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Module 9

Lecture 35

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INTRODUCTION

The terms caisson, pier, drilled shaft, and drilled pier are often used interchangeably in foundation engineering; all refer to a cast-in-place pile generally having a diameter of about 2.5 ft (≈ 750 mm) or more, with or without steel reinforcement and with or without an enlarged bottom. Sometimes the diameter can be as small as 1 ft (≈ 305 mm).

To avoid confusion, we use the term drilled shaft for a hole drilled or excavated to the bottom of a structure’s foundation and then filled with concrete. Depending on the soil conditions, casings or laggings (boards or sheet piles) may be used to prevent the soil around the hole from caving in during construction. The diameter of the shaft is usually large enough for a person to enter for inspection.

The use of drilled-shaft foundations has several advantages:

1. A single drilled shaft may be used instead of a group of piles and the pile cap.
2. Construction drilled shafts in deposits of dense sand and gravel is easier than driving piles.
3. Drilled shafts may be constructed before completion of grading operations.
4. When piles are driven by a hammer, the ground vibration may cause damage to nearby structures, which the use of drilled shafts avoids.
5. Piles driven into clay soils may produce ground heaving and because previously driven piles to move laterally, which does not occur during construction of drilled shafts.
6. There is no hammer noise during the construction of drilled shafts, as there is during pile driving.
7. Because the base of a drilled shaft can be enlarged, it provides great resistance to the uplifting load.
8. The surface over which the base of the drilled shaft is constructed can be visually inspected.
9. Construction of drilled shafts generally utilizes mobile equipment, which, under proper soil conditions, may prove to be more economical than methods of constructing pile foundations.
10. Drilled shafts have high resistance to lateral loads.

DRILLED SHAFTS

TYPES OF DRILLED SHAFTS

Drilled shafts are classified according to the ways in which they are designed to transfer the structural load to the substratum. Figure 9.1a shows a drilled straight shaft. It extends through the upper layer(s) of poor soil, and its tip rests on a strong load-bearing soil layer or rock. The shaft can be cased with steel shell or pipe when required (as in the case of
cased, cast-in-place concrete piles; figure 9.4 from chapter 9). For such shafts, the resistance to the applied load may develop from end bearing and also from side friction at the shaft perimeter and soil interface.

![Diagram of drilled shaft types](image)

Figure 9.1 Types of drilled shaft: (a) straight-shaft; (b) and (c) belled shaft; (d) straight-shaft socketed into rock

A belled shaft (figure 9.1b and c) consists of a straight shaft with a bell at the bottom, which rests on good bearing soil. The bell can be constructed in the shape of a dome (figure 9.1b), or it can be angled (figure 9.1c). For angled bells, the underreaming tools commercially available can make 30° to 45° angles with the vertical. For the majority of drilled shafts constructed in the United States, the entire load-carrying capacity is assigned to the end bearing only. However, under certain circumstances, the end-bearing capacity and the side friction are taken into account. In Europe, both the side frictional resistance and the end-bearing capacity are always taken into account.

Straight shafts can also be extended into an underlying rock layer (figure 9.1d). In the calculation of the load-bearing capacity of such shafts, the end bearing and the shear stress developed along the shaft perimeter and rock interface can be taken into account.

**CONSTRUCTION PROCEDURES**

One of the oldest methods of construction of drilled shafts is the Chicago method (figure 9.2a). In this method, circular holes with diameters of 3.5 ft (1.1 m) or more are excavated by hand for depths of 2-6 ft (0.6-1.8 m) at a time. The sides of the excavated hole are then lined with vertical boards, referred to as laggings. They are held tightly in place by two circular steel rings. After placement of the rings, the excavation is continued for another 2-6 ft (0.6-1.8 m). When the desired depth of excavation is reached, the bell is excavated. Following the completion of the excavation the hole is filled with concrete.
In the Gow method of construction (figure 9.2b), the hole is excavated by hand. Telescopic metal shells are used to maintain the shaft. The shells can be removed one section at a time as concreting progresses. The minimum diameter of a Gow drilled shaft is about 4 ft (1.22 m). Any given section of the shell is about 2 in. (50 mm) less in diameter than the section immediately above it. Shafts as deep as 100 ft (30 m) have been installed by this method.

Most shaft excavations are now done mechanically rather than by hand. Open helix augers (flight augers) are common excavation tools. These augers have cutting edges or cutting teeth. Those with cutting edges are used mostly for drilling in soft, homogeneous soil; those with cutting teeth are for drilling in hand soil and hard pan. The auger is attached to a square shaft referred to as the Kelly and pushed into the soil and rotated. When the flights are filled with soil, the auger is raised above the ground surface, and the soil is dumped into a pile by rotating the auger at high speed. These augers are available in various diameters; sometimes they may be as large as 10 ft (3 m) or more.

When the excavation is extended to the level of the load-bearing stratum, the auger is replaced by underreaming tools to shape the bell, if required. An underreamer essentially consists of a cylinder with two cutting blades hinged to the top of the cylinder (figure 9.2.3). When the underreamer is lowered into the hole, the cutting blades stay folded inside the cylinder. When the bottom of the hole is reached, the blades are spread outward, and the underreamer is rotated. The loose soil falls inside the cylinder, which is raised periodically and emptied until the bell is completed. Most underreamers can cut bells with diameters as large as three times the diameter of the shaft.
Another common drilling device is the bucket-type drill. It is essentially a bucket with an opening and cutting edges at the bottom. The bucket is attached to the Kelly and rotated. The loose soil is collected in the bucket, which is periodically raised and emptied. Holes as large as 16-18 ft (5-5.5m) in diameter can be drilled with this type of equipment.

When rock is encountered during drilling, core barrels with tungsten carbide teeth attached to the bottom of the barrels are used. Shot barrels are also used for drilling into hard rock. The principle of rock coring by a shot barrel is shown in figure 9.4. The drill stem is attached to the shot barrel’s plate. The barrel has some feeder slots through which chilled steel shots are supplied to the bottom of the bore hole. The steel shots cut the rock when the barrel is rotated. Water is supplied to the drill hole through the drill stem. Fine rocks re steel particles (produced by the grinding of the steel shots) are washed upward, and they settle on the upper portion o the barrel.
The Benoto machine is another type of drilling equipment that is generally used when drilling conditions are difficult and many boulders are in the soil. It essentially consists of a steel tube that can be oscillated and pushed into the soil. A tool usually referred to as the hammer grab, which is fitted with cutting blades and jaws, is used to break up the soil and rock inside the tube and remove them.

**Use of Casings and Drilling Mud**

When holes are driven in soft clays, the soil tends to squeeze in and close the hole. In such situations, casings may be used to keep the hole open and may have to be driven before excavation begins. Holes made in gravelly and sandy soils also tend to cave in. Excavation of drilled-shaft holes in these soils can be continued either by casing as the hole progresses or by using drilling mud. As pointed out in chapter 2, drilling mud is also used during field exploration.

**Inspection of the Bottom of the Hole**

![Figure 9.4 Schematic diagram of shot barrel](image)
In many instances, the bottom of the hole must be inspected to ensure that the load-bearing stratum is what was anticipated and that the bell is properly done. For these reasons, an inspector must descend to the bottom of the hole. Several safety precautions must be observed during this procedure:

1. If a casing is not already in the hole, one should be lowered by crane into it to prevent the hole and the bell from collapsing.
2. The hole should be tested for the presence of poisonous or explosive gases, which can be done by using a miner’s safety lamp.
3. The inspector should wear a safety harness.
4. The inspector should also carry a safety lamp and an air tank.

OTHER DESIGN CONSIDERATIONS’

For the design of ordinary drilled shafts without casings, a minimum amount of vertical steel reinforcement is always desirable. Minimum reinforcement is 1% of the gross cross-sectional area of the shaft. In California, a reinforcing cage having a length of about 12 ft (3.65 m) is used in the top part of the shaft, and no reinforcement is provided at the bottom. This procedure helps in the construction process because the cage is placed after most of the concreting is complete.

For drilled shafts with nominal reinforcement, most building codes suggest using a design concrete strength, $f_c$, on the order of $f'_c/4$. Thus the minimum shaft diameters becomes

$$f_c = 0.25 f'_c = \frac{Q_w}{A_{gs}} = \frac{Q_w}{\pi D_s^2}$$

Or

$$D_s = \sqrt{\frac{Q_w}{\frac{\pi}{4} (0.25) f'_c}} = 2.257 \sqrt{\frac{Q_w}{f'_c}}$$  \[1.1\]

Where

$D_s$ = diameter of the shaft

$f'_c$ = 28-day concrete strength

$Q_w$ = working load of the drilled shaft

$A_{gs}$ = gross cross sectional area of the shaft

Depending on the loading conditions, the reinforcement percentage may sometimes be too high. In that case, use of a single rolled-steel section at the center of the pier (figure 9.5b) may be considered. In that case,
\[ Q_w = (A_{gs} - A_s)f_c + A_s f_s \]  \[8.2\]

Figure 9.5 Drilled shafts with (a) steel casing and (b) a central steel core

Where

\[ A_s = \text{area of the steel section} \]

\[ f_s = \text{allowable strength of steel} \approx 0.5\sigma_{\text{yield}} \]

When a permanent steel casing is used for construction instead of a central rolled steel section (figure 9.5a), equation (2) may be used. However, \( f_s \), for steel should be on the order of \( 0.4f_c \).

If drilled shafts are likely to be subjected to tensile loads, reinforcement should be continued for the entire length of the shaft.

**Concrete Mix Design**

The concrete mix design for drilled shafts is not much different from that for any other concrete structure. When a reinforcing cage is used, consideration should be given to the ability of the concrete to flow through the reinforcement. In most cases, a concrete slump of about 6 in. (150 mm) is considered satisfactory. Also, the maximum size of the aggregate should be limited to about 0.75 in. (20 mm).

**LOAD TRANSFER MECHANISM**

The load transfer mechanism from drilled shafts to soil is similar to that of piles as described in section 5. Figure 9.6 shows the load test results of a drilled shaft in a clay soil in Houston, Texas (Reese, Touma, and O’Neill, 1976). This drilled shaft had a diameter of 2.5 ft (0.76 m) and a depth of penetration of 23.1 ft (7.04 m). The soil profile as the site is shown in figure 9. 6a. Figure 9. 6b shows the load-settlement curves. It may be seen that the total load carried by the drilled shaft was 140 tons (1246 kN). the load carried by side resistance was about 90 tons (801 kN) and the rest was carried by point
bearing. It is also interesting to note that, with a downward movement of about 0.25 in. (6.35 mm), full side resistance was mobilized. However, about 1 in. (25.4 mm) of downward movement was required for mobilization of full point resistance. This is similar to that observed in the case of piles. Figure 9.6c shows the load-distribution curves for different stages of the loading, which are similar to those shown in figure 9.10.

Figure 9.6 Load test results for a drilled shaft in Houston, Texas: (a) soil profile, (b) load-displacement curves, (c) load-distribution curves at various stages of loading (after Reese, et al, 1976).

**ESTIMATED OF LOAD-BEARING CAPACITY – GENERAL**

The ultimate load-bearing capacity of a drilled shaft (figure 9.7) is
\[ Q_u = Q_p + Q_s \] [8.3]

Figure 9.7 Ultimate bearing capacity of drilled shafts: (a) with bell; (b) straight shaft

Where

\( Q_u \) = ultimate load
\( Q_p \) = ultimate load \(-\) carrying capacity at the base
\( Q_s \) = frictional (skin) resistance

The equation for the ultimate base load is similar to that for shallow foundations:

\[ Q_p = A_p \left( c N_c^* + q' N_q^* + 0.3 \gamma D_b N_f^* \right) \] [8.4]

Where

\( N_c^*, N_q^*, N_f^* \) = the bearing capacity factors
\( q' \) = vertical effective stress at the level of the bottom of the pier
\( D_b \) = diameter of the base (see figure 9.7a and b)
\( A_p \) = area of the base = \( \pi/4D_b^2 \)
In most cases, the last term (containing $N_q^*$) is neglected except for relatively short drilled shafts, so

$$Q_p = A_p (cN_c^* + q q')$$ \hspace{1cm} \text{[8.5]}

The net load-carrying capacity at the base (that is, the gross load minus the weight of the pier) may be approximated as

$$Q_{p(\text{net})} = A_p (cN_c^* + q q^* - q') = A_p [cN_c^* + q q^* - 1]$$ \hspace{1cm} \text{[8.6]}

The expression for the frictional, or skin, resistance, $Q_s$, is similar to that for piles:

$$Q_s = \int_{L_1}^L p f \, dz$$ \hspace{1cm} \text{[8.7]}

Where

$$p = \text{shaft perimeter} = \pi D_s$$

$$f = \text{unit frictional (or skin) resistance}$$

The following two sections describe the procedures for obtaining the ultimate and allowable load-bearing capacities of drilled shafts in sand and clay.