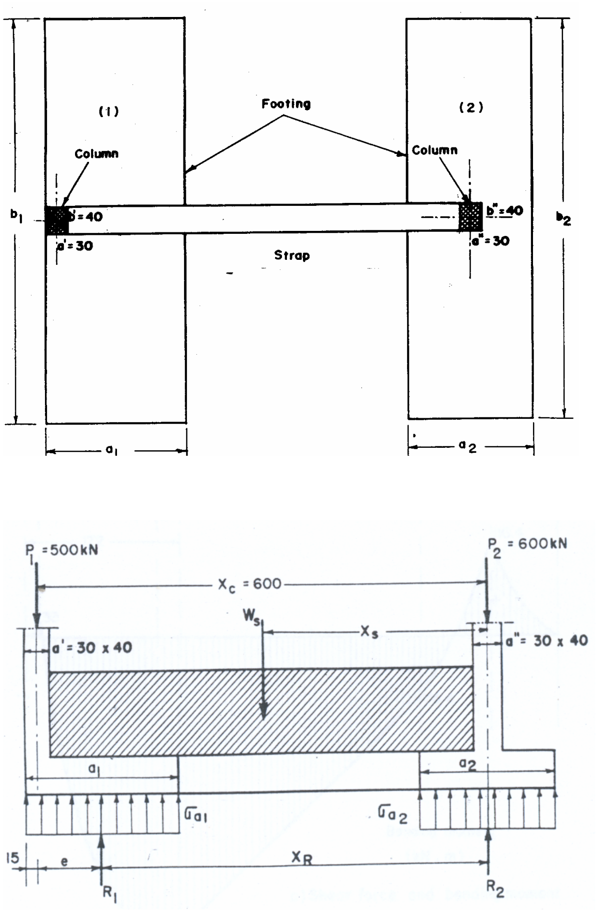


Figure: Strap and cantilever footing.

Example 4.9:

A mat foundation is to be designed by the conventional method (Rigid Method) for the loadings shown in the figure below. All columns are 40cm X 40cm.

Use concrete C-30 and steel S-300

Soil Data: Allowable soil pressure, $s_{all,\ soil}$ =50KN/cm^2.

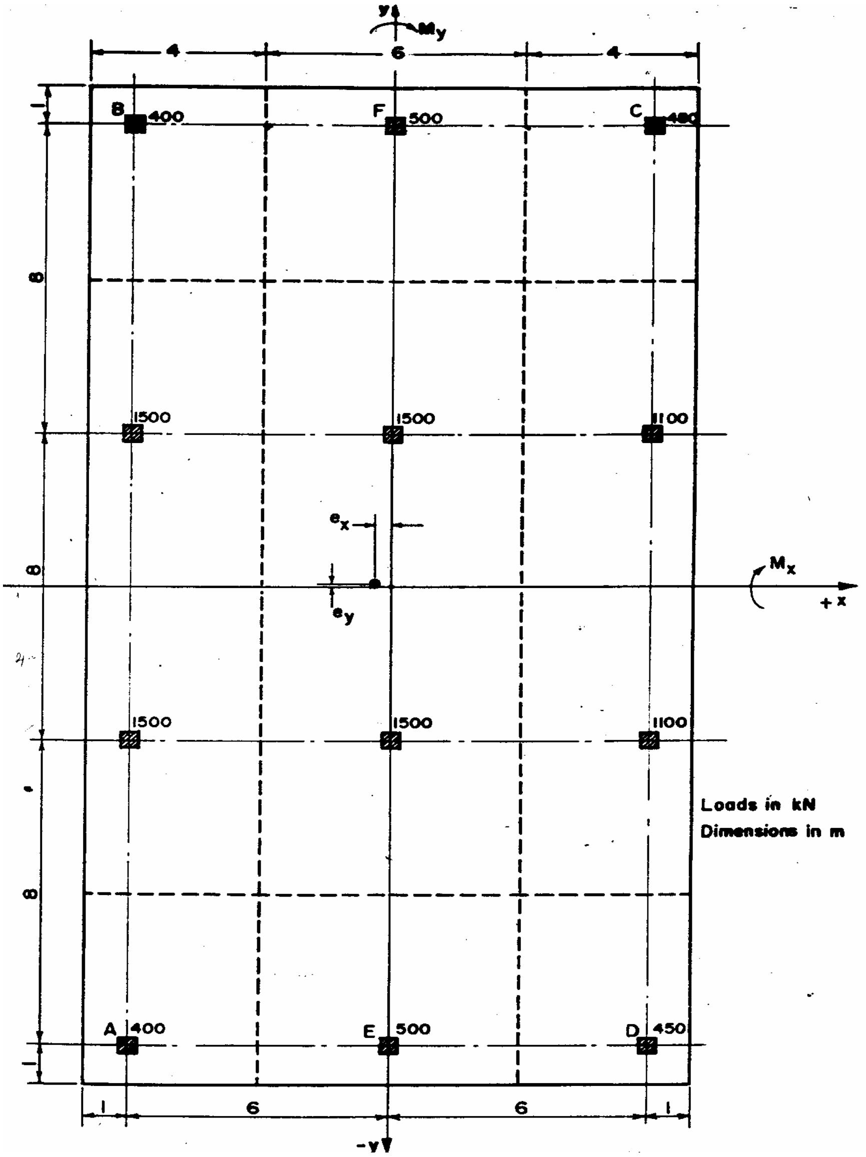


Figure: Design of a uniform mat foundation.

Example 4.10:

Design a Ribbed mat foundation for the column loads given in the figure below.

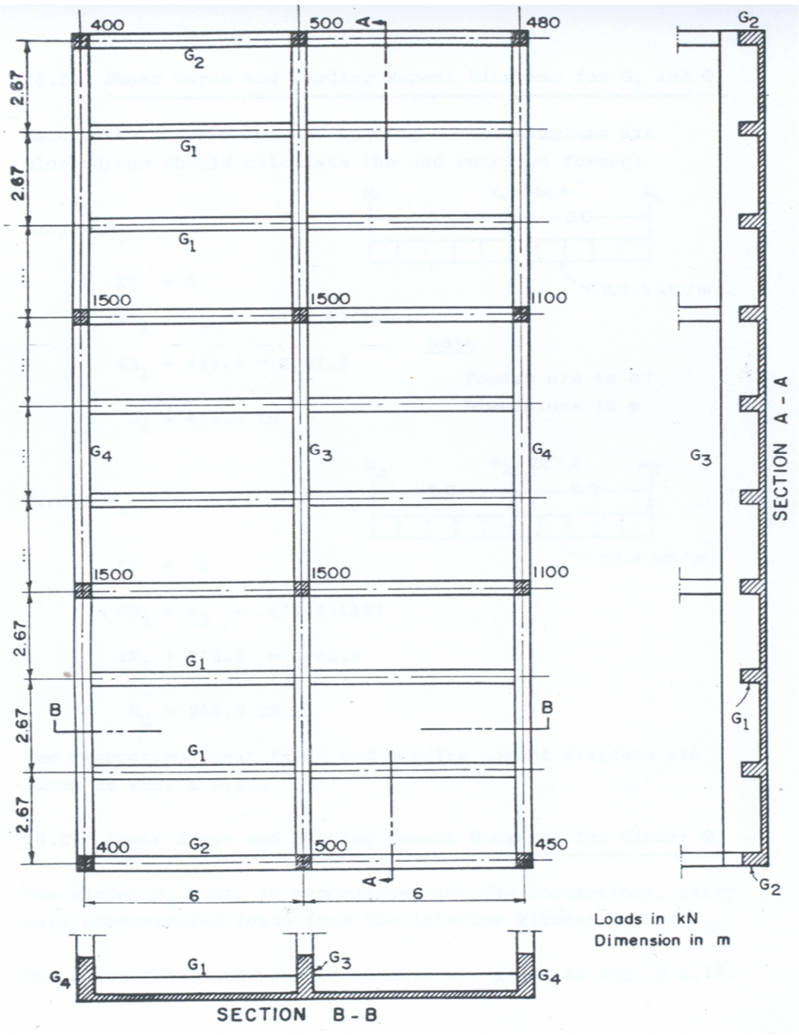


Figure: Design of Ribbed mat foundation.