Design of Retaining Walls and Bulkheads

20.1. INTRODUCTION

(*a*) **Design of Retaining Walls.** Retaining walls are relatively rigid walls used for supporting the soil mass laterally so that the soil can be retained at different levels on the two sides. The lateral earth pressures acting on the retaining walls have been discussed in the preceding chapter. The types of retaining walls and their design features are explained in this chapter. However, the design is limited to the determination of the shear forces and bending moments. Actual structural design is outside the scope of this text.

(*b*) **Bulkheads.** Sheet pile walls, or bulkheads, are special type of earth retaining structures in which a continuous wall is constructed by joining sheet piles. Sheet piles are made of timber, steel or reinforced concrete and consist of special shapes which have interlocking arrangements. Sheet pile walls are used for water front structures, canal locks, coffer dams, river protection, etc. Sheet pile walls are embedded in the ground to develop passive resistance in the front to keep the wall in equilibrium. Various types of sheet pile walls and their analysis and design are discussed in this chapter.

20.2. TYPES OF RETAINING WALLS

The most common types of retaining walls are classified as under:

(1) **Gravity Retaining Walls.** These walls depend upon their weight for stability [Fig. 20.1 (*a*)]. The walls are usually constructed of plain concrete or masonry. Such walls are not economical for large heights.

(2) **Semi-Gravity Retaining Walls.** The size of the section of a gravity retaining wall may be reduced if a small amount of reinforcement is provided near the back face [Fig. 10.1 (*b*)]. Such walls are known as semi-gravity walls.

(3) **Cantilever Retaining Walls.** Cantilever retaining walls are made of reinforced cement concrete. The wall consists of a thin stem and a base slab cast monolithically [Fig. 20.1(*c*)]. This type of wall is found to be economical upto a height of 6 to 8 m.

(4) **Counterfort Retaining Walls.** Counterfort retaining walls have thin vertical slabs, known as counterforts, spaced across the vertical stem at regular intervals [Fig. 20.1(*d*)]. The counterforts tie the vertical stem with the base slab. Thus the vertical stem and the base slab span between the counterforts. The purpose of providing the counterforts is to reduce the shear force and bending moments in the vertical stem and the base slab. The counterfort retaining walls are economical for a height more than 6 to 8 m.

[Note : Counterforts are on the side of the back fill].

20.3. PRINCIPLES OF THE DESIGN OF RETAINING WALLS

Before the actual design, the soil parameters that influence the earth pressure and the bearing capacity of the soil must be evaluated. These include the unit weight of the soil, the angle of shearing resistance, the

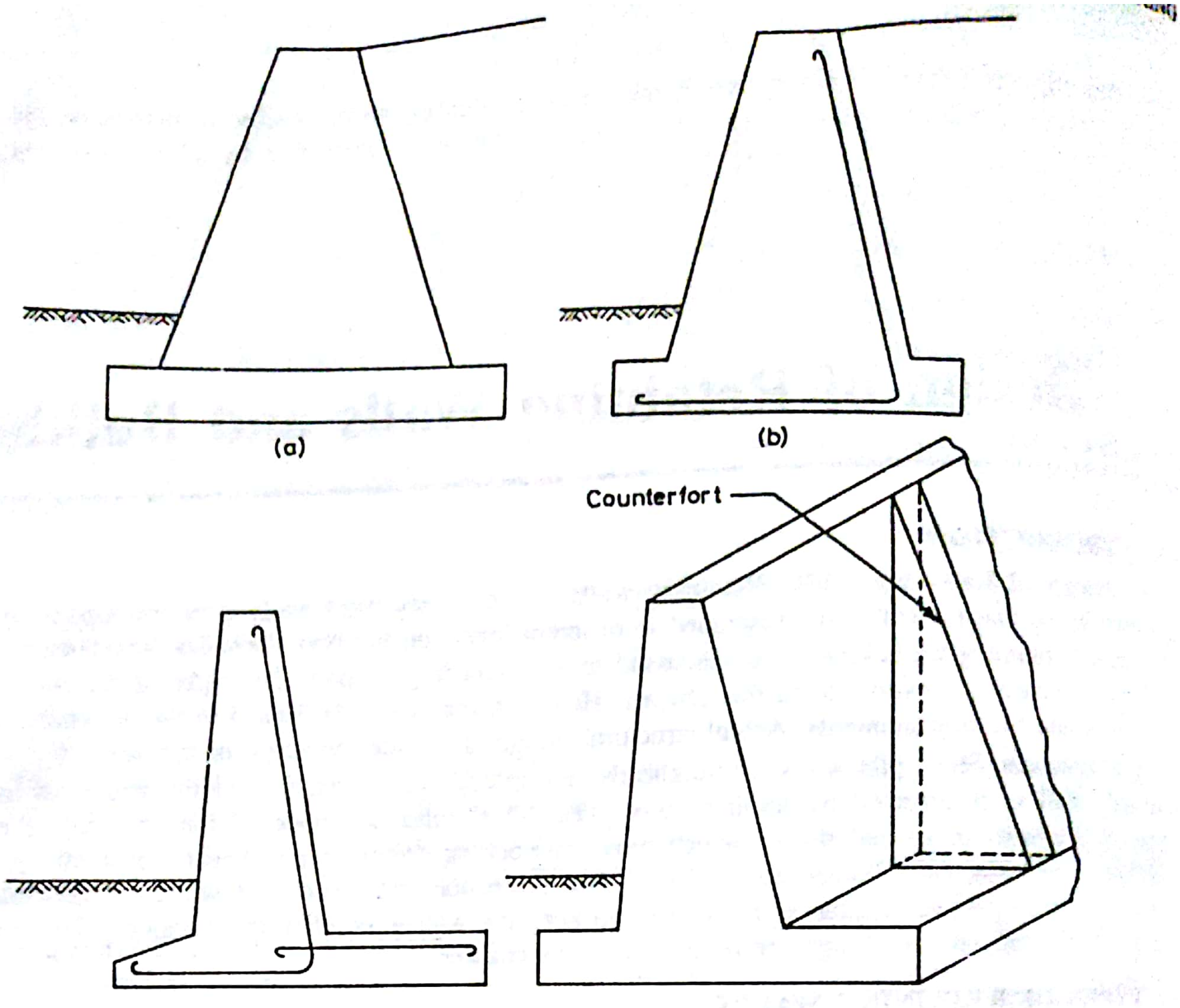

Fig. 20.1. Different Types of Retaining walls.

cohesion intercept and the angle of wall friction. Knowing these parameters, the lateral earth pressure and the bearing capacity of the soil can be determined. Methods for the computation of earth pressure have been discussed in chapter 19. The bearing capacity theories are explained in chapter 23. With the earth pressure known, the retaining wall as a whole is checked for stability.

Fig. 20.2 shows a retaining wall with a smooth back face and no surcharge. The active pressure P_a acts horizontally, as shown. The front face of the wall is subjected to a passive pressure (P_p) below the soil surface. However, it is doubtful whether the full passive resistance would develop. Moreover, often P_p is small and therefore it may be neglected. This gives more conservative design.

The weight W of the wall and the active pressure P_a have their resultant R which strikes the base at point D. There is an equal and opposite reaction R' at the base between the wall and the foundation. For convenience, R' is resolved into the vertical and horizontal components (R_v' and R_H').

From the equilibrium of the system,

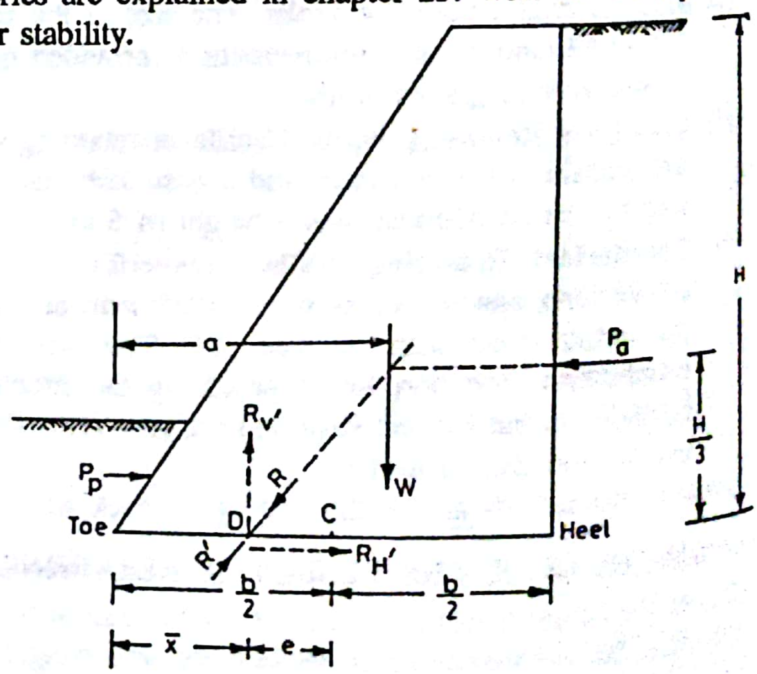

Fig. 20.2.

$$R_V' = W, \quad \text{and} \quad R_H' = P_a$$

The third equation of equilibrium, namely the moment equation, is used to determine the eccentricity e of the force R_v' relative to the centre C of the base of the wall. Obviously, by taking moments about the toe,

$$R_v' \times \bar{x} = W \times a - P_a(H/3)$$

or

$$\bar{x} = \frac{W \times a - P_a \times H/3}{R_V'} \quad \text{...(20.1)}$$

where $\bar{x}$ is the distance of the point D from the toe.

Thus, eccentricity,

$$e = b/2 - \bar{x} \quad \text{...(20.2)}$$

where b = width of the base.

For a safe design, the following requirements must be satisfied.

(1) No Sliding

The wall must be safe against sliding. In other words,

$$\mu R_V > R_H$$

where R_V and R_H are vertical and horizontal components of R, respectively. The factor of safety against sliding is given by

$$F_s = \frac{\mu R_V}{R_H} \quad \text{...(20.3)}$$

where μ = coefficient of friction between the base of the wall and the soil (= tan δ).

A minimum factor of safety of 1.5 against sliding is generally recommended.

(2) No Overturning

The wall must be safe against overturning about toe. The factor of safety against overturning is given by

$$F_0 = \frac{\Sigma M_R}{\Sigma M_O} \quad \text{...(20.4)}$$

where ΣM_R = sum of resisting moment about toe,

and ΣM_O = sum of overturning moment about toe.

In Fig. 20.2,

$$F_0 = \frac{W \times a}{P_a \times H/3} \quad \text{...(20.5)}$$

The factor of safety against overturning is usually kept between 1.5 to 2.0.

(3) No bearing capacity failure

The pressure caused by R_V at the toe of the wall must not exceed the allowable bearing capacity of the soil.

The pressure distribution at the base is assumed to be linear. The maximum pressure is given by

$$p_{max} = \frac{R_V}{b}(1 + 6e/b) \quad \text{...(20.6)}$$

The factor of safety against bearing failure is given by

$$F_b = \frac{q_{na}}{p_{max}} \quad \text{...(20.7)}$$

where q_{na} = allowable bearing pressure.

A factor of safety of 3 is usually specified, provided the settlement is also within the allowable limit.

(4) No tension

There should be no tension at the base of the wall. When the eccentricity (e) is greater than $b/6$, tension develops at the heel. Tension is not desirable. The tensile strength of the soil is very small and the tensile crack would develop. The effective base area is reduced. In such a case, the maximum stress is given by

$$p_{max} = \frac{4}{3}\left(\frac{R_V}{b-2e}\right) \qquad ...(20.8)$$

20.4. GRAVITY RETAINING WALLS

As in design of all other structures, a trial section is first chosen and analysed. If the stability checks yield unsatisfactory results, the section is changed, and rechecked. Fig. 20.3 shows the general proportion of a gravity retaining wall of overall height H. The top width of the stem should be at least 0.3 m for proper placement of concrete in the stem. The depth (D) of the foundation below the soil surface should be at least 0.6 m. The base width of the wall is generally between 0.5 H to 0.7 H; with an average of $2H/3$.

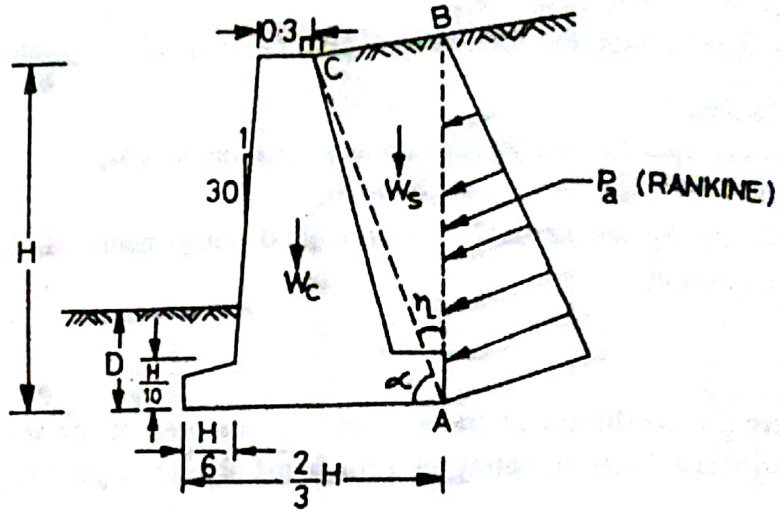

Fig. 20.3. Gravity wall—Rankine Pressure.

The earth pressure can be computed using either Rankine's theory or Coulomb's theory. For using Rankine's theory, a vertical line AB is drawn through the heel point A. It is assumed that the Rankine active conditions exist along the vertical line AB. However, the assumption for the development of Rankine's conditions along AB is theoretically justified only if the shear zone bounded by the line AC is not obstructed by the stem of the wall, where AC makes an angle η with the vertical, given by

$$\eta = (45° + i/2) - \phi'/2 - \sin^{-1}\left(\frac{\sin i}{\sin \phi'}\right) \qquad ...(20.9)$$

where i is the angle of surcharge.

The angle α which the line AC makes with the horizontal is given by,

$$\alpha = \left(45° + \frac{\phi'}{2}\right) - \frac{i}{2} + \sin^{-1}\left(\frac{\sin i}{\sin \phi'}\right) \qquad ...(20.10)$$

When $i = 0$, the value of α is equal to $(45° + \phi'/2)$ (Fig. 20.4).

While checking the stability, the weight of soil (W_s) above the heel in the zone ABC should also be taken into consideration, in addition to the earth pressure (P_a) on the vertical plane AB and the weight of the wall (W_c).

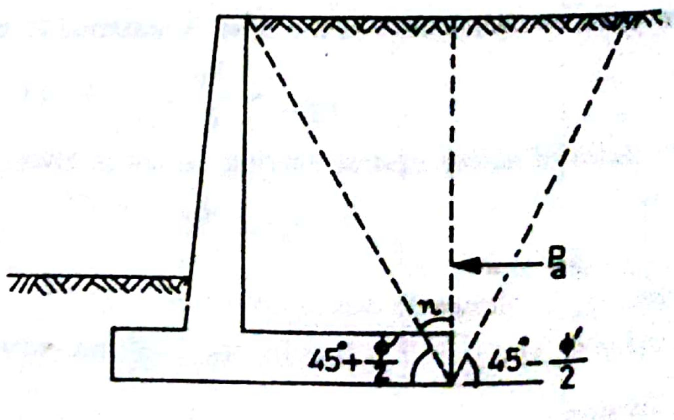

Fig. 20.4.

Coulomb's theory can also be used for the determination of earth pressure (Fig. 20.5). As the Coulomb theory gives directly the lateral pressure on the back face (P_a), the forces to be considered are only P_a (Coulomb) and the weight of the wall (W_c). In this case, the weight of soil (W_s) is not to be considered separately.

Once the forces acting on the wall have been determined, the stability is checked using the procedure discussed in the preceding section. For convenience, the section of the retaining wall is divided into rectangles and triangles for the computation of weight and the determination of the line of action of the weights.

Semi-gravity Retaining walls. The base width of the semi-gravity retaining walls is slightly smaller than that of a corresponding gravity wall. The rest of the design procedure is the same as that for gravity retaining walls.

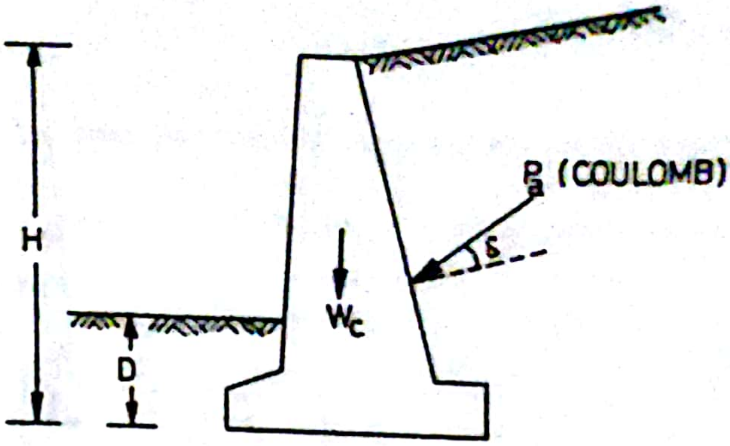

Fig. 20.5. Gravity wall—Coulomb Pressure.

20.5. CANTILEVER RETAINING WALLS

Fig. 20.6 shows a cantilever retaining wall. The general proportions for an overall height of H are also shown. The top width of the stem is at least 0.3 m. The width of the base slab is kept about $2H/3$. The width of the stem at bottom, the thickness of the base slab and the length of the toe projection, each is kept about 0.1 H.

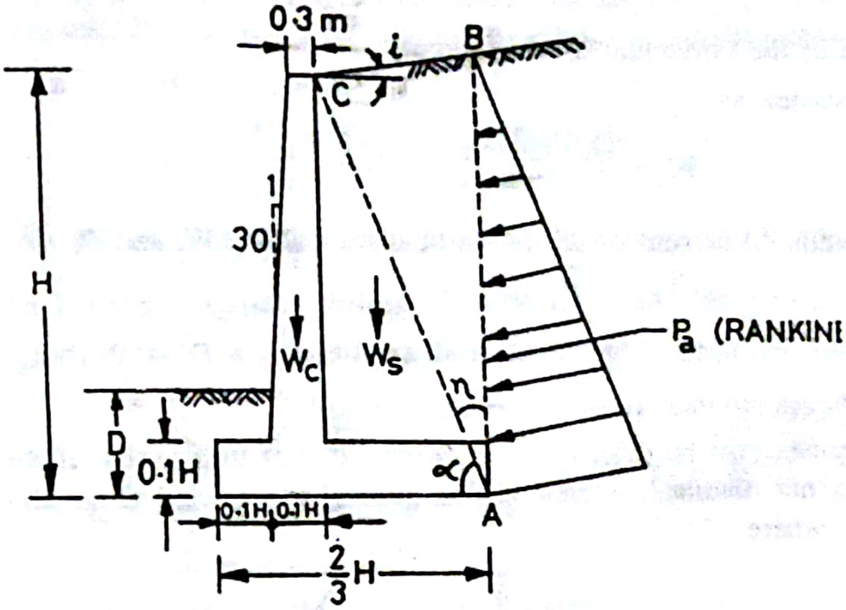

Fig. 20.6. Cantilever Retaining wall.

The earth pressure is computed using Rankine's theory on the vertical plane AB, provided the shear zone bounded by the line AC is not obstructed by the stem of the wall. The line AC makes an angle η with the vertical given by Eq. 20.9.

Fig. 20.7 shows the forces acting on the wall. The Rankine pressure P_a acts at an angle i with the horizontal. It is resolved into the vertical and horizontal components P_v and P_h, as shown. The passive pressure P_p is also shown, but generally it is neglected. For convenience, the weight of soil (W_s) over the slab is divided into two parts (1) and (2). Likewise, the weight of stem is divided into two parts (3) and (4).

(a) Factor of safety against sliding

The factor of safety against sliding may be expressed as

$$F_s = \frac{\Sigma F_R}{\Sigma F_d} \qquad \text{...(20.11)}$$

where ΣF_R = sum of the horizontal resisting forces,

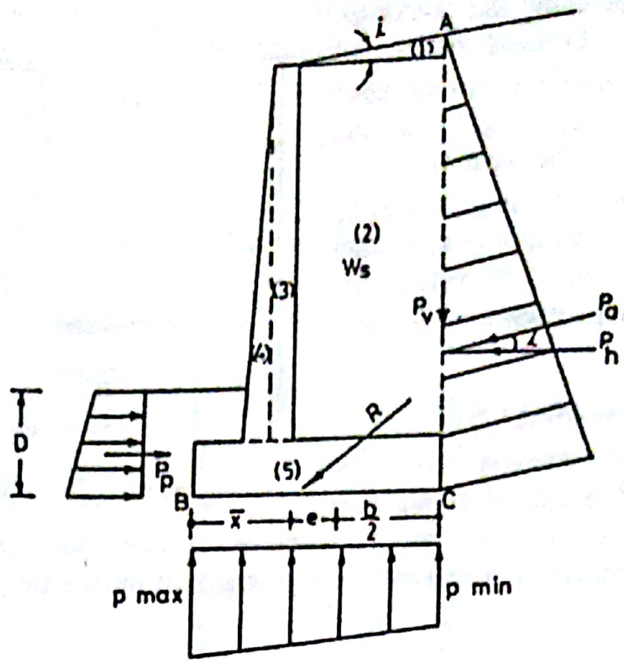

Fig. 20.7. Forces on a Cantilever wall.

and ΣF_d = sum of the horizontal driving forces.

Eq. 20.11 can be written as

$$F_s = \frac{(\Sigma V) \tan \phi_2 + bc_2 + P_p}{P_h} \qquad ...(20.12)$$

where b = base width, ΣV = sum of all the vertical forces, W_c, W_s and P_v.

$$P_v = P_a \sin i \text{ and } P_h = P_a \cos i.$$

P_p = passive force in the front of the wall $(= 1/2\, K_{p2}\, \gamma_2\, D^2 + 2c_2 \sqrt{K_{p2}}\, D)$

where c_2, γ_2 and ϕ_2 are parameters of the foundation soil.

The factor of safety can also be determined from Eq. 20.3 if μ is given. If the required factor of safety of 1.5 against sliding is not obtained, a base key is generally provided (Fig. 20.8). The key increases the passive resistance to P_p' where

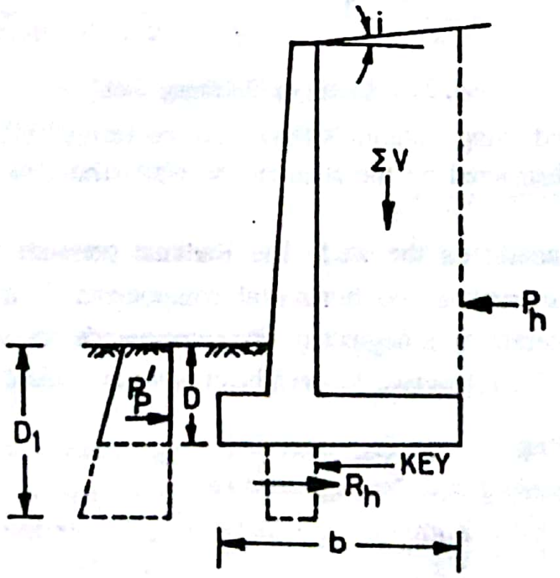

Fig. 20.8. Key in a retaining wall.

$$P_p' = \frac{1}{2}\gamma_2 (D_1)^2 K_{p2} + 2c_2 D_1 \sqrt{K_{p2}} \quad ...(20.13)$$

where D_1 is the depth of the bottom of the key wall from soil surface.

Generally, the base key is constructed just below the stem and some of the main steel of the stem is extended into the key.

The friction angle ϕ_2 and c_2 are generally reduced to about one-half to two-thirds of the values for extra safety, as the full passive resistance is doubtful.

Factor of safety against Overturning

Eq. 20.4 can be used to obtain the factor of safety against overturning,

$$F_o = \frac{\Sigma M_R}{\Sigma M_o}$$

where ΣM_R = sum of the resisting moments about toe,

ΣM_o = sum of the overturning moments about toe.

The only overturning force is P_h, acting at a height of $H/3$.

$$M_0 = P_h \times H/3 \quad ...(20.14)$$

The resisting moments (M_R) are due to weights W_1, W_2, W_3, W_4 and W_5 of the soil and the concrete. The vertical component of pressure P_v also helps in resisting moment. Its resisting moment is given by

$$M_v = P_v \times b \quad ...(20.15)$$

Therefore

$$F_o = \frac{M_1 + M_2 + M_3 + M_4 + M_5 + M_v}{P_h \times H/3} \quad ...(20.16)$$

where $M_1, M_2, \ldots M_5$ are the moments due to W_1, W_2 ... W_5 about toe.

Factor of safety against bearing capacity failure

The sum of the vertical forces acting on the base is equal to ΣV. The horizontal force is P_h. The resultant force (R) is given by

$$R = \sqrt{(\Sigma V)^2 + (P_h)^2}$$

The net moment of these forces about toe B is given by

$$\Sigma M = \Sigma M_R - \Sigma M_0$$

The distance $\bar{x}$ of the point E, from the toe, where R strikes the base is given by

$$\bar{x} = \frac{\Sigma M}{\Sigma V} \quad ...(20.17)$$

Hence, the eccentricity e of R is given by

$$e = b/2 - \bar{x} \quad ...(20.18)$$

If $e > b/6$, the section should be changed, as it indicates tension. The pressure distribution under the base slab is determined as

$$p_{max} = \frac{\Sigma V}{b}\left(1 + \frac{6e}{b}\right) \quad ...[20.19(a)]$$

and

$$p_{min} = \frac{\Sigma V}{b}\left(1 - \frac{6e}{b}\right) \quad ...[20.19(b)]$$

The factor of safety against bearing capacity failure is given by Eq. 20.7.