5

Shallow Foundations

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Shallow foundations are those that transmit structural loads to the near-surface soils. These include *spread footing foundations* and *mat foundations*. This chapter introduces both types of foundations, then Chapters 6 to 10 discuss the various geotechnical and structural design aspects.

5.1 SPREAD FOOTINGS

A spread footing (also known as a *footer* or simply a *footing*) is an enlargement at the bottom of a column or bearing wall that spreads the applied structural loads over a sufficiently large soil area. Typically, each column and each bearing wall has its own spread footing, so each structure may include dozens of individual footings.

Spread footings are by far the most common type of foundation, primarily because of their low cost and ease of construction. They are most often used in small to medium-size structures on sites with moderate to good soil conditions, and can even be used on some large structures when they are located at sites underlain by exceptionally good soil or shallow bedrock.

Spread footings may be built in different shapes and sizes to accommodate individual needs, as shown in Figure 5.1. These include the following:

- *Square spread footings* (or simply *square footings*) have plan dimensions of $B \times B$. The depth from the ground surface to the bottom of the footing is D and the thickness is T. Square footings usually support a single centrally-located column.

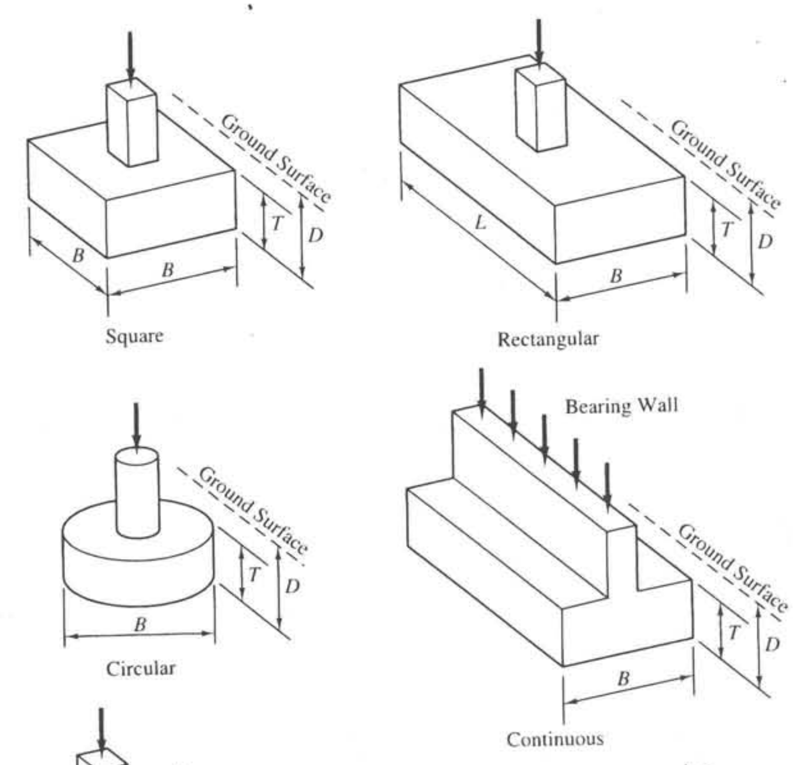

Figure 5.1 Spread footing shapes and dimensions.

- *Rectangular spread footings* have plan dimensions of $B \times L$, where L is the longest dimension. These are useful when obstructions prevent construction of a square footing with a sufficiently large base area and when large moment loads are present.
- *Circular spread footings* are round in plan view. These are most frequently used as foundations for light standards, flagpoles, and power transmission lines. If these foundations extend to a large depth (i.e., D/B greater than about 3), they may behave more like a deep foundation (see Chapter 11).

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- *Continuous spread footings* (also known as *wall footings* or *strip footings*) are used to support bearing walls.
- *Combined footings* are those that support more than one column. These are useful when columns are located too close together for each to have its own footing.
- *Ring spread footings* are continuous footings that have been wrapped into a circle. This type of footing is commonly used to support the walls of above-ground circular storage tanks. However, the contents of these tanks are spread evenly across the total base area, and this weight is probably greater than that of the tank itself. Therefore, the geotechnical analyses of tanks usually treat them as circular foundations with diameters equal to the diameter of the tank.

Sometimes it is necessary to build spread footings very close to a property line, another structure, or some other place where no construction may occur beyond one or more of the exterior walls. This circumstance is shown in Figure 5.2. Because such a footing cannot be centered beneath the column, the load is eccentric. This can cause the footing to rotate and thus produce undesirable moments and displacements in the column.

One solution to this problem is to use a *strap footing* (also known as a *cantilever footing*), which consists of an eccentrically loaded footing under the exterior column connected to the first interior column using a *grade beam*. This arrangement, which is similar to a combined footing, provides the necessary moment in the exterior footing to counter the eccentric load. Sometimes we use grade beams to connect all of the spread footings in a structure to provide a more rigid foundation system.

Materials

Before the mid-nineteenth-century, almost all spread footings were made of masonry, as shown in Figure 5.3. *Dimension-stone footings* were built of stones cut and dressed to specific sizes and fit together with minimal gaps, while *rubble-stone footings* were built from random size material joined with mortar (Peck et al., 1974). These footings had very little tensile strength, so builders had to use large height-to-width ratios to keep the flexural stresses tolerably small and thus avoid tensile failures.

Although masonry footings were satisfactory for small structures, they became large and heavy when used in heavier structures, often encroaching into the basement. For example, the masonry footings beneath the nine-story Home Insurance Building in Chicago (built in 1885) had a combined weight equal to that of one of the stories (Peck, 1948). As larger structures became more common, it was necessary to develop footings that were shorter and lighter, yet still had the same base dimensions. This change required structural materials that could sustain flexural stresses.

The *steel grillage footings* used in the ten-story Montauk Block Building in Chicago in 1882, may have been the first spread footings designed to resist flexure. They included several layers of railroad tracks, as shown in Figure 5.4. The flexural strength of the steel permitted construction of a short and lightweight footing. Steel grillage footings, modified to use I-beams instead of railroad tracks, soon became the dominant design. They prevailed until the advent of reinforced concrete in the early twentieth century.

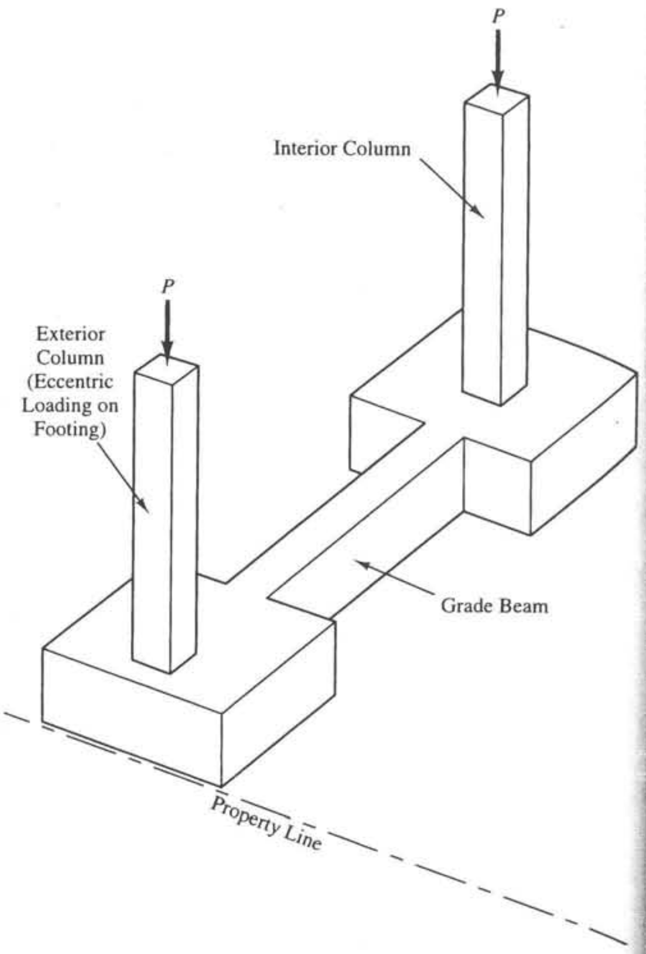
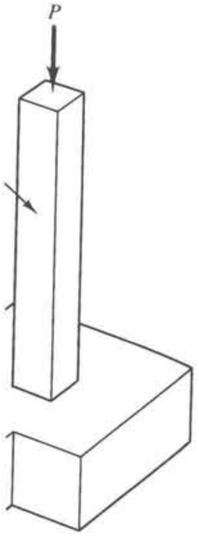


Figure 5.2 Use of a strap footing to support exterior columns when construction cannot extend beyond the property line.

Figure 5.5 shows a typical reinforced concrete footing. These are very strong, economical, durable, and easy to build. Reinforced concrete footings are much thinner than the old masonry footings, so they do not require large excavations and do not intrude into basements. Thus, nearly all spread footings are now made of reinforced concrete.

Construction Methods

Contractors usually use a *backhoe* to excavate spread footings, as shown in Figure 5.6. Typically, some hand work is also necessary to produce a clean excavation. Once the excavation is open, it is important to check the exposed soils to verify that they are comparable to those used in the design. Inspectors often check the firmness of these soils using a



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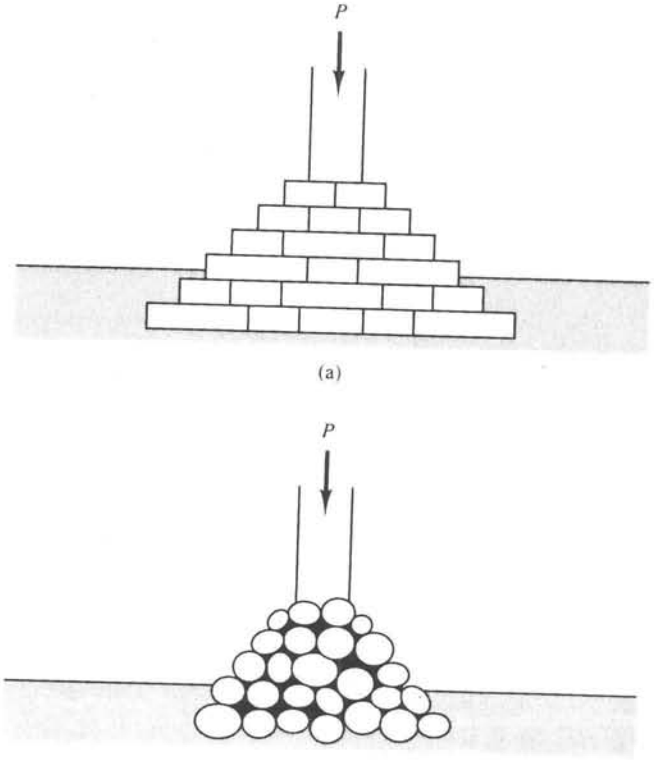

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Figure 5.3 (a) Dimension-stone footing, and (b) Rubble-stone footing.

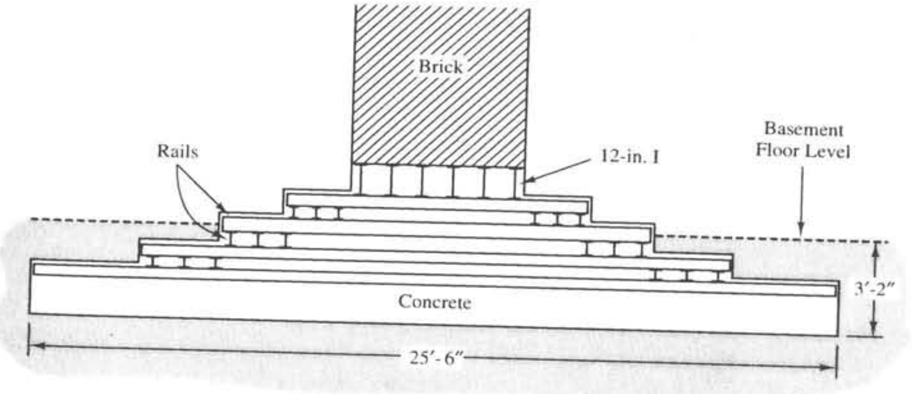

Figure 5.4 Steel grillage footing made from railroad tracks, Montauk Block Building, Chicago, 1882. The concrete that surrounded the steel was for corrosion protection only (Peck, 1948).

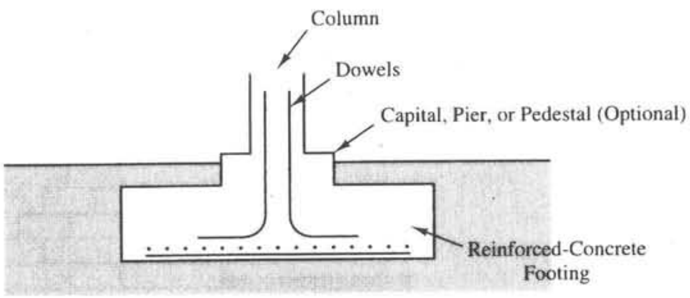

Figure 5.5 Reinforced concrete spread footing.

9-mm (3/8 in) diameter steel probe. If the soil conditions are not as anticipated, especially if they are too soft, it may be necessary to revise the design accordingly.

Most soils have sufficient strength to stand vertically until it is time to pour the concrete. This procedure of pouring the concrete directly against the soil is known as pouring a *neat footing*, as shown in Figure 5.7a. Sometimes shallow wooden forms are placed above the excavation, as shown in Figure 5.7b, so the top of the footing is at the proper elevation. If the soil will not stand vertically, such as with clean sands or gravels, it is necessary to make a larger excavation and build a full-depth wooden form, as shown in Figure 5.7c. This is known as a *formed footing*.

Once the excavation has been made and cleaned, and the forms (if needed) are in place, the contractor places the reinforcing steel. If the footing will support a wood or steel structure, threaded *anchor bolts* and/or steel brackets are embedded into the con-

Figure 5.6 A backhoe making an excavation for a spread footing.

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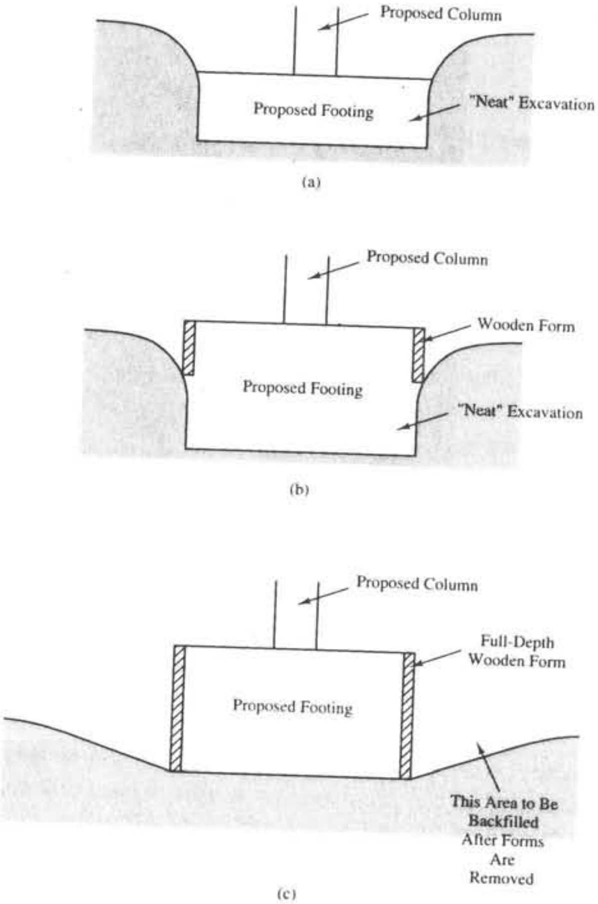

Figure 5.7 Methods of placing concrete in footings: (a) Neat excavation, (b) Neat excavation with wooden forms at the top, (c) Formed footing with full-depth wooden forms.

crete. For concrete or masonry structures, short steel rebars, called *dowels* are placed such that they extend above the completed footing, thus providing for a lap splice with the column or wall steel. Chapter 9 discusses these connections in more detail. Finally, the concrete is placed and, once it has cured, the forms are removed. Figure 5.8 shows a completed spread footing.

5.2 MATS

The second type of shallow foundation is a *mat foundation*, as shown in Figure 5.9. A mat is essentially a very large spread footing that usually encompasses the entire footprint of the structure. They also are known as *raft foundations*. They are always made of reinforced concrete.

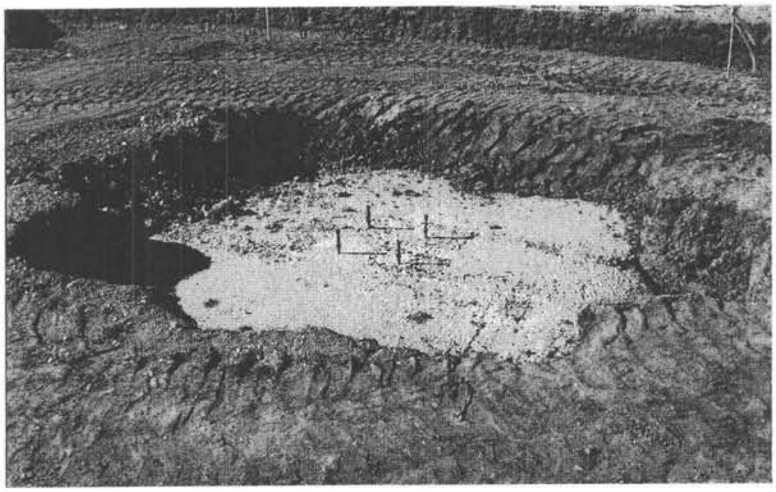

Figure 5.8 A completed spread footing. The four bolts extending out of the footing will be connected to the base plate of a steel column.

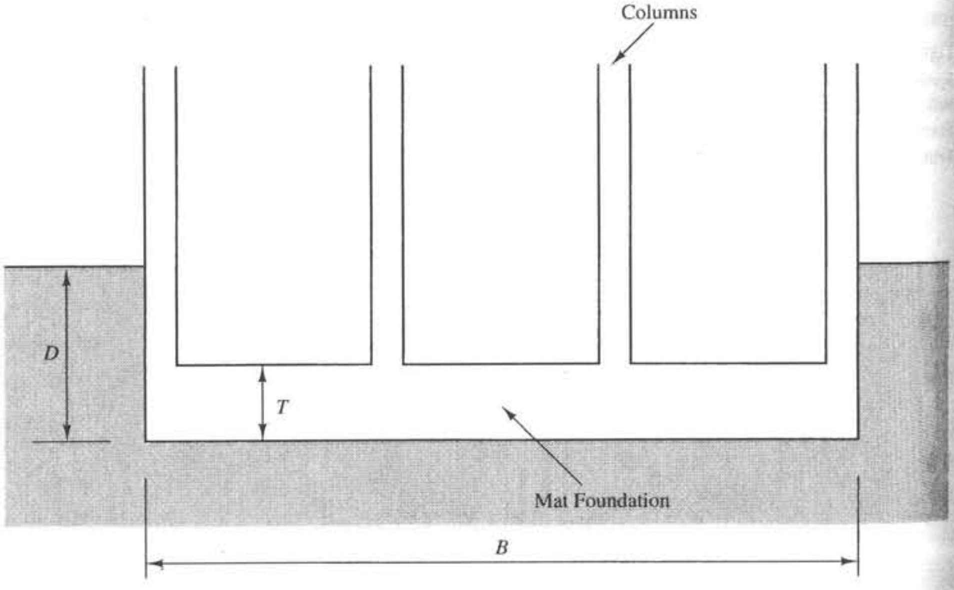

Figure 5.9 A mat foundation.

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5.3 BEARING P

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Foundation engineers often consider mats when dealing with any of the following conditions:

- The structural loads are so high or the soil conditions so poor that spread footings would be exceptionally large. As a general rule of thumb, if spread footings would cover more than 50 percent of the building footprint area, a mat or some type of deep foundation will usually be more economical.
- The soil is very erratic and prone to excessive differential settlements. The structural continuity and flexural strength of a mat will bridge over these irregularities. The same is true of mats on highly expansive soils prone to differential heaves.
- The structural loads are erratic, and thus increase the likelihood of excessive differential settlements. Again, the structural continuity and flexural strength of the mat will absorb these irregularities.
- The lateral loads are not uniformly distributed through the structure and thus may cause differential horizontal movements in spread footings or pile caps. The continuity of a mat will resist such movements.
- The uplift loads are larger than spread footings can accommodate. The greater weight and continuity of a mat may provide sufficient resistance.
- The bottom of the structure is located below the groundwater table, so waterproofing is an important concern. Because mats are monolithic, they are much easier to waterproof. The weight of the mat also helps resist hydrostatic uplift forces from the groundwater.

Many buildings are supported on mat foundations, as are silos, chimneys, and other types of tower structures. Mats are also used to support storage tanks and large machines. The seventy five story Texas Commerce Tower in Houston is one of the largest mat-supported structures in the world. Its mat is 3 m (9 ft 9 in) thick and is bottomed 19.2 m (63 ft) below the street level.

5.3 BEARING PRESSURE

The most fundamental parameter that defines the interface between a shallow foundation and the soil that supports it is the *bearing pressure*. This is the contact force per unit area along the bottom of the foundation. Engineers recognized the importance of bearing pressure during the nineteenth century, thus forming the basis for later developments in bearing capacity and settlement theories.

Distribution of Bearing Pressure

Although the integral of the bearing pressure across the base area of a shallow foundation must be equal to the force acting between the foundation and the soil, this pressure is not necessarily distributed evenly. Analytical studies and field measurements (Schultze, 1961; Dempsey and Li, 1989; and others) indicate that the actual distribution depends on several factors, including the following:

- Eccentricity, if any, of the applied load
- Magnitude of the applied moment, if any
- Structural rigidity of the foundation
- Stress-strain properties of the soil
- Roughness of the bottom of the foundation

Figure 5.10 shows the distribution of bearing pressure along the base of shallow foundations subjected to concentric vertical loads. Perfectly flexible foundations bend as necessary to maintain a uniform bearing pressure, as shown in Figures 5.10a and 5.10b, whereas perfectly rigid foundations settle uniformly but have variations in the bearing pressure, as shown in Figures 5.10c and 5.10d.

Real spread footings are close to being perfectly rigid, so the bearing pressure distribution is not uniform. However, bearing capacity and settlement analyses based on such a distribution would be very complex, so it is customary to assume that the pressure beneath concentric vertical loads is uniform across the base of the footing, as shown in Figure 5.10e. The error introduced by this simplification is not significant.

Mat foundations have a much smaller thickness-to-width ratio, and thus are more flexible than spread footings. In addition, we evaluate the flexural stresses in mats more carefully and develop more detailed reinforcing steel layouts. Therefore, we conduct more detailed analyses to determine the distribution of bearing pressure on mats. Chapter 10 discusses these analyses.

When analyzing shallow foundations, it is customary and reasonable to neglect any sliding friction along the sides of the footing and assume that the entire load is transmitted to the bottom. This is an important analytical difference between shallow and deep foundations, and will be explored in more detail in Chapter 11.

Computation of Bearing Pressure

The *bearing pressure* (or *gross bearing pressure*) along the bottom of a shallow foundation is:

$$\boxed{q = \frac{P + W_f}{A} - u_D} \tag{5.1}$$

Where:

q = bearing pressure

P = vertical column load

W_f = weight of foundation, including the weight of soil above the foundation, if any on depends on

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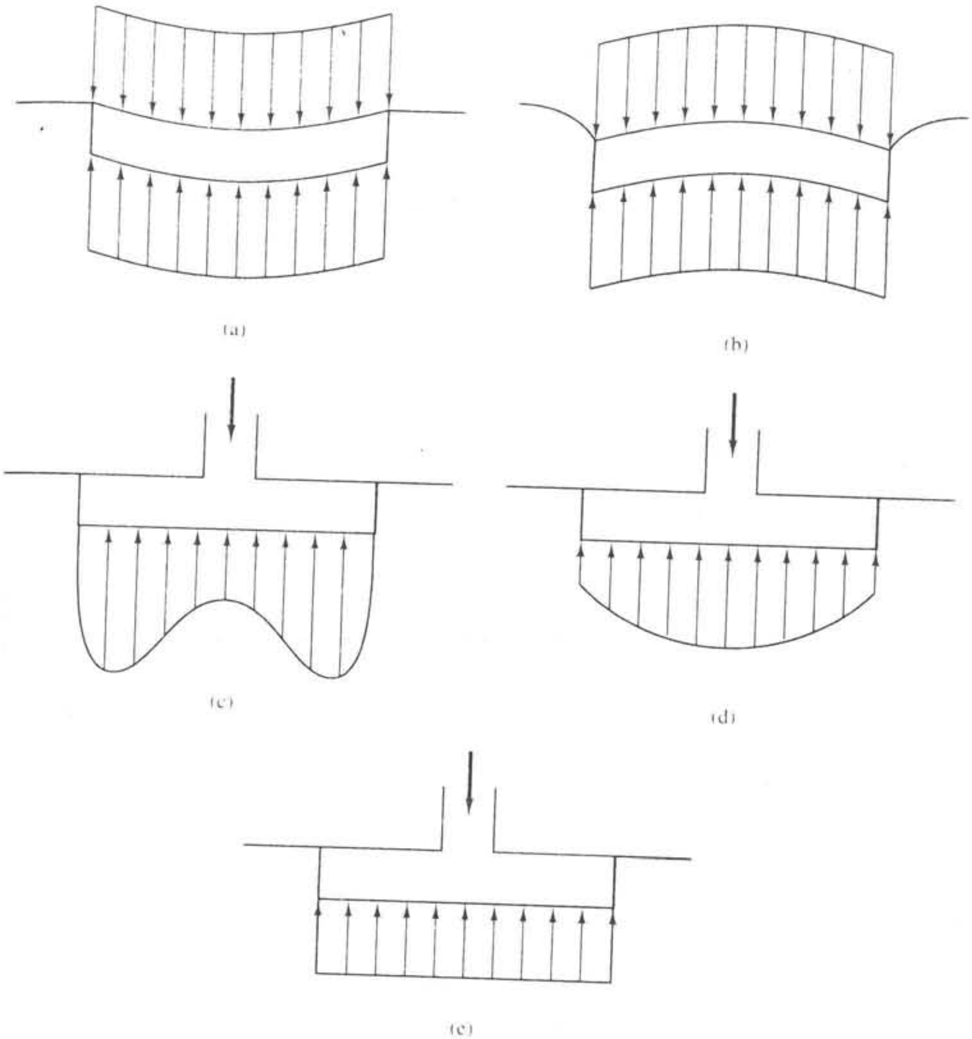
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Figure 5.10 Distribution of bearing pressure along the base of shallow foundations subjected to concentric vertical loads: (a) flexible foundation on clay, (b) flexible foundation on sand, (c) rigid foundation on clay, (d) rigid foundation on sand, and (e) simplified distribution (after Taylor, 1948).

A = base area of foundation (B^2 for square foundations or BL for rectangular foundations)

u_D = pore water pressure at bottom of foundation (i.e., at a depth D below the ground surface).

Virtually all shallow foundations are made of reinforced concrete, so W_f is computed using a unit weight for concrete of 150 lb/ft^3 or 23.6 kN/m^3.

The pore water pressure term accounts for uplift pressures (buoyancy forces) that are present if a portion of the foundation is below the groundwater table. If the groundwater table is at a depth greater than D, then set $u_D = 0$.

For continuous footings, we express the applied loads as a force per unit length, such as 2000 kN/m. For ease of computation, we identify this unit length as b, which is usually 1 m or 1 ft as shown in Figure 5.11. Thus, the load is expressed using the variable P/b, and the weight using W_f/b.

The bearing pressures for continuous footings is then:

$$\boxed{q = \frac{P/b + W_f/b}{B} - u_D} \tag{5.2}$$

Example 5.1

The 5-ft square footing shown in Figure 5.12 supports a column load of 100 k. Compute the bearing pressure.

Solution

Use 150 lb/ft^3 for the unit weight of concrete, and compute W_f as if the concrete extends from the ground surface to a depth D (this is conservative when the footing is covered with soil because soil has a lower unit weight, but the error introduced is small).

$$W_f = (5\text{ ft})(5\text{ ft})(4\text{ ft})(150\text{ lb/ft}^3) = 15{,}000\text{ lb}$$

$$A = (5\text{ ft})(5\text{ ft}) = 25\text{ ft}^2$$

$$u_D = \gamma_w z_w = (62.4\text{ lb/ft}^3)(4\text{ ft} - 3\text{ ft}) = 62\text{ lb/ft}^2$$

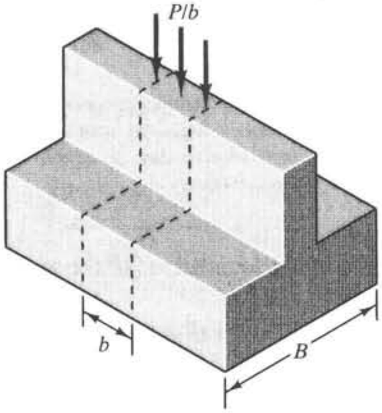

Figure 5.11 Definitions for loads on continuous footings.

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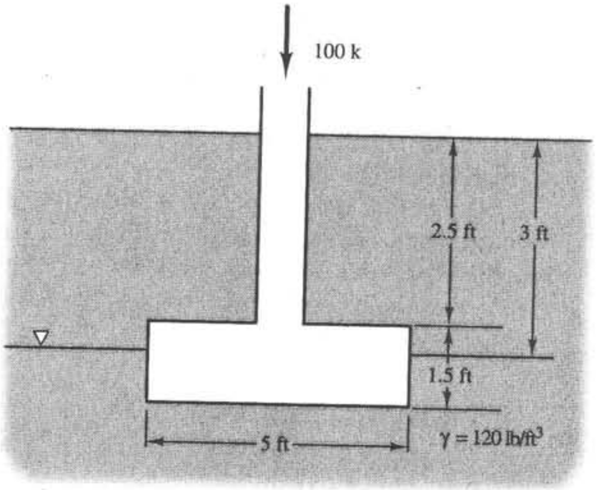

Figure 5.12 Spread footing for Example 5.1.

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\begin{aligned}
q &= \frac{P + W_f}{A} - u_D \\
&= \frac{100{,}000\ \mathrm{lb} + 15{,}000\ \mathrm{lb}}{25\ \mathrm{ft}^2} - 62\ \mathrm{lb/ft^2} \\
&= \mathbf{4538\ lb/ft^2} \qquad \Leftarrow \textit{Answer}
\end{aligned}
$$

Example 5.2

A 0.70-m wide continuous footing supports a wall load of 110 kN/m. The bottom of this footing is at a depth of 0.50 m below the adjacent ground surface and the soil has a unit weight of 17.5 kN/m^3. The groundwater table is at a depth of 10 m below the ground surface. Compute the bearing pressure.

Solution

Use 23.6 kN/m^3 for the unit weight of concrete.

$$
\begin{aligned}
W_f/b &= (0.70\ \mathrm{m})(0.50\ \mathrm{m})(23.6\ \mathrm{kN/m^3}) = 8\ \mathrm{kN/m} \\
u_D &= 0 \\
q &= \frac{P/b + W_f/b}{B} - u_D = \frac{110\ \mathrm{kN/m} + 8\ \mathrm{kN/m}}{0.70\ \mathrm{m}} - 0 = \mathbf{169\ kPa} \qquad \Leftarrow \textit{Answer}
\end{aligned}
$$

Net Bearing Pressure

An alternative way to define bearing pressure is the *net bearing pressure*, q', which is the difference between the gross bearing pressure, q, and the initial vertical effective stress, σ_{z0}', at depth D. In other words, q' is a measure of the increase in vertical effective stress at depth D (Coduto, 1994).

Use of the net bearing pressure simplifies some computations, especially those associated with settlement of spread footings, but it makes others more complex. Some engineers prefer this method, while others prefer to use the gross bearing pressure. Therefore, it is important to understand which definition is being used. In this book we will use only the gross bearing pressure for designing shallow foundations because:

- This is the most commonly used method.
- The presumptive bearing pressures presented in building codes use this method [IBC 1805.4.1.1].
- It is conceptually easier.
- It simplifies the analysis of floating foundations.

Floating Foundations

Mat foundations are often placed in deep excavations, as shown in Figure 5.13. In addition to providing underground space, such as for subterranean parking, this design decreases the bearing pressure because the weight of the foundation is substantially less than the weight of the excavated soil. In other words, the weight of the structure and the foundation is partially offset by the removal of soil from the excavation. This reduction in q significantly reduces the settlement. Such designs are called *floating foundations*, and they are discussed in more detail in Chapter 18.

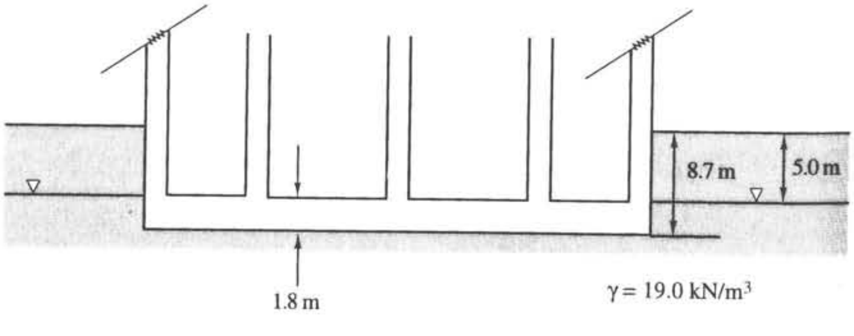

Figure 5.13 A floating foundation.

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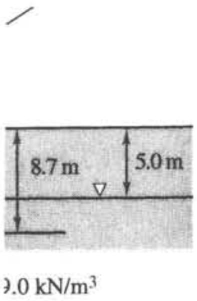

Example 5.3

The mat foundation in Figure 5.13 is to be 50 m wide, 70 m long, and 1.8 m thick. The sum of the column and wall loads is 805 MN. Compute the average bearing pressure, then compare it with the initial vertical effective stress in the soil immediately below the mat.

Solution

Use $\gamma_{conc} = 23.6\ \text{kN/m}^3$

$$W_f = (50\ \text{m})(70\ \text{m})(1.8\ \text{m})(23.6\ \text{kN/m}^3) = 149{,}000\ \text{kN}$$

$$u_D = \gamma_w z_{wD} = (9.8\ \text{kN/m}^3)(8.7\ \text{m} - 5.0\ \text{m}) = 36\ \text{kPa}$$

$$A = (50\ \text{m})(70\ \text{m}) = 3500\ \text{m}^2$$

$$q = \frac{P + W_f}{A} - u_D$$

$$= \frac{805{,}000\ \text{kN} + 149{,}000\ \text{kN}}{3500\ \text{m}^2} - 36\ \text{kPa}$$

$$= \mathbf{237\ kPa} \quad \Leftarrow \textit{Answer}$$

Note: Mat foundations are neither perfectly flexible nor perfectly rigid. Thus, the actual bearing pressure will vary across the base area. This computation produced the average value.

The vertical effective stress at a depth D before construction was:

$$\sigma'_{zD} = \Sigma\,\gamma H - u = (19.0\ \text{kN/m}^3)(8.7\ \text{m}) - 36\ \text{kPa} = \mathbf{129\ kPa} \qquad \Leftarrow \textit{Answer}$$

Thus, the net result of making the excavation and constructing the building will result in a 237 − 129 = 108 kPa increase in the vertical effective stress immediately below the mat. ⇐ *Answer*

Foundations with Eccentric or Moment Loads

Most foundations are built so the vertical load acts through the centroid, thus producing a fairly uniform distribution of bearing pressure. However, sometimes it becomes necessary to accommodate loads that act through other points, as shown in Figure 5.14a. These are called *eccentric loads*, and they produce a non-uniform bearing pressure distribution. The eccentricity, e, of the bearing pressure is equal to:

$$\boxed{e = \frac{Pe_1}{P + W_f}} \tag{5.3}$$

or, for continuous footings:

$$\boxed{e = \frac{(P/b)\,e_1}{P/b + W_f/b}} \tag{5.4}$$