BEARING CAPACITY OF SHALLOW FOUNDATIONS

Introduction

A foundation, often constructed from concrete, steel or wood, is a structure designed to transfer loads from a superstructure to the soil underneath the superstructure. In general, foundations are categorized into two groups, namely, shallow and deep foundations. Shallow foundations are comprised of footings, while deep foundations include piles that are used when the soil near the ground surface has no enough strength to stand the applied loading. The ultimate bearing capacity, \( q_u \) (in kPa) is the load that causes the shear failure of the soil underneath and adjacent to the footing. In this chapter, we will discuss equations used to estimate the ultimate bearing capacity of soils.

Bearing Failure Modes

Figure 1: Modes of bearing failures (a) General shear (b) Local shear and (c) Punching shear.
Relative density of the soil and size of the foundation are among the major factors that affect the mode of bearing failure likely to occur. The modes of bearing failure are generally separated into three categories: The **general shear failure** (Fig. 1a) is usually associated with soils of low compressibility such as dense sand and stiff cohesive soils. In this case, if load is gradually applied to the foundation, settlement will increase. At a certain point – when the applied load per unit area equals to the ultimate load \(q_u\), the footing undergoes a large settlement without further increase of \(q\) and a sudden failure in the soil supporting the foundation will take place. When the foundation settles under the application of a load, a triangular wedge-shaped zone of soil (marked I) is pushed down, and, in turn, it presses the zones marked II and III sideways and then upward. At the ultimate pressure, \(q_u\), the soil passes into a state of plastic equilibrium and failure occurs by sliding.

For the **local shear failure** (Fig. 1b), which is common in sands and clays of medium compaction, the failure surface will gradually extend outward from the foundation but will not reach the ground surface as shown by the solid segment in Fig. 1b. The shear resistance is fully developed over only part of the failure surface (solid segment of the line). The triangular wedge-shaped zone (marked I) below the footing moves downward, but unlike general shear failure, the slip surfaces end somewhere inside the soil. Some signs of soil bulging are seen, however.

In the case of **punching shear failure**, a condition common in loose and very compressible soils, considerable vertical settlement may take place with the failure surfaces restricted to vertical planes immediately adjacent to the sides of the foundation; the ground surface may be dragged down. After the first yield has occurred the load-settlement curve will be steep slightly, but remain fairly flat.

**Basic definitions:**

**Bearing capacity:** It is the load carrying capacity of the soil.

**Ultimate bearing capacity or Gross bearing capacity** \(q_u\): It is the maximum pressure that a foundation soil can withstand without undergoing shear failure.

**Net ultimate bearing capacity** \(q_{u\text{-(net)}}\): It is the net pressure that can be applied to the footing by external loads that will just initiate failure in the underlying soil. It is equal to ultimate bearing capacity minus the stress due to the weight of the footing and any soil or surcharge directly above it. Assuming the density of the footing (concrete) and soil \(\gamma\) are close enough to be considered equal, then

\[
q_{u\text{-(net)}} = q_u - \gamma D_f
\]

where,

\(D_f\) = is the depth of the footing,
Safe bearing capacity: It is the bearing capacity after applying the factor of safety (FS).

These are of two types,

**Safe net bearing capacity** ($q_{ns}$): It is the net soil pressure which can be safely applied to the soil considering only shear failure. It is given by,

$$q_{ns} = \frac{q_{u(net)}}{FS}$$

**Safe gross bearing capacity** ($q_s$): It is the maximum gross pressure which the soil can carry safely without shear failure. It is given by,

$$q_s = q_{ns} + \gamma D_f$$

Allowable Bearing Pressure: It is the maximum soil pressure without any shear failure or settlement failure

![Figure 2: Bearing capacity of footing](image)

Fig. 2 Bearing capacity of footing

**Terzaghi’s Bearing Capacity Theory:**

Assumptions
- Depth of foundation is less than or equal to its width.
- Base of the footing is rough.
- Soil above bottom of foundation has no shear strength; is only a surcharge load against the overturning load
- Surcharge upto the base of footing is considered.
- Load applied is vertical and non-eccentric.
- The soil is homogenous and isotropic.
- L/B ratio is infinite.
The shapes of the failure surfaces under ultimate loading conditions are given in Figure 03.

The zones of plastic equilibrium represented in this figure by the area gedcf may be subdivided into

1) Zone I of Elastic Equilibrium
2) Zones II of Radial Shear State
3) Zones III of Rankine Passive State

**Mechanism of Failure:**
- The sinking of Zone I creates two zones of plastic equilibrium, II and III, on either side of the footing.
- Zone II is the radial shear zone whose remote boundaries bd and af meet the horizontal surface at angles \(45° - \phi/2\), whereas Zone III is a passive Rankine zone.
- The boundaries de and fg of those zones are straight lines and they meet the surface at angles of \(45° - \phi/2\).
- The curved parts cd and cf in Zone are parts of logarithmic spirals whose centers are located at b and a respectively.

The first term in the equation is related to cohesion of the soil. The second term is related to the depth of the footing and overburden pressure. The third term is related to the width of the footing and the length of shear stress area. The bearing capacity factors, \(N_c\), \(N_q\), \(N_\gamma\), are function of internal friction angle, \(\phi\).
Terzaghi’s Bearing capacity equations:

\[ q_u = q_c + q_q + q_\gamma \]

\[ q_u = c N_c + q N_q + 0.5 \gamma B N_\gamma \]

\[ q_u = c N_c + \gamma D N_q + 0.5 \gamma B N_\gamma \]

Strip footings: \[ q_u = c N_c + \gamma D N_q + 0.5 \gamma B N_\gamma \]

Square footings: \[ q_u = 1.3 c N_c + \gamma D N_q + 0.4 \gamma B N_\gamma \]

Circular footings: \[ q_u = 1.3 c N_c + \gamma D N_q + 0.3 \gamma B N_\gamma \]

Rectangular footing: \[ q_u = c N_c (1+0.3 B/L) + \gamma D N_q + 0.5 \gamma B N_\gamma (1-0.2 B/L) \]

Where:
- \( c \) = Cohesion of soil,
- \( \gamma \) = unit weight of soil,
- \( D \) = depth of footing,
- \( B \) = width of footing

\( N_c, N_q \) and \( N_\gamma \) are called the bearing capacity factors and are obtained as follows:

\[ N_q = \frac{e^{(3\pi/2 - \phi') \tan \phi'}}{2 \cos^2 (45 + \phi' / 2)} \]

\[ N_c = \cot \phi' (N_q - 1) \]

\[ N_\gamma = \frac{1}{2} \tan \phi' \left( \frac{K_{py}}{\cos^2 \phi'} - 1 \right) \]
Table 16.1 Terzaghi’s Bearing Capacity Factors $N_c$, $N_q$ and $N_y$—Eqs. (16.11), (16.12), and (16.13), respectively

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*N_q values from Kumbhokar (1993)*
Effects of Groundwater Table on Bearing Capacity

Case I Water table located above the base of footing [Fig. 23.11 (a)]

The effective surcharge is reduced as the effective weight below the water table is equal to the submerged unit. Therefore,

\[ q = D_w \gamma + a \gamma' \]  \hspace{1cm} ...(23.30)

where \( D_w \) = depth of water table below the ground surface,
\( a \) = height of water table above the base of footing.

Alternatively, Eq. 23.30 can be written as, substituting \( a = D_f - D_w \),

\[ q = \gamma' D_f + (\gamma - \gamma') D_w \]  \hspace{1cm} ...(23.31)

Moreover, the unit weight in the third term of Eq. 23.25 is equal to the submerged unit weight. Thus Eq. 23.25 becomes

\[ q_u = c' N_c + [\gamma' D_f + (\gamma - \gamma') D_w] N_q + 0.5 \gamma' B N_t \]  \hspace{1cm} ...(23.32)

If \( D_w = 0 \) (i.e. \( a = D_f \)),
\[ q_u = c' N_c + \gamma' D_f N_q + 0.5 \gamma' B N_t \]  \hspace{1cm} ...(23.33(a))

If \( a = 0 \) (i.e. \( D_f = D_w \)),
\[ q_u = c' N_c + \gamma D_f N_q + 0.5 \gamma' B N_t \]  \hspace{1cm} ...(23.33(b))

Case II Water table located at a depth \( b \) below base [Fig. 23.11 (b)]

If the water table is located at the level of the base of footing or below it, the surcharge term is not affected. However, the unit weight in the third term of Eq. 23.25 is modified as

\[ \bar{\gamma} = \gamma' + \frac{b}{B} (\gamma - \gamma) \]  \hspace{1cm} ...(23.34)

where \( b \) = depth of water table below the base,
\( B \) = base width of the footing.

Therefore,
\[ q_u = c' N_c + \gamma D_f N_q + 0.5 B \left[ \gamma' + \frac{b}{B} (\gamma - \gamma) \right] N_t \]  \hspace{1cm} ...(23.35(a))

When \( b = 0 \), i.e. W/T at the base,
\[ q_u = c' N_c + \gamma D_f N_q + 0.5 B \gamma' N_t \]  \hspace{1cm} ...(23.35(b))

When \( b = B \), i.e. W/T at depth \( B \) below the base,
\[ q_u = c' N_c + \gamma D_f N_q + 0.5 B \gamma N_t \]  \hspace{1cm} ...(same as Eq. 23.25)

Hence, when the ground water table is located at a depth \( b \) equal to or greater than \( B \), there is no effect on the ultimate bearing capacity.
**Factor of Safety:**

Generally, a factor of safety, $Fs$, of about 3 or more is applied to the ultimate soil-bearing capacity to arrive at the value of the allowable bearing capacity. An $Fs$ of 3 or more is not considered too conservative. In nature, soils are neither homogeneous nor isotropic. Much uncertainty is involved in evaluating the basic shear strength parameters of soil.

There are two basic definitions of the allowable bearing capacity of shallow foundations. They are gross allowable bearing capacity, and net allowable bearing capacity.

The gross allowable bearing capacity can be calculated as

$$q_{all} = \frac{q_u}{F_s}$$

As defined by Eq. $q_{all}$ is the allowable load per unit area to which the soil under the foundation should be subjected to avoid any chance of bearing capacity failure. It includes the contribution of (a) the dead and live loads above the ground surface, $W(DL)$; (b) the self-weight of the foundation, $WF$; and (c) the weight of the soil located immediately above foundation, $WS$. Thus,

$$q_{all} = \frac{q_u}{F_s} = \frac{\left[W(D+L) + WF + WS\right]}{A}$$

where $A$ area of the foundation.

The net allowable bearing capacity is the allowable load per unit area of the foundation in excess of the existing vertical effective stress at the level of the foundation. The vertical effective stress at the foundation level is equal to $q_{gDf}$. So, the net ultimate load is

$$q_{u(\text{net})} = q_u - q$$

$$q_{all(\text{net})} = \frac{q_{u(\text{net})}}{F_s} = \frac{q_u - q}{F_s}$$

If we assume that the weight of the soil and the weight of the concrete from which the foundation is made are approximately the same, then

$$q = \gamma D_f = \frac{WS + WF}{A}$$

$$q_{all(\text{net})} = \frac{W(D+L)}{A} = \frac{q_u - q}{F_s}$$
Example 16.1

A continuous foundation is shown in Figure 16.8. Using Terzaghi’s bearing capacity factors, determine the gross allowable load per unit area \( q_{\text{all}} \) that the foundation can carry. Given:

- \( \gamma = 110 \text{ lb/ft}^3 \)
- \( c' = 200 \text{ lb/ft}^2 \)
- \( \phi' = 20^\circ \)
- \( D_f = 3 \text{ ft} \)
- \( B = 4 \text{ ft} \)
- Factor of safety = 3

Assume general shear failure.
Example 16.2

A square foundation is shown in Figure 16.9. The footing will carry a gross mass of 30,000 kg. Using a factor of safety of 3, determine the size of the footing—that is, the size of $B$. Use Eq. (16.12).

\[ \rho = 1850 \text{ kg/m}^3 \]
\[ \delta' = 35^\circ \]
\[ c' = 0 \]
Example 16.3

A continuous footing is shown in Figure 16.19. Using Terzaghi’s bearing capacity factors, determine the gross allowable load per unit area (qall) that the footing can carry. Assume general shear failure. Given: $\gamma = 115$ lb/ft$^3$, $c' = 600$ lb/ft$^2$, $\phi' = 25^\circ$, $D_l = 3.5$ ft, $B = 4$ ft, and factor of safety 3.

Solution:

Example 16.4

A square footing is shown in Figure 16.20. Determine the gross allowable load, Qall, that the footing can carry. Use Terzaghi’s equation for general shear failure ($F_s = 3$). Given: $\gamma = 105$ lb/ft$^3$, $\gamma_{sat} = 118$ lb/ft$^3$, $c' = 0$, $\phi' = 35^\circ$, $B = 5$ ft, $D_l = 4$ ft, and $h = 2$ ft.
Example 16.5

A square footing (B  B) must carry a gross allowable load of 42,260 lb. The base of the footing is to be located at a depth of 3 ft below the ground surface. For the soil, we are given that γ= 110 lb/ft3, c’= 200 lb/ft², and ϕ’=20°. If the required factor of safety is 3, determine the size of the footing. Use Terzaghi’s bearing capacity factors and general shear failure of soil.

Solution:
GENERAL BEARING CAPACITY EQUATION

The General Bearing Capacity Equation can be written in the following form-

\[ q_u = c N_c F_{cs} F_{cd} F_{ci} + q N_q F_{qs} F_{qd} F_{qi} + \frac{1}{2} \gamma B N_r F_{ys} F_{yd} F_{yi} \]

Where,

\( q_u = \text{Ultimate Bearing Capacity} \)
\( c = \text{cohesion} \)
\( q = \text{effective stress at the level of the bottom of the foundation} \)
\( \gamma = \text{unit weight of soil} \)
\( B = \text{width of foundation (= diameter for a circular foundation)} \)
\( F_{cs}, F_{qs}, F_{ys} = \text{shape factors} \)
\( F_{cd}, F_{qd}, F_{yd} = \text{depth factors} \)
\( F_{ci}, F_{qi}, F_{yi} = \text{load inclination factors} \)
\( N_c, N_q, N_r = \text{bearing capacity factors} \)

Bearing Capacity Factors

\[ N_c = (N_q - 1) \cot \phi \]
\[ N_q = \tan^2 \left( 45 + \frac{\phi}{2} \right) \frac{e^{n \tan \phi}}{2} \]
\[ N_r = (N_q - 1) \tan (1.4 \phi) \text{ (Meyerhof)} \]
\[ N_r = 1.5 (N_q - 1) \tan \phi \text{ (Hansen)} \]
\[ N_r = 2 (N_q + 1) \tan \phi \text{ (Vesic)} \]
Ultimate Load for Shallow Foundations Under Eccentric Load

In several instances, as with the base of a retaining wall, foundations are subjected to moments in addition to the vertical load, as shown in Figure 09a. In such cases, the distribution of pressure by the foundation on the soil is not uniform. The nominal distribution of pressure is-

\[ q_{\text{max}} = \frac{Q}{BL} + \frac{6M}{B^2L} \]

and

\[ q_{\text{min}} = \frac{Q}{BL} - \frac{6M}{B^2L} \]

Where,

\( Q = \text{total vertical load} \)

\( M = \text{moment on the foundation} \)

Figure 09b shows a force system equivalent to that shown in Figure 09a. The distance

\[ e = \frac{M}{Q} \]

is the eccentricity. Substituting Eq. (3.35) into Eqs. (3.33) and (3.34) gives

\[ q_{\text{max}} = \frac{Q}{BL} \left( 1 + \frac{6e}{B} \right) \]

and

\[ q_{\text{min}} = \frac{Q}{BL} \left( 1 - \frac{6e}{B} \right) \]
Figure 09 Nature of Pressure Distribution for Eccentric Loading

Note that, in these equations, when the eccentricity $e$ becomes $B/6$, $q_{\text{min}}$ is zero. For $e > B/6$, $q_{\text{min}}$ will be negative, which means that tension will develop. Because soil cannot take any tension, there will then be a separation between the foundation and the soil underlying it. The nature of the pressure distribution on the soil will be as shown in Figure 09a. The value of $q_{\text{max}}$ is then

$$q_{\text{max}} = \frac{4Q}{3L(B - 2e)}$$

The exact distribution of pressure is difficult to estimate.

Figure 10 shows the nature of failure surface in soil for a surface strip foundation subjected to an eccentric load. The factor of safety for such type of loading against bearing capacity failure can be evaluated as
\[ FS = \frac{Q_{ult}}{Q} \]

Where, \( Q_{ult} \) = ultimate load carrying capacity

![Figure 10 Failure surface for a surface strip foundation subjected to an eccentric load](image)

The following sections describe several theories for determining \( Q_{ult} \)

**One-Way Eccentricity**

![Figure 11 One-Way Eccentricity](image)
**Effective Area Method (Meyerhoff, 1953)**

In 1953, Meyerhof proposed a theory that is generally referred to as the effective area method.

The following is a step-by-step procedure for determining the ultimate load that the soil can support and the factor of safety against bearing capacity failure:

**STEP 1**

Determine the effective dimensions of the foundation

\[ B' = \text{effective width} = B - 2e \]

\[ L' = \text{effective length} = L \]

Note that if the eccentricity were in the direction of the length of the foundation, the value of \( L' \) would be equal to \( L - 2e \). The value of \( B' \) would equal \( B \). The smaller of the two dimensions (i.e., \( L' \) and \( B' \)) is the effective width of the foundation.

**STEP 2**

Use the following equation for the ultimate bearing capacity:

\[ q_u = cN_cF_{cs}F_{cd}F_{cl} + qN_qF_{qs}F_{qd}F_{ql} + \frac{1}{2} \gamma B'N_y F_{ys}F_{yd}F_{yl} \]

To evaluate \( F_{cs}, F_{qs} \) and \( F_{ys} \), use the relationships given in Table 03 with effective length and effective width dimensions instead of \( L \) and \( B \), respectively. To determine \( F_{cd}, F_{qd} \) and \( F_{yd} \), use the relationships given in Table 03. However, do not replace \( B \) with \( B' \).

**STEP 3**

The total ultimate load that the foundation can sustain is

\[ Q_{ult} = q_u \left( \frac{A'}{B'} \right) (L') \]

Where, \( A' = \text{effective area} \)

**STEP 4**

The factor of safety against bearing capacity failure is

\[ FS = \frac{Q_{ult}}{Q} \]
Example 16.4

A rectangular footing $1.5 \text{ m} \times 1 \text{ m}$ is shown in Figure 16.15. Determine the magnitude of the gross ultimate load applied eccentrically for bearing capacity failure in soil.

\begin{itemize}
  \item $e = 0.1 \text{ m}$
  \item $\gamma = 18 \text{ kN/m}^3$
  \item $c' = 0$
  \item $\phi' = 30^\circ$
\end{itemize}

\textit{Figure 16.15}
Plate-Load Test

In some cases, conducting field-load tests to determine the soil-bearing capacity of foundations is desirable. The standard method for a field-load test is given by the American Society for Testing and Materials (ASTM) under Designation D-1194 (ASTM, 1997). Circular steel bearing plates 162 to 760 mm (6 to 30 in.) in diameter and 305 mm × 305 mm (1 ft × 1 ft) square plates are used for this type of test.

A diagram of the load test is shown in Figure 16.16. To conduct the test, one must have a pit of depth \( D_p \) excavated. The width of the test pit should be at least four times the width of the bearing plate to be used for the test. The bearing plate is placed on the soil at the bottom of the pit, and an incremental load on the bearing plate is applied. After the application of an incremental load, enough time is allowed for settlement to occur. When the settlement of the bearing plate becomes negligible, another incremental load is applied. In this manner, a load-settlement plot can be obtained, as shown in Figure 16.17.
From the results of field load tests, the ultimate soil-bearing capacity of actual footings can be approximated as follows:

For clays,

\[ q_u(footing) = q_u(plate) \]  \hspace{1cm} (16.53)

For sandy soils,

\[ q_u(footing) = q_u(plate) \frac{B_{(footing)}}{B_{(plate)}} \]  \hspace{1cm} (16.54)

For a given intensity of load \( q \), the settlement of the actual footing also can be approximated from the following equations:

In clay,

\[ S_e(footing) = S_e(plate) \frac{B_{(footing)}}{B_{(plate)}} \]  \hspace{1cm} (16.55)
In sandy soil,

\[ S_{\text{footing}} = S_{\text{plate}} \left( \frac{2B_{\text{footing}}}{B_{\text{footing}} + B_{\text{plate}}} \right)^2 \]

**Example 16.6**

The ultimate bearing capacity of a 700-mm diameter plate as determined from field load tests is 280 kN/m². Estimate the ultimate bearing capacity of a circular footing with a diameter of 1.5 m. The soil is sandy.

**Summary and General Comments**

In this chapter, theories for estimating the ultimate and allowable bearing capacities of shallow foundations were presented. Procedures for field-load tests and estimation of the allowable bearing capacity of granular soil based on limited settlement criteria were discussed briefly.

Several building codes now used in the United States and elsewhere provide presumptive bearing capacities for various types of soil. It is extremely important to realize that they are *approximate values only*. The bearing capacity of foundations depends on several factors:

1. Subsoil stratification
2. Shear strength parameters of the subsoil
3. Location of the groundwater table
4. Environmental factors
5. Building size and weight
6. Depth of excavation
7. Type of structure

Hence, it is important that the allowable bearing capacity at a given site be determined based on the findings of soil exploration at that site, past experience of foundation construction, and fundamentals of the geotechnical engineering theories for bearing capacity.

The allowable bearing capacity relationships based on settlement considerations such as those given in Section 16.9 do not take into account the settlement caused by consolidation of the clay layers. Excessive settlement usually causes the building to crack, which ultimately may lead to structural failure. Uniform settlement of a structure does not produce cracking; on the other hand, differential settlement may produce cracks and damage to a building.
<table>
<thead>
<tr>
<th><strong>Modes of Shear Failure (Summary)</strong></th>
<th><strong>General</strong></th>
<th><strong>Local</strong></th>
<th><strong>Punching</strong></th>
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</thead>
<tbody>
<tr>
<td><strong>Relative Settlement</strong></td>
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<td>Large</td>
</tr>
<tr>
<td><strong>Bulging</strong></td>
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<td>Less</td>
<td>No</td>
</tr>
<tr>
<td><strong>Tilting of Footing</strong></td>
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<td>Not expected</td>
<td>Not expected</td>
</tr>
<tr>
<td><strong>Ultimate Load</strong></td>
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<td>Not well defined</td>
<td>Not well defined</td>
</tr>
<tr>
<td><strong>Failure Pattern</strong></td>
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<td>Wedge +</td>
<td>Not well defined</td>
</tr>
<tr>
<td></td>
<td>Slip Surface +</td>
<td>Slip Surface +</td>
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<tr>
<td></td>
<td>Bulging</td>
<td>Bulging(no or less)</td>
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<tr>
<td><strong>Occurs in (Soil Type)</strong></td>
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<td>Less compressible</td>
<td>Highly Compressible</td>
</tr>
</tbody>
</table>