S_0 = settlement calculated by Terzaghi theory of consolidation;

$$= m_v \, \Delta p H \tag{6-8}$$

$$= \frac{C_c}{1 + e_0} \, H \log_{10} \frac{p_0 + \Delta p}{p_0} \tag{3-4}$$

where m_v = coefficient of volume compressibility of the clay. This value is determined by consolidation test.

Δp = vertical stress due to load on footing.

H = thickness of the compressible clay. The clay thickness should be divided into several layers to obtain reasonably accurate settlement of a thick layer.

C_c = compression index, also determined by consolidation test.

p_0 = vertical effective pressure due to soil overburden.

The computation of settlement due to consolidation is illustrated in the design example, sheet 2 DE 6.

3. *Settlement due to secondary consolidation.* When an undisturbed soil sample is tested in the consolidometer (or oedometer) the rate of volume decrease checks very closely with the theory. However, when the sample is one hundred per cent consolidated (according to the theory of consolidation) the volume decrease does not stop according to the theory, but instead the sample continues to compress at a reduced and rather constant rate. The amount of consolidation that can be computed by the theory is called primary consolidation; whereas the slow consolidation that takes place afterwards is called secondary consolidation, Sec. 3-5.

6-9 Eccentric Loading

Eccentric loading may result from a load applied off the center of the footing or from a concentric load plus a bending moment. For the purpose of determining the pressure under the footing the moment may be removed by shifting the vertical load to a fictitious location with an eccentricity e = moment/vertical load. In the analysis of an eccentrically loaded footing two separate problems are confronted:

1. For the purpose of structural design, the pressure against the bottom of the footing, commonly called contact pressure, is assumed to have a planar distribution. When the load is applied within the kern of the footing area, common flexural formulae are applicable.

$$q = \frac{Q}{A} \pm \frac{M_x}{I_y} x + \frac{M_y}{I_x} y \tag{6-9}$$

where q = contact pressure at a given point (x, y);

Q = vertical load;

A = area of footing;

x and y = coordinates of the point at which the contact pressure is calculated;

M_x, M_y = load Q multiplied by eccentricity parallel to x and y axes, respectively;

I_x, I_y = moment of inertia of the footing area about the x and y axes, respectively.

Equation (6-9) is valid when one of the following conditions exists:

(a) The footing is symmetrical about x and y axes.

(b) The footing is symmetrical about x axis and $e_y = 0$.

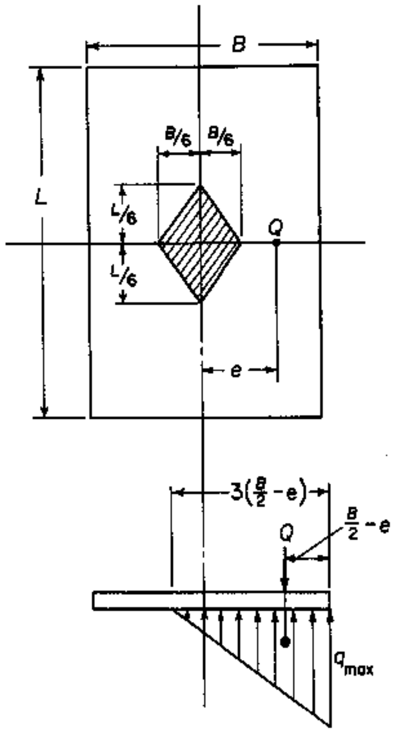
(c) The footing is symmetrical about y axis and $e_x = 0$.

For rectangular footings, Eq. (6-9) may be written in a simpler form:

$$q = \frac{Q}{A}\left(1 \pm 6\frac{e_l}{L} \pm 6\frac{e_b}{B}\right) \tag{6-9a}$$

When e_x, e_y or e_b, e_l exceed a certain limit, Eq. (6-9) or (6-9a) gives a negative value of q which indicates tension between the soil and bottom of footing. Unless the footing is weighted down by surcharge loads, the soil cannot be relied upon for bonding to the footing and offering tensile resistance. Therefore, the flexural formulae Eq. (6-9) and (6-9a) are applicable only when the load is applied within a limited area which is known as the kern and is shown shaded in Fig. 6-14(a). The procedure for determination of soil pressure when the load is applied outside the kern is simple in principle but laborious. Cases for rectangular and circular footings have been worked out and the kerns are shown by shaded areas in Fig. 6-14 [(a) and (c)]. For footings of other shapes, the graphical method of successive trials is probably the simplest for practical solutions (Roark, 1954).

The graphical method, similar to any other method, is based on the assumption that the pressure varies linearly with the distance to the neutral axis from zero at the neutral axis to a maximum at the most remote point and on the requirement of statical equilibrium that the resultant of the soil pressure should lie on the line of action of the applied load Q. The procedure is as follows. Draw a trial neutral axis *N-N*, Fig. 6-14(b) and a line *ab* perpendicular to *N-N*, starting from point *b* which is most remote. The area between point *b* and *N-N* is under compression while the area on the other side of *N-N* is unstressed. The intensity of stress at a given point varies in simple proportion with its perpendicular distance from *N-N*. The compression area is divided into several narrow strips of uniform width dy, running parallel to

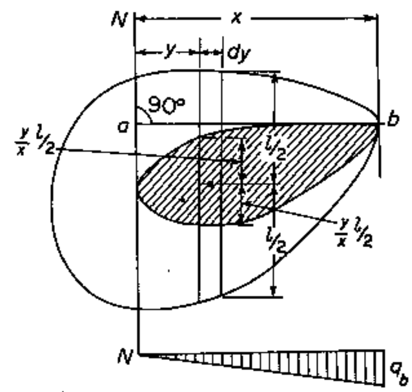


For $e \leq B/6$ $\quad q = \frac{Q}{A}\left[1 \pm 6\frac{e}{B}\right]$

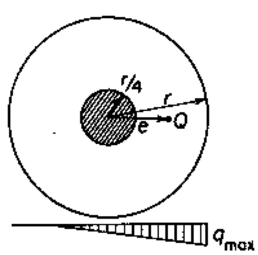
For $e > B/6$ $\quad q_{max} = \frac{Q}{A}\left[\frac{4B}{3B-6e}\right]$ OR $\frac{2Q}{3(L)(B/2 - e)}$

$q_{min} = 0$ at a distance of $3\left(\frac{B}{2} - e\right)$ from edge of footing

(a) Rectangular footing, load on one of the center lines of footing.



(b) General procedure.



For $e \leq r/4$ $\quad q = \frac{Q}{A}\left[1 \pm 4\frac{e}{r}\right]$

For $e > r/4$ $\quad q_{max} = k\frac{Q}{A}$

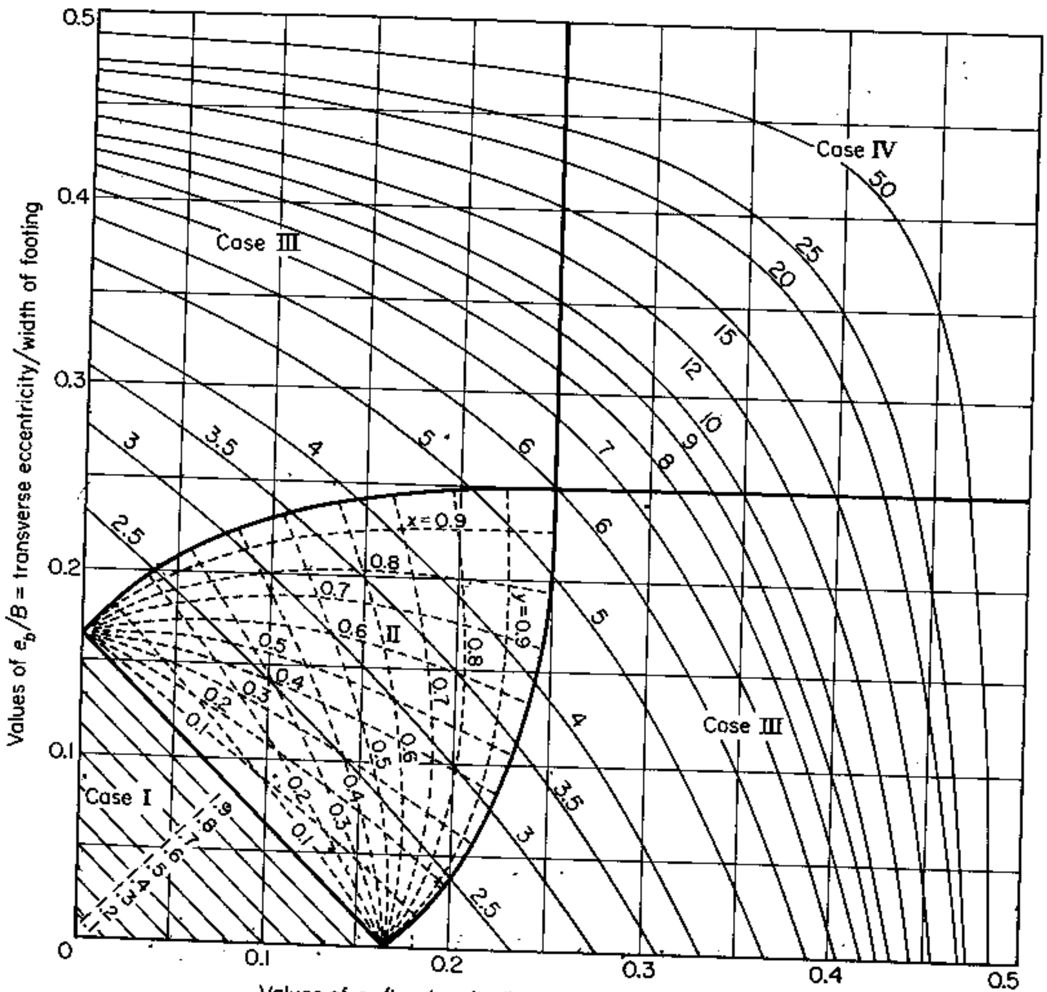
$A = \pi r^2$

k values are tabulated below

e/r =	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.90
k =	2.00	2.20	2.43	2.70	3.10	3.55	4.22	4.92	5.90	7.20	9.20	13.0	80.0

(c) Circular footing.

Fig. 6-14 Pressure distribution used for structural design of eccentrically loaded footings.



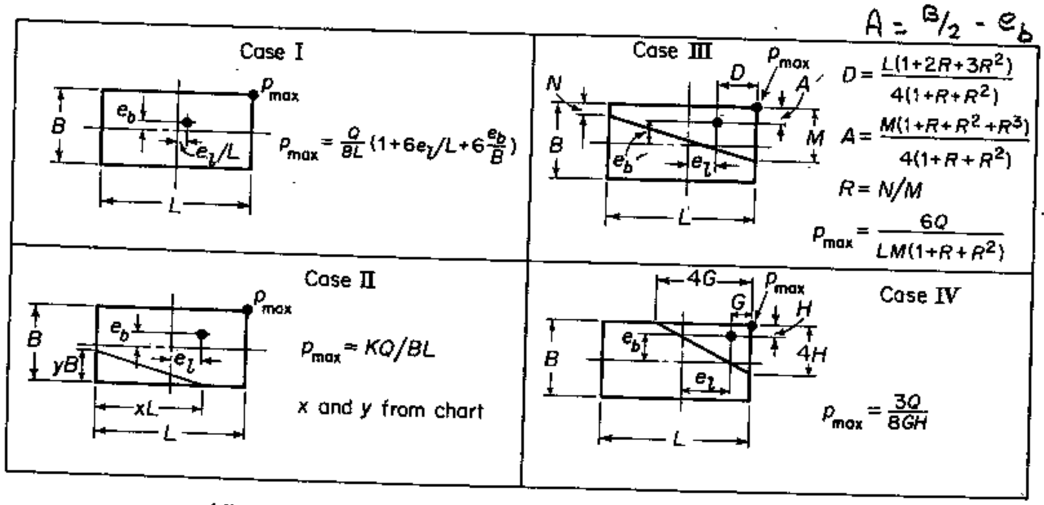
Solid curves give values of K

Maximum pressure $p_{max} = K \times Q/BL$

Q = concentrated load on footing

$D = L/2 - e_L$

$A = B/2 - e_b$



(d) Rectangular footing, double eccentricity. After AREA.

N-N. The unit pressure acting on this strip is equal to $(Y/X)q_b$, where q_b is the unit pressure at point b, and the total pressure is equal to $(Y/X)q_b l dy$. The total pressure may be represented by the shaded strip with a length of $(Y/X)l$. This shaded strip, if under a uniform pressure q_b, carries the same load as the whole strip under the actual pressure $(Y/X)q_b$. Therefore, it may be called a transformed strip. All the transformed strips form a transformed area. If the location of the trial neutral axis N-N is correct, the centroid of the transformed area will coincide with the point of action of the load Q. For practical purposes, the centroid or center of gravity of the transformed area may be determined by cutting out a cardboard of the same shape and balancing the board on a pencil point. The cardboard will balance only when it is supported on the center of gravity. Several such trials will enable the engineer to approach the correct location of the neutral axis.

2. For determination of ultimate or allowable bearing capacity of an eccentrically loaded footing, the concept of *useful width* has been introduced. By this concept, the portion of the footing which is symmetrical about the load is considered useful and the other portion is simply assumed superfluous for the convenience of computation. If the eccentricities are e_l and e_b, as shown in Fig. 6-15, the useful widths are $B - 2e_b$ and $L - 2e_l$, the equivalent area $(B - 2e_b)(L - 2e_l)$ is considered as subjected to a central load for determination of bearing capacity.

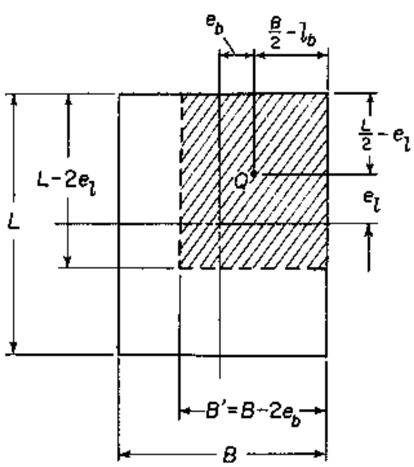


Fig. 6-15 Useful widths for determination of bearing capacity of eccentrically loaded footing on cohesive soils.

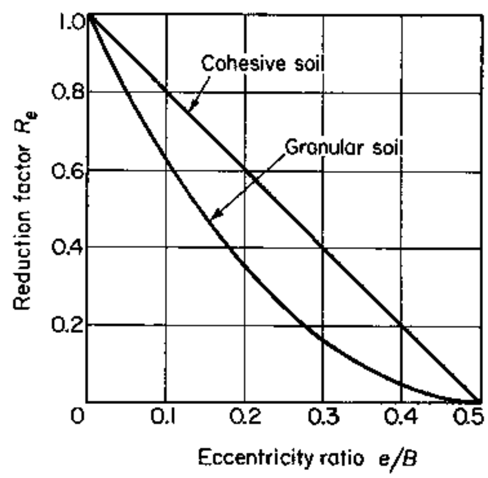


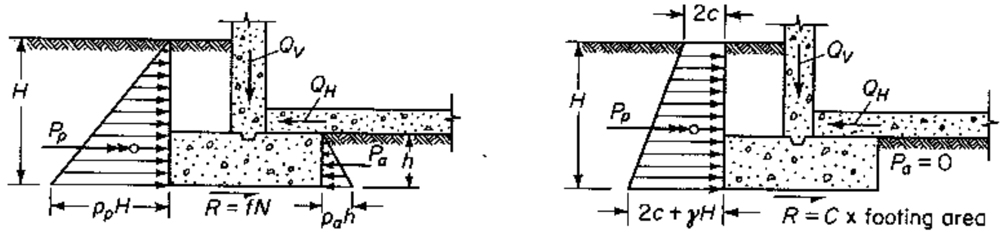
Fig. 6-16 Bearing capacity of eccentrically loaded footing. After AREA.

The concept above simply means that the bearing capacity of a footing decreases linearly with the eccentricity of load, as is shown by a straight line in Fig. 6-16. In cohesive soils, this linear relationship prevails, but in granular soils, however, the reduction is parabolic rather than linear, (Meyerhof, 1953).

Therefore, the reduction factor shown in Fig. 6-16 should be used for design purposes: First the bearing capacity of the footing is determined on the basis that the load is applied at the centroid of the footing. Then, this bearing capacity is corrected by multiplying with the factor shown in Fig. 6-16.

6-10 Inclined Load

The conventional method of stability analysis of footings subjected to inclined loads is as follows: the inclined load Q is resolved into a vertical component Q_v and a horizontal component Q_H. The stability of the footing against ultimate failure under the vertical load is treated by the same principles for footings subjected to vertical load only, and the effect of the horizontal component is ignored. Then, the stability of the footing against the horizontal force is analysed by calculating the factor of safety against sliding which is defined as the ratio between the total horizontal resistance and the horizontal force. The total horizontal resistance in general consists of a passive resistance of soil, P_p, and a frictional resistance R, Fig. 6-17. The value of P_p can be



N = total vertical force acting on the base of footing

Factor of safety against sliding $= \dfrac{P_p - P_a + R}{Q_H}$

Granular soils

Type of Soil	P_p psf		Coef. of Friction, f
	submerged	dry or moist	
Sand and/or gravel with less than 5% silt	210	350	0.55
Sand and/or gravel with 5% or more silt	180	250	0.45
Silt or soils containing more than 30% silt	120	150	0.35

Cohesive soils

Type of Soil	Cohesive Strength c = psf	Unit Weight, r pcf
Very soft clay	200	110
Soft clay	400	120
Medium, stiff, and hard clay	600	125

The values above may be used in small jobs. Backfill must be well compacted to insure the design passive pressure

Fig. 6-17 Conventional method of analysis of footings subjected to inclined loads.

determined by the principles discussed in Chapter 4. However, for smaller projects, conservative values such as those shown in the figure may be used. It should be emphasized that high values of passive earth pressure P_p may not be realized in granular soils unless it is backfilled and well compacted in layers.