# 11

# Drilled Shaft Foundations

## 11–1 INTRODUCTION

The terms *drilled caisson*, *pier*, and *drilled shaft* are used interchangeably by engineers to denote a cylindrical foundation to transfer structure load to bedrock or a hard stratum. A drilled shaft is a type of deep foundation that is constructed in place by drilling a hole into the soil, often to bedrock or a hard stratum, and subsequently placing concrete in the hole. The concrete may or may not contain reinforcing steel. Some drilled shafts have straight sides throughout; others are constructed with enlarged bases (see Figure 11–1). The enlarged base area results in a decreased contact pressure (soil pressure) at the shaft's base.

The purpose of a drilled shaft is to transmit a structural load to the shaft's base, which may be bedrock or another hard stratum. In essence, a drilled shaft is primarily a compression member with an axial load applied at its top, a reaction at its bottom, and lateral support along its sides.

Drilled shafts are constructed by using auger drill equipment to form the hole in the soil. Soil is removed from the hole during drilling, in contrast to the driven pile, which only compresses soil aside. Thus, such problems as shifting and lifting of driven piles do not occur with drilled shafts. In some cases, such as in dry, strong cohesive soil, the hole may be drilled dry and without any side support. In this case, concrete placed in the hole makes direct contact with the soil forming the sides of the hole. If cohesionless soil and/or groundwater is encountered, a bentonite slurry may be introduced during drilling to prevent the soil from caving in. (Protective casing may also be used to prevent a cave-in.) In this case, concrete is placed from the bottom up so as to displace the slurry. If a casing is used, it is slowly removed as concrete is placed, and the operator makes sure that soil does not fall into the excavated hole and mix with the concrete.

Drilled shafts are a popular type of deep foundation for several reasons. Drilling equipment is relatively light and easy to use compared to pile-driving equipment,

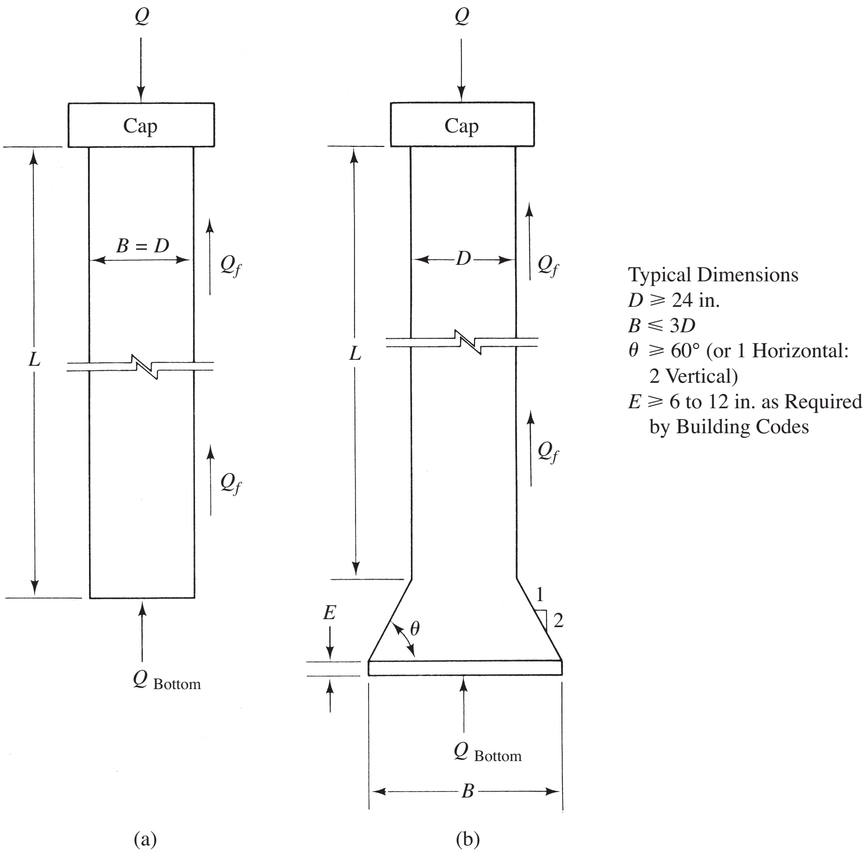


**FIGURE 11–1** Drilled shafts: (a) straight-shaft; (b) belled.

resulting perhaps in lower construction costs. Also, drilling equipment is much quieter than pile drivers and does not cause massive ground vibrations, giving drilled shafts the advantage in areas near schools and hospitals. Lesser ground vibrations result in less adverse effects on adjacent piles. Another advantage of drilled shafts is that they can be drilled to greater depths through very dense soil and gravel. Furthermore, drilled shafts do not displace soil as they are drilled, thereby reducing or even eliminating the problem of unwanted lifting of piles. Finally, drilled shafts afford better (visual) inspection and testing of the subsoil encountered.

## 11–2 BEARING CAPACITY OF DRILLED SHAFTS

As with a pile, a drilled shaft gets its supporting power from two sources–skin friction and bearing capacity at the shaft's base. Thus, at failure, the load on a drilled shaft may be expressed (as for a pile) by Eq. (10-1), which is reproduced as follows:

$$Q_{\text{ultimate}} = Q_{\text{friction}} + Q_{\text{tip}} \tag{10–1}$$

To evaluate bearing capacity, it is helpful to consider separately drilled shafts in cohesive soils and in cohesionless soils.

## Drilled Shafts in Cohesive Soils

The analysis of drilled shafts in cohesive soils is similar to that of piles in that the shaft's total bearing capacity results from resistance provided by its end bearing and skin friction, in accordance with Eq. (10–1). The methods for evaluating the terms in the equation differ, however. The design criteria that follow are based on empirical methods developed by the U.S. Department of Transportation, Federal Highway Administration (O'Neil and Reese, 1999).

For drilled shafts in cohesive soils, the $Q_{\text{friction}}$ term in Eq. (10–1) represents the capacity or resistance developed along the shaft; it can be evaluated by multiplying the shaft resistance, $f_s$, by the shaft surface area (i.e., $f_s A_{\text{surface}}$). The $Q_{\text{tip}}$ term in Eq. (10–1) represents the downward capacity developed by the base; it can be evaluated by multiplying the end bearing, $q_b$, by the area of the base ($q_b A_{\text{base}}$). Hence, Eq. (10–1) becomes

$$Q_{\text{ultimate}} = f_s A_{\text{surface}} + q_b A_{\text{base}} \tag{11–1}$$

The value of $f_s$ can be obtained from

$$f_s = \alpha_z c_{uz} \tag{11–2}$$

where $\alpha_z$ is an empirical adhesion factor for soil at depth $z$ and $c_{uz}$ is the undrained shear strength at depth $z$. $\alpha_z$ is zero for the top 1.5 m (5 ft) section for both straight shafts and belled shafts and for the bottom section one diameter height from the base of a straight shaft or one diameter height from the top of a belled base (see Figure 11–2). For $c_u/p_a$ less than 1.5, $\alpha_z$ is 0.55. [$c_u$ is the undrained shear strength as

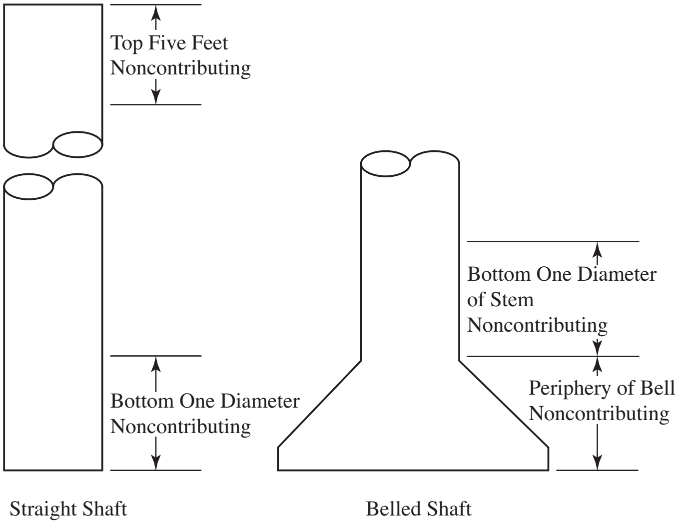


**FIGURE 11–2** Exclusion zones for computation of side resistance for drilled shafts in cohesive soils. *Source:* M. W. O'Neil and L. C. Reese, 1999.

indicated by unconsolidated undrained (UU) triaxial compression tests and $p_a$ is atmospheric pressure = 100 kPa = 2 ksf.] For $c_u/p_a$ between 1.5 and 2.5, $\alpha_z$ is determined by

$$\alpha_z = 0.55 - 0.1[(c_u/p_a) - 1.5] \tag{11–3}$$

The value of $q_b$ in Eq. (11–1) for a depth greater than three times the base diameter can be obtained from

$$q_b = N_c c_u \tag{11–4}$$

where $c_u$ is the average undrained shear strength of the soil between the base and two base diameters beneath the base, and $N_c$ is 9 for $c_u$ greater than 96 kPa or 2 ksf, $N_c$ is 8 for $c_u$ equal to 48 kPa or 1 ksf, and $N_c$ is 6.5 for $c_u$ equal to 24 kPa or 0.5 ksf. For intermediate values of $c_u$, $N_c$ is determined by linear interpolation.

For depths less than three times the base diameter, the value of $q_b$ can be obtained from

$$q_b = (2/3)[1 + (1/6)(\text{depth/base diameter})]N_c c_u \tag{11–5}$$

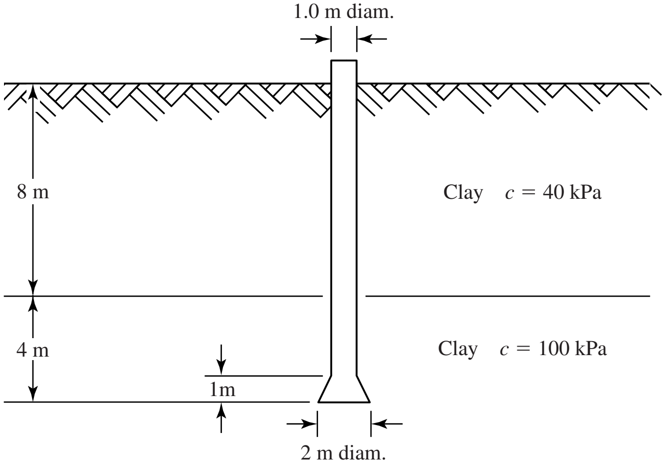
When using the preceding formulation for drilled shafts in cohesive soils, a factor of safety of 2.5 is commonly applied to the computed total (ultimate) capacity to find allowable capacity.

### EXAMPLE 11–1

*Given*

1. A 1-m diameter drilled shaft is constructed in clay with a 2.00-m base.
2. Soil conditions and a sketch of the foundation are shown in Figure 11–3.
3. The excavation is drilled dry.

**FIGURE 11–3**



*Required*

Maximum allowable axial design load on the foundation.

**Solution**

From Eq. (11–1),

$$Q_{\text{ultimate}} = f_s A_{\text{surface}} + q_b A_{\text{base}} \qquad \textbf{(11–1)}$$

$$f_s = \alpha_z c_{uz} \qquad \textbf{(11–2)}$$

For 0- to 8-m depth, $c_u/p_a = (40\ \text{kN/m}^2)/(100\ \text{kN/m}^2) = 0.40$. Since 0.40 is less than 1.5, $\alpha_z$ is 0.55. For 8- to 12-m depth, $c_u/p_a = 1.00$ and $\alpha_z$ is 0.55.

$$\begin{aligned}
f_{\text{shaft}_1} &= (0.55)(40\ \text{kN/m}^2) = 22\ \text{kN/m}^2 \\
f_{\text{shaft}_2} &= (0.55)(100\ \text{kN/m}^2) = 55\ \text{kN/m}^2 \\
A_{\text{shaft}_1} &= (\pi \times 1\ \text{m})(8\ \text{m} - 1.5\ \text{m}) = 20.4\ \text{m}^2 \\
A_{\text{shaft}_2} &= (\pi \times 1\ \text{m})(4\ \text{m} - 1\ \text{m} - 1\ \text{m}) = 6.28\ \text{m}^2
\end{aligned}$$

Since the depth (12 m) is greater than three times the base diameter ($3 \times 2\ \text{m} = 6\ \text{m}$),

$$q_b = N_c c_u \qquad \textbf{(11–4)}$$

Since $c_u$ (100 kPa) is greater than 96 kPa, $N_c$ is 9.

$$\begin{aligned}
q_b &= (9)(100\ \text{kN/m}^2) = 900\ \text{kN/m}^2 \\
A_{\text{base}} &= (\pi)(2\ \text{m})^2/4 = 3.14\ \text{m}^2
\end{aligned}$$

Substituting into Eq. (11–1),

$$\begin{aligned}
Q_{\text{ultimate}} &= (22\ \text{kN/m}^2)(20.4\ \text{m}^2) + (55\ \text{kN/m}^2)(6.28\ \text{m}^2) \\
&\quad + (900\ \text{kN/m}^2)(3.14\ \text{m}^2) \\
&= 3620\ \text{kN} \\
Q_{\text{allowable}} &= Q_{\text{ultimate}}/2.5 = (3620\ \text{kN})/2.5 = 1448\ \text{kN}
\end{aligned}$$

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## Drilled Shafts in Cohesionless Soils

The analysis of drilled shafts in cohesionless soils (sands and gravels) is similar to that of drilled shafts in cohesive soils, in accordance with Eq. (11–1), differing only in the methods for evaluating the terms in the equation. Again, the design criteria that follow are based on empirical methods developed by the U.S. Department of Transportation, Federal Highway Administration (O'Neil and Reeves, 1999).

For drilled shafts in cohesionless soils, the value of $f_s$ in Eq. (11–1) can be obtained from

$$f_s = \beta\, p_v \qquad \textbf{(11–6)}$$

where $p_v$ is the effective vertical (overburden) pressure. The value of $\beta$ depends on the standard penetration test (SPT) $N$-value (see Section 3–5).

For drilled shafts in sand or sand-gravel and an $N$-value greater than or equal to 15, $\beta$ between 0.25 and 1.20, and $f_s$ less than 4.0 ksf or 200 kPa,

$$\beta = 1.5 - n(z)^{0.5} \tag{11–7}$$

For an $N$-value less than 15,

$$\beta = (N\text{-value}/15)[1.5 - n(z)^{0.5}] \tag{11–8}$$

In Eqs. (11–7) and (11–8), $n$ is 0.135 when $z$ is in feet and 0.245 when $z$ is in meters, and $z$ is the height from ground surface to mid-height of a given layer.

For drilled shafts in sand-gravel or gravel and an $N$-value greater than 15, $\beta$ between 0.25 and 1.20, and $f_s$ less than 4.0 ksf or 200 kPa,

$$\beta = 2.0 - 0.15(z)^{0.75} \tag{11–9}$$

In Eq. (11–9) $z$ is in meters.

The value of $q_b$ in Eq. (11–1) for bases in both sand and sand-gravel for SPT $N$-values less than 50 can be obtained from

$$q_b(\text{kPa}) = 57.5\ N\text{-value} \quad (\text{For } q_{\max} < 2.9\text{ MPa}) \tag{11–10}$$

or

$$q_b(\text{ksf}) = 1.20\ N\text{-value} \quad (\text{For } q_{\max} < 60\text{ ksf}) \tag{11–11}$$

For $N$-values greater than 50,

$$q_b = 0.59[N\text{-value}(p_a/p_{vb})]^{0.8} \tag{11–12}$$

where $p_a$ is atmospheric pressure $= 100$ kPa $= 2$ ksf

$P_{vb} =$ effective vertical pressure at base elevation

As with drilled shafts in cohesive soils, a factor of safety of 2.5 is commonly applied to the computed total (ultimate) capacity to find allowable capacity for drilled shafts in cohesionless soils.

## EXAMPLE 11–2

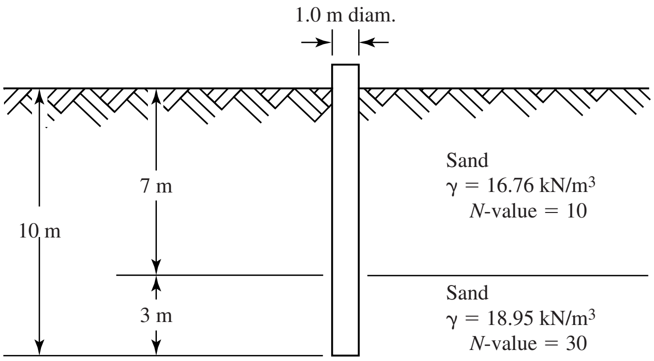
*Given*

1. A 1-m diameter straight-side drilled shaft is constructed in sand.
2. Soil conditions and a sketch of the foundation are shown in Figure 11–4.
3. The excavation is drilled dry.

*Required*

Maximum allowable axial design load on the foundation.

**FIGURE 11–4**



**Solution**

From Eq. (11–1),

$$Q_{\text{ultimate}} = f_s A_{\text{surface}} + q_b A_{\text{base}} \quad \textbf{(11–1)}$$

$$f_s = \beta p_v \quad \textbf{(11–6)}$$

For 0 to 7 m depth, since the *N*-value (10) is less than 15,

$$\beta = (N\text{-value}/15)[1.5 - n(z)^{0.5}] \quad \textbf{(11–8)}$$

$$\beta = (10/15)[1.5 - (0.245)(7\ \text{m}/2)^{0.5}] = 0.69$$

$$f_{\text{shaft}_1} = (0.69)[(16.76\ \text{kN/m}^3)(7\ \text{m}/2)] = 40.47\ \text{kN/m}^2$$

$$A_{\text{shaft}_1} = (\pi \times 1\ \text{m} \times 7\ \text{m}) = 22.0\ \text{m}^2$$

For 7 m to 10 m depth, since the *N*-value (30) is greater than 15,

$$\beta = 1.5 - n(z)^{0.5} \quad \textbf{(11–7)}$$

$$\beta = 1.5 - (0.245)(7\ \text{m} + 3\ \text{m}/2)^{0.5} = 0.79$$

$$f_{\text{shaft}_2} = (0.79)[(16.76\ \text{kN/m}^3)(7\ \text{m}) + (18.95\ \text{kN/m}^3)(3\ \text{m}/2)] = 115.1\ \text{kN/m}^2$$

$$A_{\text{shaft}_2} = (\pi \times 1\ \text{m} \times 3\ \text{m}) = 9.42\ \text{m}^2$$

Since the *N*-value (30) is less than 50 and assuming $q_{\text{max}}$ is less than 2.9 MPa,

$$q_b\ (\text{kPa}) = 57.5\ N\text{-value} \quad \textbf{(11–10)}$$

$$q_b = (57.5)(30) = 1725\ \text{kN/m}^2 \quad (< 2.9\ \text{MPa; O.K.})$$

$$A_{\text{base}} = (\pi)(1\ \text{m})^2/4 = 0.7854\ \text{m}^2$$

Substituting into Eq. (11–1),

$$Q_{\text{ultimate}} = (40.47\ \text{kN/m}^2)(22.0\ \text{m}^2) + (115.1\ \text{kN/m}^2)(9.42\ \text{m}^2) + (1725\ \text{kN/m}^2)(0.7854\ \text{m}^2)$$

$$Q_{\text{ultimate}} = 3330\ \text{kN}$$

$$Q_{\text{allowable}} = 3330\ \text{kN}/2.5 = 1332\ \text{kN}$$

## 11–3 SETTLEMENT OF DRILLED SHAFTS

*Settlement of drilled shafts in clay* depends largely on the load history of the clay. This is similar to settlement of footings. Because drilled shafts are uneconomical in normally consolidated clays and settlement thereon is excessive, drilled shafts should be used only in overconsolidated clays. Long-term settlement analysis in clay soils can be performed by using consolidation theory and assuming the drilled shaft's bottom to be a footing (Terzaghi and Peck, 1967).

*Settlement of drilled shafts in sand* "at any depth is likely to be about one-half the settlement of an equally loaded footing covering the same area on sand of the same characteristics" (Terzaghi and Peck, 1967). Generally, such settlement will not be detrimental because the shaft will normally be found on dense sand and settlement will be small. Settlement in sand can be computed by using the procedures given in Chapter 7 for footings on sand. It should be kept in mind, however, that settlement of the shaft should be about one-half the settlement computed for the equivalent footing.

*Settlement of drilled shafts on bedrock* should be very small if the rock is dry. However, water may be found at the bottom of some shafts, and it can cause some settlement—sometimes large settlement if soft rocks disintegrate upon soaking. Therefore, it is desirable that the water be pumped out and the shaft thoroughly cleaned during the last stage of drilling (Teng, 1962).

## 11–4 CONSTRUCTION AND INSPECTION OF DRILLED SHAFTS

Construction of drilled shafts consists for the most part of excavation of soil and placement of concrete (perhaps with reinforcing steel). As related in Section 11–1, drilled shafts generally are excavated by using an auger drill or another type of drilling equipment. An auger is a screwlike device (see Figure 11–5) that is attached to a shaft and rotated under power. The rotating action digs into the soil and raises it to the surface. If a caisson is to have a bell at the bottom, the bell is made by using a reamer.

While excavation is being done, soil is exposed in the walls. Soil at the shaft's bottom and exposed in the walls should be examined (and records kept) whenever possible to check the adequacy of the supporting soil at the shaft's bottom and to determine the depth to, and thickness of, different soil strata. Sometimes a person may be able to descend in the shaft for inspection.

After excavation of the soil, the concrete must be of acceptable quality and properly placed. It is preferable that concrete not strike the sides of the hole as it is being poured. A casing (see Figure 11–6), if used, is generally removed as the concrete

**FIGURE 11–5** Large auger used in drilled shaft construction.

**FIGURE 11–6** Steel casing used in drilled shaft construction.

**FIGURE 11–7** Reinforcing steel used in drilled shaft construction.

is poured. Normally, only the concrete in the upper part of the shaft is vibrated. It is always best to pour concrete in the dry, but if water is present, concrete can be placed underwater. Installation of reinforcing steel (see Figure 11–7) (if specified) should be carefully checked prior to placing concrete.

One final aspect of the overall construction process is inspection. A drilled shaft should be inspected for accuracy of the shaft's alignment and dimensions, for bearing capacity of the soil at the shaft's bottom, for proper placement of reinforcing steel

**FIGURE 11–8** Setup for a shaft field inspection.

and concrete, and so on. Normally, the owner's representative should be present during construction of the shaft to ensure that it is done properly and according to specifications. Figure 11–8 shows a setup for a shaft field inspection.

## 11–5 PROBLEMS

**11–1.** A plain-concrete drilled shaft is to be constructed in a clayey soil. The shaft's diameter is 4 ft, and the belled bottom is 8 ft in diameter. The drilled shaft extends to a total depth of 36 ft. Soil conditions are illustrated in Figure 11–9. Compute the maximum allowable axial design load on the foundation.

**FIGURE 11–9**

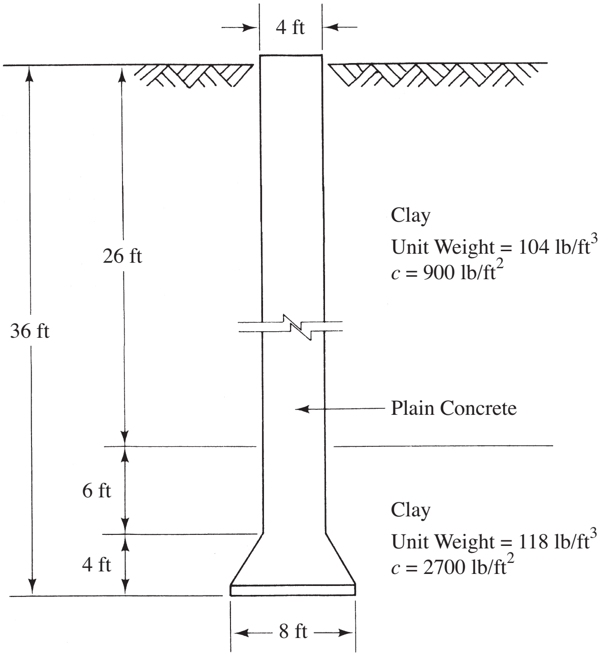
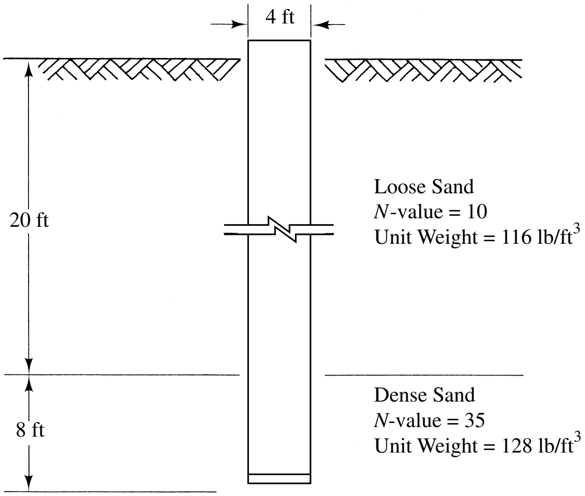


**FIGURE 11–10**



**11–2.** A drilled shaft 4 ft in diameter and supported by a straight shaft is to be constructed of plain concrete in sand. Soil conditions and a sketch of the shaft are shown in Figure 11–10. Compute the maximum allowable axial design load on the foundation.