11

Deep Foundations

For these reasons, Caesar determined to cross the Rhine, but a crossing by means of boats seemed to him both too risky and beneath his dignity as a Roman commander. Therefore, although construction of a bridge presented very great difficulties on account of the breadth, depth and swiftness of the stream, he decided that he must either attempt it or give up the idea of a crossing. The method he adopted in building the bridge was as follows. He took a pair of piles a foot and a half thick, slightly pointed at the lower ends and of a length adapted to the varying depth of the river, and fastened them together two feet apart. These he lowered into the river with appropriate tackle, placed them in position at right angles to the bank, and drove them home with pile drivers, not vertically as piles are generally fixed, but obliquely, inclined in the direction of the current. Opposite these, forty feet lower down the river, another pair of piles was planted, similarly fixed together, and inclined in the opposite direction to the current. The two pairs were then joined by a beam two feet wide, whose ends fitted exactly into the spaces between the two piles forming each pair . . . A series of these piles and transverse beams was carried right across the stream and connected by lengths of timber running in the direction of the bridge . . . Ten days after the collection of the timber had begun, the work was completed and the army crossed over.

Engineers prefer to use spread footings wherever possible, because they are simple and inexpensive to build. However, we often encounter situations where spread footings are not the best choice. Examples include the following:

- The upper soils are so weak and/or the structural loads so high that spread footings would be too large. A good rule-of-thumb for buildings is that spread footings cease to be economical when the total plan area of the footings exceeds about one-third of the building footprint area.
- The upper soils are subject to scour or undermining. This would be especially important with foundations for bridges.
- The foundation must penetrate through water, such as those for a pier.
- A large uplift capacity is required (the uplift capacity of a spread footing is limited to its dead weight).
- A large lateral load capacity is required.
- There will be a future excavation adjacent to the foundation, and this excavation would undermine shallow foundations.

In some of these circumstances, a mat foundation may be appropriate, but the most common alternative to spread footings is some type of *deep foundation*.

A deep foundation is one that transmits some or all of the applied load to soils well below the ground surface, as shown in Figure 11.1. These foundations typically extend to depths on the order of 15 m (50 ft) below the ground surface, but they can be much longer, perhaps extending as deep as 45 m (150 ft). Even greater lengths have been used in some offshore structures, such as oil drilling platforms. Since soils usually improve with depth, and this method mobilizes a larger volume of soil, deep foundations are often able to carry very large loads.

11.1 TYPES OF DEEP FOUNDATIONS AND DEFINITIONS

Engineers and contractors have developed many types of deep foundations, each of which is best suited to certain loading and soil conditions. Unfortunately, people use many different names to identify these designs. Different individuals often use the same terms to mean different things and different terms to mean the same thing. This confusion reigns in both verbal and written communications, and is often the source of misunderstanding, especially to the newcomer. This book uses terms that appear to be most commonly used and understood. This classification system is based primarily on the methods of construction, as follows:

- *Piles* are constructed by prefabricating slender prefabricated members and driving or otherwise forcing them into the ground.
- *Drilled shafts* are constructed by drilling a slender cylindrical hole into the ground, inserting reinforcing steel, and filling it with concrete.
- *Caissons* are prefabricated boxes or cylinders that are sunk into the ground to some desired depth, then filled with concrete. Some engineers use the term "caisson" to describe drilled shafts, so this is one of the more confusing terms in foundation engineering.
- *Mandrel-driven thin shells filled with concrete* consist of thin corrugated steel shells that are driven into the ground using a mandrel, then filled with concrete.
- *Auger-cast piles* are constructed by drilling a slender cylindrical hole into the ground using a hollow-stem auger, then pumping grout through the auger while it is slowly retracted.
- *Pressure-injected footings* use cast-in-place concrete that is rammed into the soil using a drop hammer.
- *Anchors* include several different kinds of deep foundations that are specifically designed to resist uplift loads.

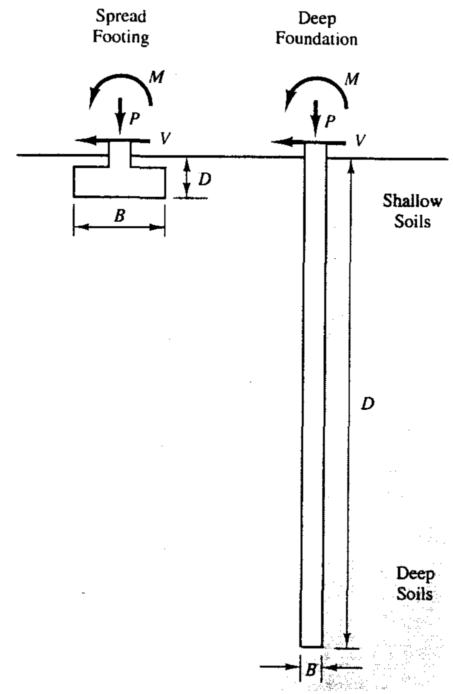


Figure 11.1 Deep foundations transfer most of the applied structural loads to deeper soil strata.

The vast majority of deep foundation designs use one of these seven types. Other types also are available, but they are not often used and are beyond the scope of this book.

The various parts of deep foundations also have different names, which is another source of confusion (Fellenius, 1996). The upper end has many names, including "top," "butt," and "head," while those for the lower end include "tip," "toe," "base," "end," "point," and "bottom." Many of these terms can easily be misunderstood. We will use the

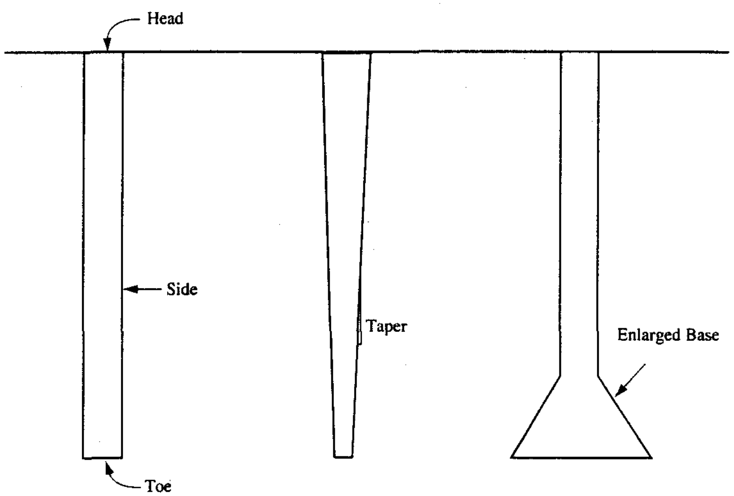


Figure 11.2 Parts of a deep foundation (a) straight foundations; (b) tapered foundations; (c) foundations with an enlarged base.

terms *head* and *toe*, as shown in Figure 11.2a, because they appear to have the least potential for confusion. These terms also are easy to remember by simply comparing the pile to a human body.

The exterior surface along the side of deep foundations is usually called the "side" or the "skin," either of which is generally acceptable. We will use the term *side*.

Most deep foundations are *straight*, which means the cross section is constant with depth, but some are *tapered*, as shown in Figure 11.2b. Others include an *enlarged base*, as shown in Figure 11.2c. The *axis* is a line through the center of the foundation and is parallel to its longest dimension.

11.2 LOAD TRANSFER

To properly select and design deep foundations, we need to understand how they transfer structural loads into the ground. These load-transfer mechanisms depend on the type of load being imposed, so it is convenient to divide structural loads into two categories:

- *Axial loads* are applied tensile or compressive loads that act parallel to the axis of the foundation, as shown in Figures 11.3a and 11.3b. These loads induce either tension or compression in the foundation, but no flexure. If the foundation is vertical, then the axial load is equal to the vertical applied load.

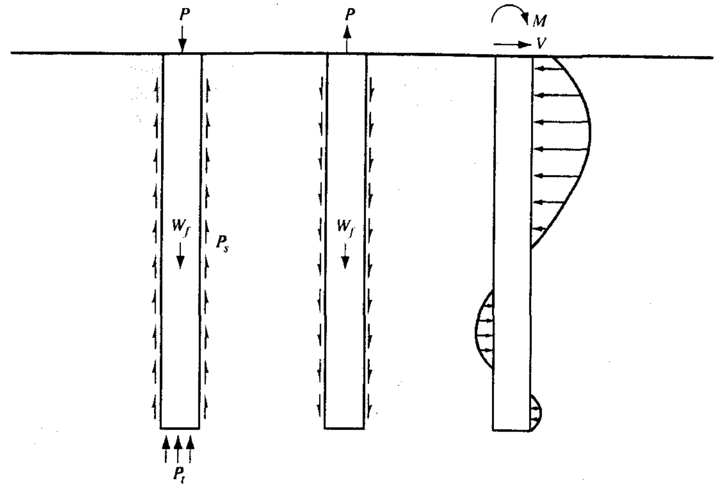


Figure 11.3 Transfer of structural loads from a deep foundation into the ground: (a) axial compressive loads; (b) axial tension loads; (c) lateral loads.

- *Lateral loads* are those that act perpendicular to the axis of the foundation, as shown in Figure 11.3c. This category includes shear and moment loads, V and M.

Axial Loads

An axial load may be either compressive (downward) or tensile (uplift). When it is compressive, deep foundations resist the load using both *side friction resistance* and *toe bearing resistance*, as shown in Figure 11.3a. However, when the load is tensile, the resistance is caused by side friction and the weight of the foundation, as shown in Figure 11.3b. In deep foundations with an enlarged base, uplift loads are also resisted by bearing along the ceiling of the enlarged base.

Lateral Loads

Lateral loads produce both shear and moment in a deep foundation, as shown in Figure 11.3c. These shears and moments produce lateral deflections in the foundation, which in turn mobilize lateral resistances in the adjacent soil. The magnitudes of these lateral deflections and resistances, and the corresponding load-bearing capacity of the foundation depend on the stiffness of both the soil and the foundation.

11.3 PILES

The first type of deep foundation is a *pile foundation*, which consists of long, slender, prefabricated structural members driven or otherwise inserted into the ground. Engineers use piles both on land and in the sea to support many kinds of structures. Piles are made from a variety of materials and in different diameters and lengths according to the needs of each project.

Although some engineers also use the word *pile* to describe certain types of cast-in-place deep foundations, we will use it only to describe prefabricated deep foundations. Cast-in-place methods are discussed later in this chapter.

History

Mankind has used pile foundations for more than 2000 years. Alexander the Great drove piles in the city of Tyre in 332 B.C., and the Romans used them extensively. Bridge builders in China during the Han Dynasty (200 B.C.–A.D. 200) also used piles. These early builders drove their piles into the ground using weights hoisted and dropped by hand (Chellis, 1961). By the Middle Ages, builders used pulleys and leverage to raise heavier weights.

Construction methods improved more quickly during the Industrial Revolution, especially when steam power became available. Larger and more powerful equipment was built, thus improving pile driving capabilities. These improvements continued throughout the twentieth century.

Pile materials also have become better. The early piles were always made of wood, and thus were limited in length and capacity. Fortunately, the advent of steel and reinforced concrete in the 1890s enabled the construction of larger and stronger piles, and better driving equipment made it possible to install them. Without these improved foundations, many of today's major structures would not have been possible.

Today, pile foundations can support very high loads, even in hostile environments. Perhaps the most impressive are those for offshore oil drilling platforms. These are as large as 10 ft (3 m) in diameter and must resist large lateral loads due to wind, wave, and earthquake forces.

Types of Piles

Most piles are now made from wood, concrete, or steel. Each material has its advantages and disadvantages and is best suited for certain applications. We must consider many factors when selecting a pile type, including the following:

- **The applied loads**—Some piles, such as timber, are best suited for low to medium loads, whereas others, such as steel, may be most cost-effective for heavy loads.
- **The required diameter**—Most pile types are available only in certain diameters.
- **The required length**—Highway shipping regulations and practical pile driver heights generally limit the length of pile segments to about 18 m (60 ft). Therefore, longer piles must consist of multiple segments spliced together during driving. Some types of piles are easily spliced, whereas others are not.
- **The local availability of each pile type**—Some pile types may be abundant in certain geographic areas, whereas others may be scarce. This can significantly affect the cost of each type.
- **The durability of the pile material in a specific environment**—Certain environments may cause piles to deteriorate, as discussed in Chapter 2.
- **The anticipated driving conditions**—Some piles tolerate hard driving, while others are more likely to be damaged.

Timber Piles

Timber piles have been used for thousands of years and continue to be a good choice for many applications. They are made from the trunks of straight trees and resemble telephone poles, as shown in Figure 11.4. Because trees are naturally tapered, these piles are driven upside down, so the largest diameter is at the head, as shown in Figure 11.5.

Many different species of trees have been used to make timber piles. Today, most new timber piles driven in North America are either Southern pine or Douglas fir because these trees are tall and straight, and are abundant enough that the materials cost is low. They typically have head diameters in the range of 150 to 450 mm (6–18 in) and lengths between 6 and 20 m (20–60 ft), but greater lengths are sometimes available, up to 24 m (80 ft) in Southern pine and 38 m (125 ft) in Douglas fir. The branches and bark must be removed, and it is sometimes necessary to trim the pile slightly to give it a uniform taper. ASTM D25 gives detailed specifications.

Figure 11.4 Groups of timber piles. Those in the foreground have been cut to the final head elevation (National Timber Piling Council).

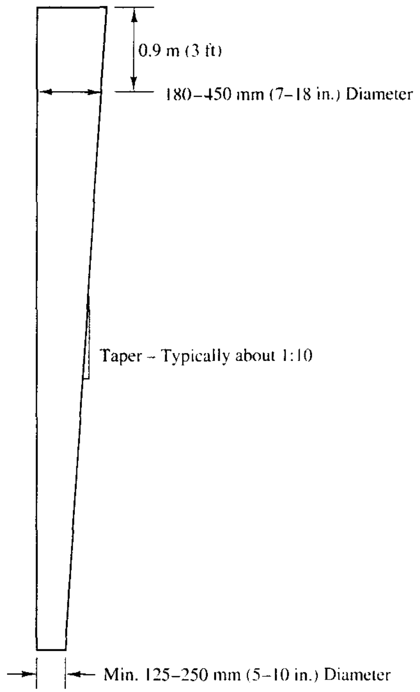


Figure 11.5 Typical timber pile.

Although it is possible to splice lengths of wood piling together to form longer piles, this is a slow and time-consuming process that makes the piles much more expensive. Therefore, if longer piles are necessary, use some other material.

Most timber piles are designed to carry downward axial loads of 100 to 400 kN (20–100 k). Their primary advantage is low construction cost, especially when suitable trees are available nearby. They are often used on waterfront structures because of their resistance to impact loads, such as those from ships.

When continually submerged, timber piles can have a very long life. For example, when the Campanile in Venice fell in 1902, its timber piles, which were driven in A.D. 900, were found in good condition and were reused (Chellis, 1962). However, when placed above the groundwater table, or in cyclic wetting conditions, timber piles are susceptible to decay, as discussed in Chapter 2. Therefore, they are nearly always treated with a preservative before installation.

When used in marine environments, timber piles are subject to attack from various marine organisms as well as abrasion from vessels and floating debris. In cooler waters

(in North America, generally north of 40 degrees latitude), piles with heavy creosote treatment will usually remain serviceable for decades (ASCE, 1984). However, in warmer waters, biological attack is more of a problem and other chemical treatments are usually necessary. Even when treated, their usable life in such environments is often limited to about ten years.

These piles are also susceptible to damage during driving. Repeated hard hammer blows can cause *splitting* and *brooming* at the head and damage to the toe. It is often possible to control these problems by:

- Using lightweight hammers with appropriate cushions between the hammer and the pile
- Using steel bands near the butt (usually necessary only with Douglas fir)
- Using a steel shoe on the toe, as shown in Figure 11.6
- Predrilling (see discussion later in this section)

Nevertheless, even these measures are not always sufficient to prevent damage. Therefore, timber piles are best suited for light driving conditions, such as friction piles in loose sands and soft to medium clays. They are usually not good for dense or hard soils or as end bearing piles.

Steel Piles

By the 1890s, steel had become widely available and many structures were being built of this new material. The use of steel piling was a natural development. Today, steel piles are very common, especially on projects that require high-capacity foundations.

Figure 11.6 Use of steel toe points to reduce damage to timber piles during driving (Associated Pile and Fitting Corp.).

Because of their high strength and ductility, steel piles can be driven through hard soils and carry large loads. They also have the highest tensile strength of any major pile type, so they are especially attractive for applications with large applied tensile loads.

Steel piles are easy to splice, so they are often a good choice when the required length is greater than about 18 m (60 ft). The contractor simply drives the first section, then welds on the next one, and continues driving. Special steel splicers can make this operation faster and more efficient. Hunt (1987) reported the case of a spliced steel pile driven to the extraordinary depth of 210 m (700 ft). They are also easy to cut, which can be important with end-bearing piles driven to irregular rock surfaces.

Steel piles have the disadvantages of being expensive to purchase and noisy to drive. In certain environments, they may be subject to excessive corrosion, as discussed in Chapter 2.

H-Piles

Special rolled steel sections, known as HP sections, or simply *H-piles*, are made specifically to be used as piles. These sections are similar to WF (wide flange) shapes as shown in Figures 11.7 and 11.8. The primary difference is that the web is thinner than the flanges in wide flange members, while they have equal thicknesses in H-piles. Dimensions and

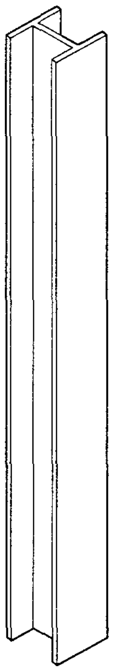


Figure 11.7 A steel H-pile.

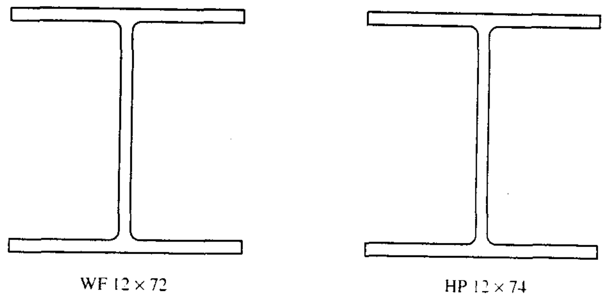


Figure 11.8 Comparison between typical wide flange (WF) and H-pile (HP) sections.

other relevant information for standard steel H-piles are listed in Table 12.1. These piles are typically 15 to 50 m (50–150 ft) long and carry working axial loads of 350 to 1800 kN 80–400 k.

H-piles are *small displacement piles* because they displace a relatively small volume of soil as they are driven. This, combined with their high strength, make them an excellent choice for hard driving conditions. They are often driven to bedrock and used as end bearing piles. If the pile will encounter hard driving, it may be necessary to use a hardened steel point to protect its toe, as shown in Figure 11.9.

Pipe Piles

Steel pipe sections are also commonly used as piles, as shown in Figure 11.10. They are typically 200 to 1000 mm (8–36 in) in diameter, 30 to 50 m (100–150 ft) long, and carry axial loads of 450 to 7000 kN (100–1500 k). A wide variety of diameters and wall thicknesses are available, and some engineers have even reclaimed used steel pipelines and

Figure 11.9 Hardened steel point attached to the toe of a steel H-pile to protect it during hard driving. (Associated Pile and Fitting Corp.)

Figure 11.10 A 16 inch (406 mm) diameter steel pipe pile.

used them as piles. Special sizes also can be manufactured as needed and pipe piles as large as 3 m (10 ft) in diameter with 75 mm (3 in) wall thickness have been used in offshore projects. Table 12.2 lists some of the more common sizes.

Pipe piles have a larger moment of inertia than H-piles, so they may be a better choice if large lateral loads are present.

Pipe piles may be driven with a *closed-end* or with an *open-end*. A closed-end pipe has a flat steel plate or a conical steel point welded to the toe. These are *large displacement piles* because they displace a large volume of soil. This increases the load capacity, but makes them more difficult to drive. Conversely, an open-end pipe has nothing blocking the toe and soil enters the pipe as it is being driven. The lower portion of small diameter open-end pipe piles usually becomes jammed with soil, thus forming a *soil plug*. Thus, an open-end pipe pile displaces less soil than a closed-end one, but more than an H-pile. Open-ended piles are primarily used in offshore construction.

Closed-end pipe piles can be inspected after driving because the inside is visible from the ground surface. Thus, it is possible to check for integrity and alignment.

Special steel pipe piles are also available, such as the *monotube pile*, which is tapered and has longitudinal flutes.

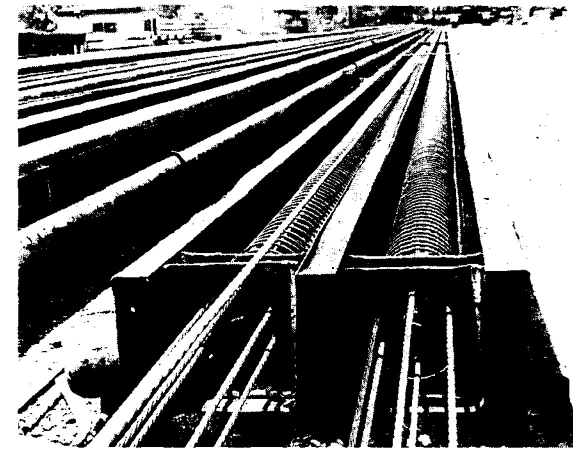


Figure 11.11 These steel forms are used to manufacture prestressed concrete piles. The prestressing cables, visible in the foreground, are in place and have been subjected to a tensile force. The spiral reinforcement also is in place. The next step will be to fill the forms with high quality concrete, cover them with a tarp, and steam-cure them overnight. The next day, the tension on the cables will be released, then the piles will be removed from the forms and allowed to cure.

Concrete Piles

Concrete piles are precast reinforced concrete members driven into the ground. This category does not include techniques that involve casting the concrete in the ground; They are covered later in this chapter.

Figure 11.11 shows steel molds used to manufacture precast prestressed concrete piles. This is usually done at special manufacturing facilities, then shipped to the construction site. Figure 11.12 shows completed piles ready to be driven.

Concrete piles usually have a square or octagonal cross section, as shown in Figure 11.13, although other shapes have been used (ACI, 1980). They are typically 250 to 600 mm (10–24 in) in diameter, 12 to 30 m (40–100 ft) long, and carry working axial loads of 450 to 3500 kN (100–800 k). A few nearshore projects have been built using much larger concrete piles.

Although conventionally-reinforced concrete piles were once common, prestressed piles have almost completely replaced them, at least in North America. These improved designs have much more flexural strength and are therefore less susceptible to damage during handling and driving. Prestressing is usually a better choice than post-tensioning because it allows piles to be cut, if necessary, without losing the prestress force.

Several methods are available to splice concrete piles, as shown in Figure 11.14. Although these techniques are generally more expensive than those for splicing steel

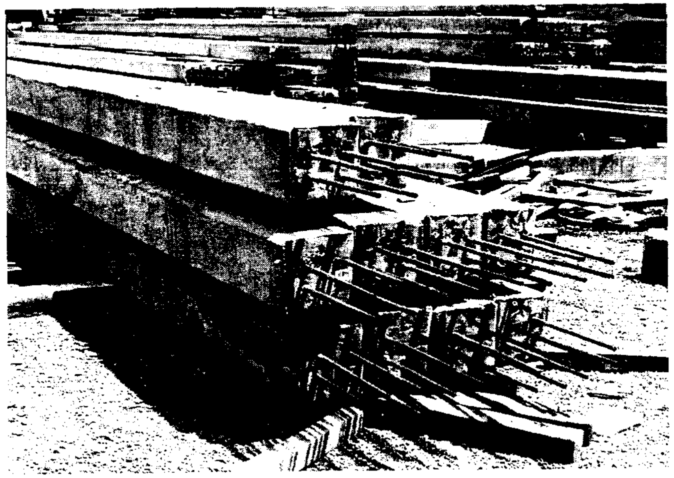


Figure 11.12 These 14-inch (356 mm) square prestressed concrete piles are stacked in a contractor's yard and are ready to be driven. The bars emerging from the end of these piles are conventional rebars that have been embedded in the end of the pile (they are not the reinforcing tendons). These rebars are used to structurally connect the pile with the pile cap.

piles, they can be cost-effective in some situations. However, unlike steel, concrete piles are difficult and expensive to cut. Therefore, they are best suited for use as friction piles that do not meet *refusal* during driving (refusal means that the pile cannot be driven any further, so it becomes necessary to cut off the upper portion) or as toe-bearing piles where the required length is uniform and predictable.

Concrete piles do not tolerate hard driving conditions as well as steel, and are more likely to be damaged during handling or driving. Nevertheless, concrete piles are very popular because they are often less expensive than steel piles, yet still have a large load capacity.

Composite Piles

A *composite pile* is one that uses two or more materials. For example, a steel pipe pile filled with concrete. Normal concrete piles are not considered to be composite piles even though they contain reinforcing steel.

Concrete-Filled Steel Pipe Piles

Sometimes steel pipe piles are filled with concrete after driving. These will have more uplift capacity due to their greater weight, enhanced shear and moment capacity because of the strength of the concrete, and a longer useful life in corrosive environments. However,

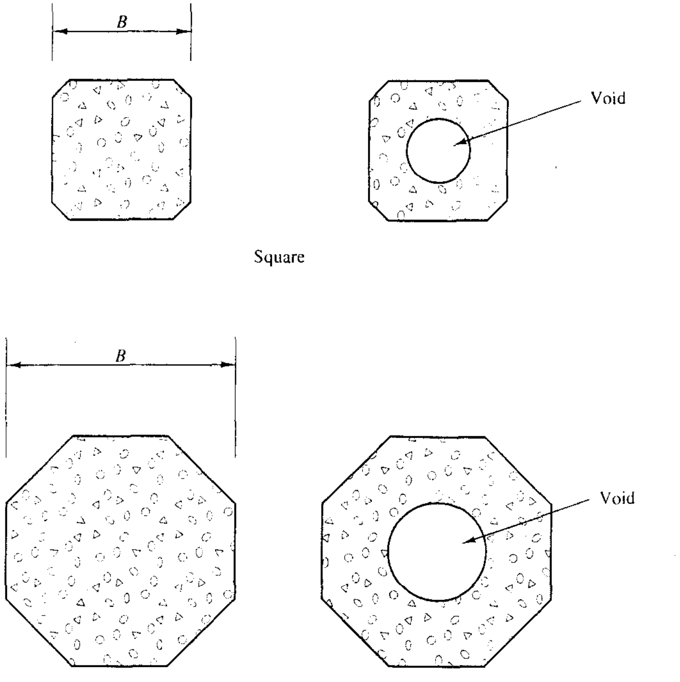


Figure 11.13 Cross sections of typical concrete piles.

there is little, if any, usable increase in the downward load capacity because a pipe with sufficient wall thickness to withstand the driving stresses will probably have enough capacity to resist the applied downward loads. The net downward capacity may even be less because of the additional weight of the concrete in the pile.

Plastic-Steel Composite Piles

A plastic-steel composite pile consists of a steel pipe core surrounded by a plastic cover as shown in Figure 11.15, or steel rebars embedded in plastic. The plastic cover is typically made of recycled material, thus making this design attractive from a resource conservation perspective (Heinz, 1993).

Plastic-steel composite piles have been used successfully in waterfront applications (see Figure 11.16), where their resistance to marine borers, decay, and abrasion along with their higher strength make them superior to timber piles. Although the materials cost for plastic-steel composites is higher, their longer life and resource conservation benefits make them an attractive alternative to timber piles.

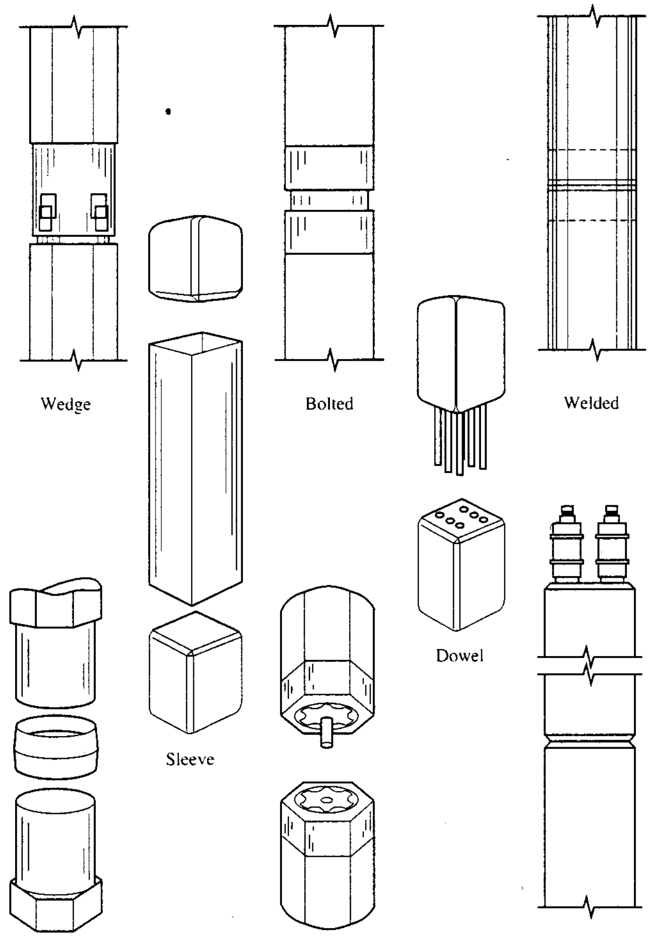


Figure 11.14 Typical splices for concrete piles (Precast/Prestressed Concrete Institute).

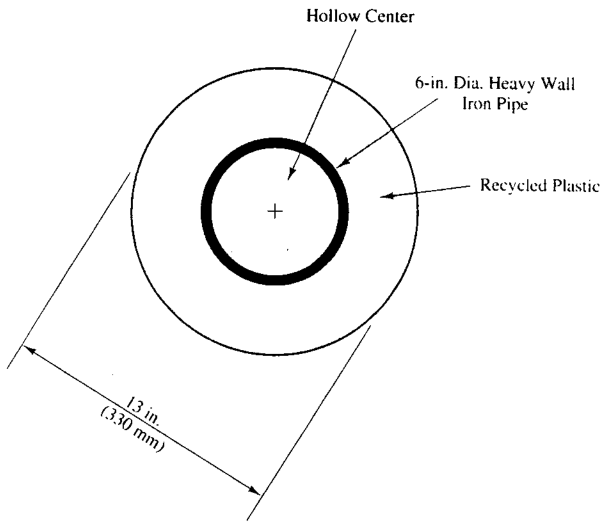


Figure 11.15 Cross section of a typical plastic-steel composite pile.

Construction Methods and Equipment

The construction of deep foundations is much more complex than that of shallow foundations, and the construction methods have a much greater impact on their performance. Therefore, design engineers must understand how contractors build pile foundations.

Pile-Driving Rigs

Piles are installed using a *pile-driving rig* (or simply the *pile driver*). Its function is to raise and temporarily support the pile while it is being driven and to support the pile hammer. Early rigs were relatively crude, but modern pile drivers, such as the ones in Figures 11.17 and 11.18, are much more powerful and flexible. Vertical tracks, called *leads*, guide the hammer as the pile descends into the ground. Hydraulic or cable-operated actuators allow the operator to move the leads into the desired alignment.

Hammers

The *pile hammer* is the device that provides the impacts necessary to drive the pile. Repeated blows are necessary, so the hammer must be capable of cycling quickly. It also must deliver sufficient energy to advance the pile, while not being powerful enough to break it. The selection of a proper hammer is one of the keys to efficient pile driving.

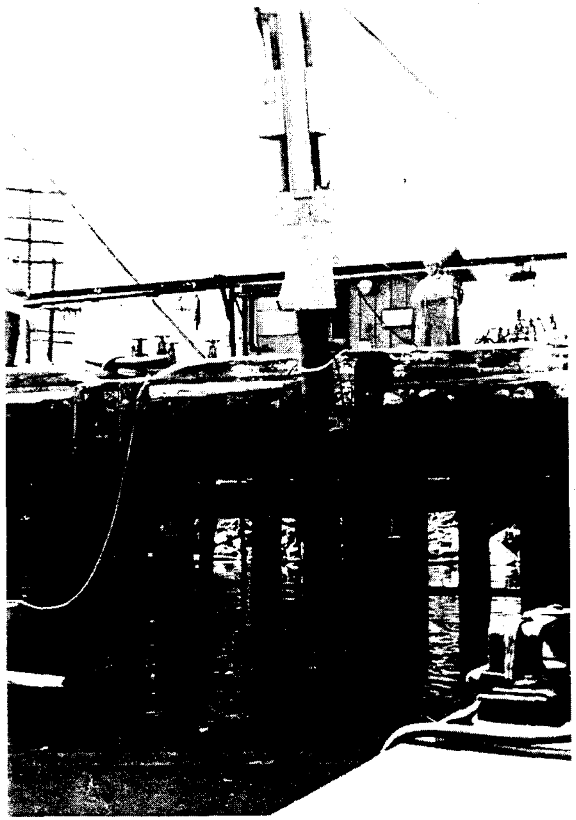


Figure 11.16 Installation of a plastic-steel composite pile in a waterfront application. The existing piles are timber (Photo courtesy of Plastic Pilings, Inc.).

Drop Hammers

The original type of pile hammer was the *drop hammer*. They consisted of a weight that was hoisted up, and then dropped directly onto the pile. These hammers became much larger and heavier during the late nineteenth century as described by Powell (1884):

> The usual method of driving piles is by a succession of blows given by a heavy block of wood or iron, called a ram, monkey or hammer, which is raised by a rope or chain, passed over a pulley fixed at the top of an upright frame, and allowed to fall freely on the head of the pile to be driven. The construction of a pile-driving machine is very simple. The guide frame

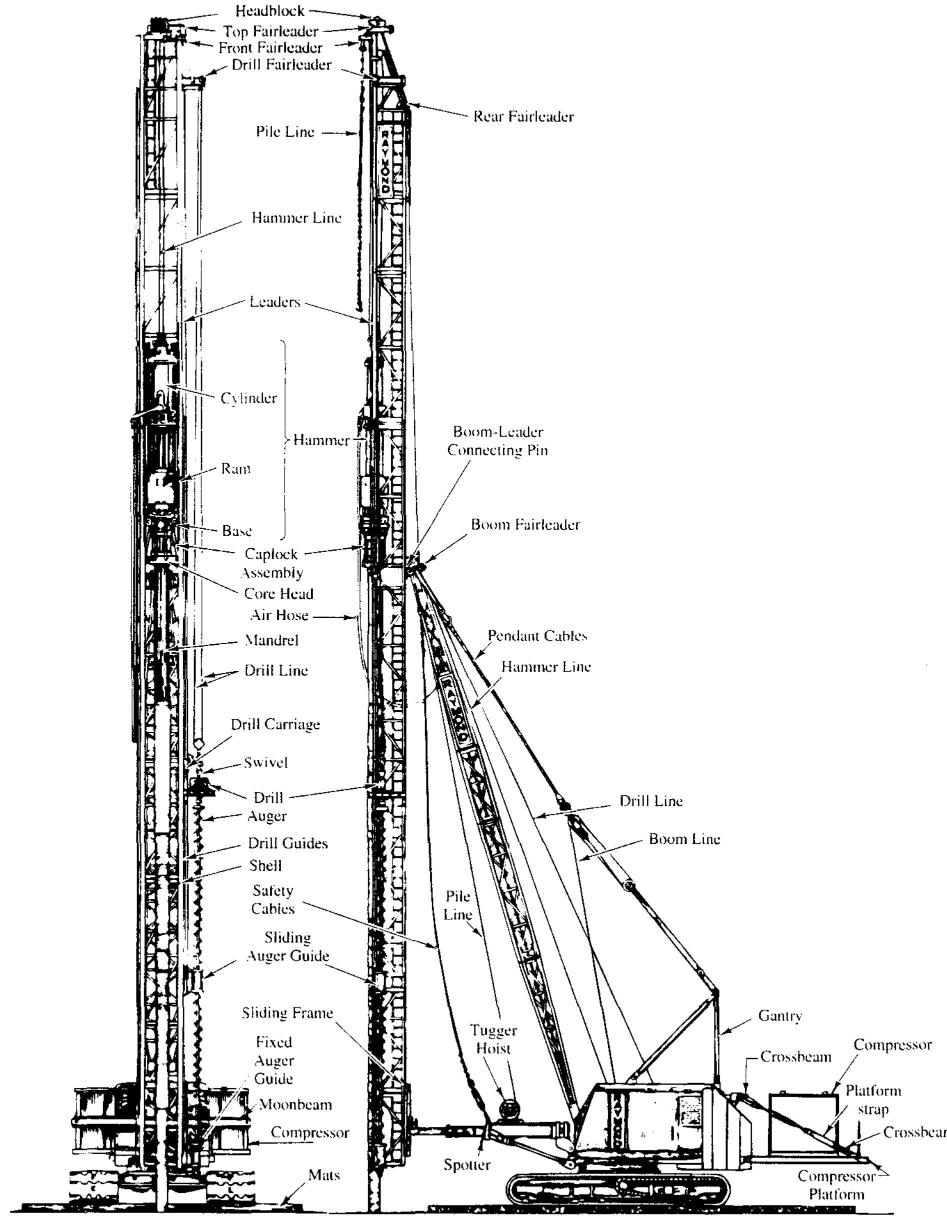


Figure 11.17 A modern pile-driving rig (Raymond International Builders).

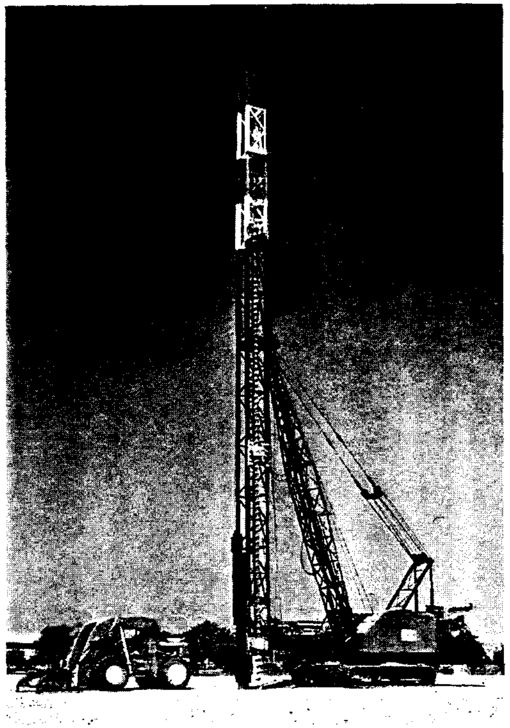


Figure 11.18 A modern pile driver. The hammer is at the bottom of the leads, and the predrilling auger is attached to the side of the leads. The forklift on the left is used to transport the piles to the rig.

> is about the same in all of them: the important parts are the two upright timbers, which guide the ram in its descent. The base of the framing is generally planked over and loaded with stone, iron, or ballast of some kind, to balance the weight of the ram. The ram is usually of cast-iron, with projecting tongue to fit the grooves of frame. Contractors have all sizes of frames, and of different construction, to use with hand or steam power, from ten feet to sixty feet in height. The height most in use is one of twenty feet, with about a twelve hundred pound ram. In some places the old hand-power method has to be used to avoid the danger of producing settling in adjoining buildings from jarring.

These hammers could deliver only about three to twelve blows per minute.

Drop hammers have since been replaced by more modern designs. They are now rarely used in North America for foundation piles, but they are sometimes used to install sheet piles. Drop hammers are effective for installing foundation piles in the very soft clays of Scandinavia, and thus are still used there (Broms, 1981). Drop hammers also form part of the *pressure-injected footing* process described in Section 11.8.

Steam, Pneumatic, and Hydraulic Hammers

New types of hammers began to appear in the late 1800s. These consisted of a self-contained unit with a ram, anvil, and raising mechanism, as shown in Figure 11.13. These hammers had slightly larger weights, but much shorter strokes than the drop hammers. For example, the "Nasmyth steam pile-drivers" of the 1880s had 1400 to 2300 kg (3000–5000 lb) rams with a stroke of about 900 mm (3 ft). Although these hammers delivered less energy per blow, they were more efficient because they cycled much more rapidly (about 60 blows/min for the Nasmyth hammer).

The early self-contained hammers used steam to raise the ram. This steam was produced by an on-site boiler. *Steam hammers* are still in use. Later, *pneumatic hammers* (powered by compressed air) and *hydraulic hammers* (powered by high-pressure hydraulic fluid) were introduced. The hydraulic hammers are becoming increasingly popular.

All three types can be built as a *single-acting hammer* or as a *double-acting hammer*. Single acting hammers raise the ram by applying pressure to a piston, as shown in Figure 11.19a. When the ram reaches the desired height, typically about 900 mm (3 ft), an exhaust valve opens and the hammer drops by gravity and impacts the anvil. When compared to other types, this design is characterized by a low impact velocity and heavy ram weights. These hammers have fixed strokes, which means each drop of the hammer delivers the same amount of energy to the pile.

A double-acting hammer, shown in Figure 11.19b, uses pressure for both the upward and downward strokes, thus delivering a greater impact than would be possible by gravity alone. The impact energy depends to some degree upon the applied pressure and therefore can be controlled by the operator. These hammers usually have shorter strokes and cycle more rapidly than single-acting hammers. Practical design limitations prevent these hammers from delivering as much energy as comparable single-acting hammers, so they are principally used for driving sheet piles.

A *differential hammer*, shown in Figure 11.19c, is similar to a double-acting hammer in that it uses air, steam, or hydraulic pressure to raise and lower the ram, but it differs in that it has two pistons with differing cross-sectional areas. This allows differential hammers to use the heavy rams of single-acting hammers and operate at the high speed and with the controllability of double-acting hammers.

Steam and pneumatic differential hammers cycle slowly under soft driving conditions and faster as the penetration resistance increases. The reverse is true of hydraulic hammers.

Diesel Hammers

A diesel hammer, shown in Figure 11.20, is similar to a diesel internal combustion engine. The ram falls from a high position and compresses the air in the cylinder below. At a certain point in the stroke, diesel fuel is injected (in either atomized or liquid form) and the air-fuel mixture is further compressed until the ram impacts the anvil. Combustion occurs about this time, forcing the ram up and allowing another cycle to begin.

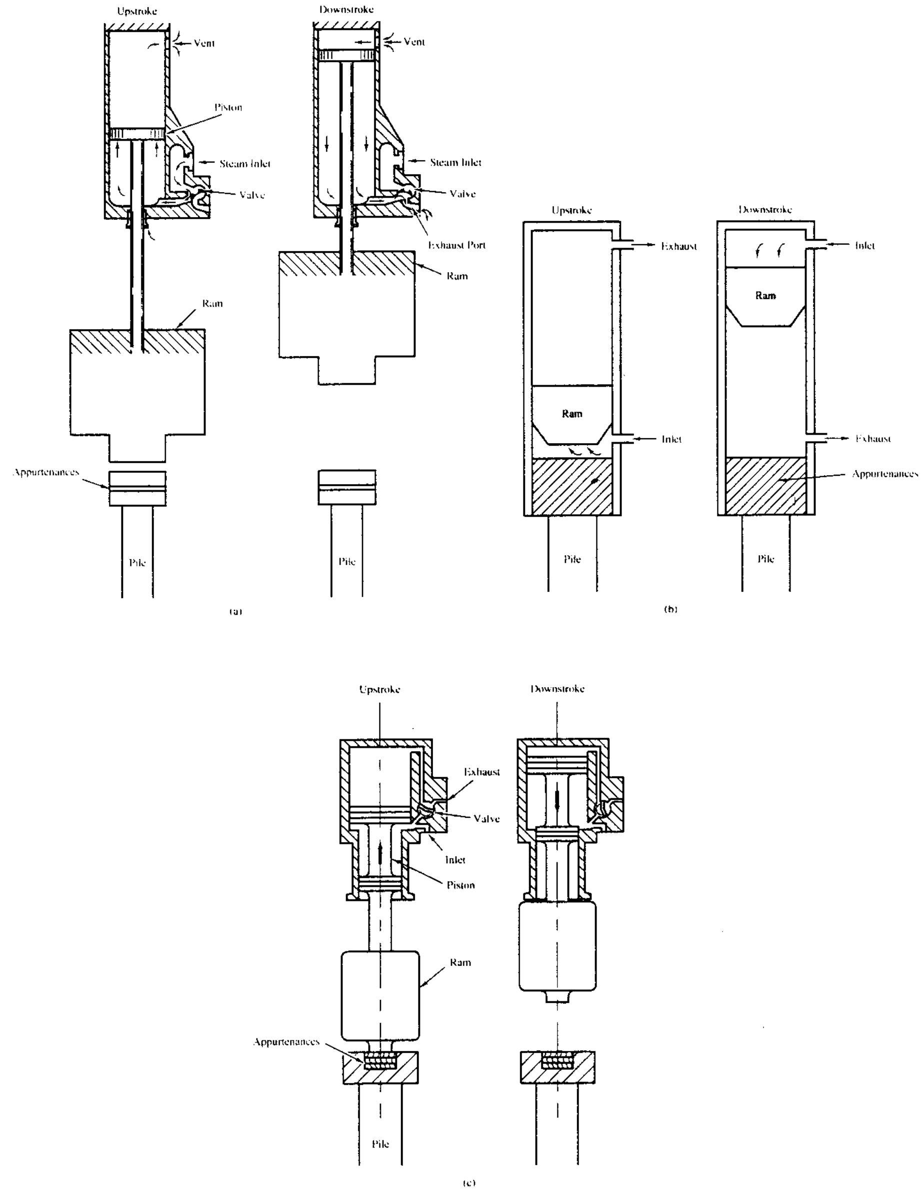
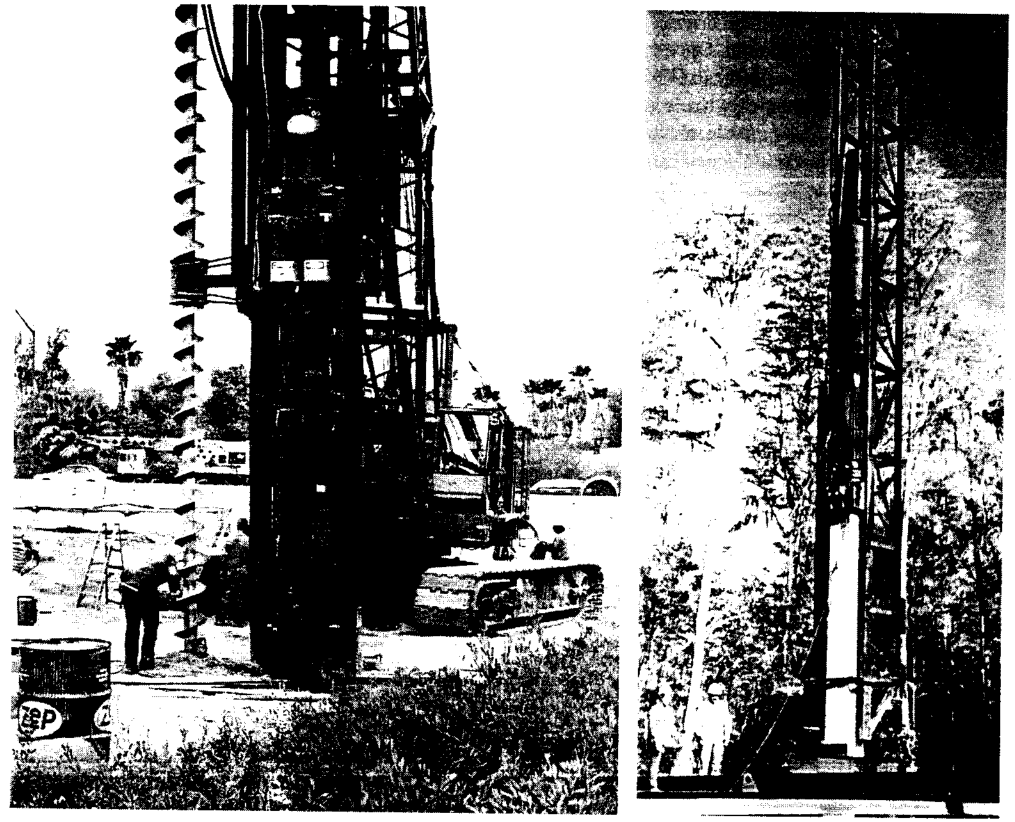


Figure 11.19 Self-contained pile-driving hammers: (a) single-acting; (b) double-acting; (c) differential.



(a) (b)

Figure 11.20 Open-top diesel pile hammers. a) This hammer is at the bottom of the leads. The auger to the left is for predrilling. b) This hammer is in the process of driving a concrete pile. The ram is near the top of its stroke, and is visible at the top of the hammer (photo b courtesy of Goble, Rausche, Likins, and Associates).

Diesel hammers are either of the open-top (single acting) or closed-top (double acting) type. The closed-top hammer includes a bounce chamber above the ram that causes the hammer to operate with shorter strokes and at higher speeds than an open-top hammer with an equivalent energy output.

The operator and field engineer can monitor the energy output of a diesel hammer by noting the rise of the ram (in an open-top hammer) or the bounce chamber pressure (in a closed-top hammer). Diesel hammers develop their maximum energy under hard driving conditions and may be difficult to operate under soft conditions, which sometimes occur early in the driving sequence, because of a lack of proper combustion or insufficient hammer rebound. Once firm driving conditions are encountered, open-top hammers typically deliver forty to fifty five blows per minute, while closed-top hammers typically deliver about ninety blows per minute.

Although diesel hammers have been popular for many years, the exhaust is a source of air pollution, so air quality regulations may restrict their use in some areas.

Vibratory Hammers

A *vibratory hammer* (Warrington, 1992) is not a hammer in the same sense as those discussed earlier. It uses rotating eccentric weights to create vertical vibrations, as shown in Figure 11.21. When combined with a static weight, these vibrations force the pile into the ground. The operating frequency of vibratory hammers may be as high as 150 Hz and can be adjusted to resonate with the natural frequency of the pile.

Vibratory hammers are most effective when used with piles being driven into sandy soils. They operate more quickly and with less vibration and noise than conventional impact hammers. However, they are ineffective in clays or soils containing obstructions such as boulders.

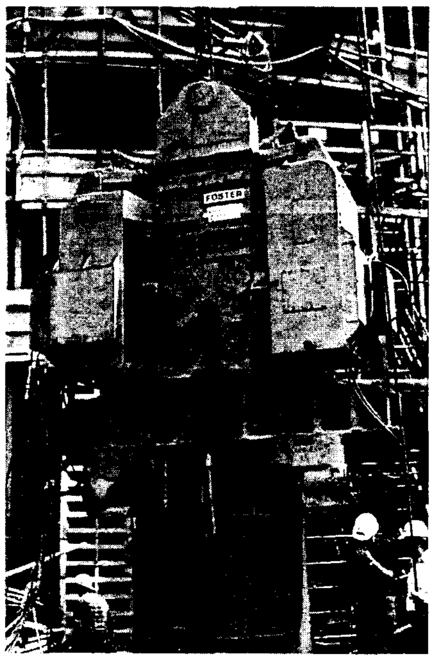


Figure 11.21 A vibratory pile hammer. This hammer is extracting a steel pipe used as a casing for a drilled shaft foundation (ADSC: The International Association of Foundation Drilling).

Appurtenances

A pile-driving system also includes other components that are placed between the pile hammer and the pile, as shown in Figure 11.22. The ram hits a steel *striker plate*. It then transmits the impact energy through a *hammer cushion* (also known as a *capblock*) to a *drive head* (also known as a *drive cap*, *bonnet*, *hood*, or *helmet*). The drive head is placed directly on the pile except for a concrete pile where a *pile cushion* is inserted between them.

The cushions soften the sharp blow from the hammer by spreading it out over a longer time. Ideally, they should do this without absorbing too much energy. Hammer cushions do this to protect the hammer, and may consist of hardwood, or the more efficient man-made materials. Pile cushions, which are generally used only with concrete piles, are intended to protect the pile. They are usually made of plywood.

The optimal selection of the pile hammer and appurtenances is part of the key to efficient pile driving. Wave equation analyses, discussed in Chapter 14, can be very useful in this regard.

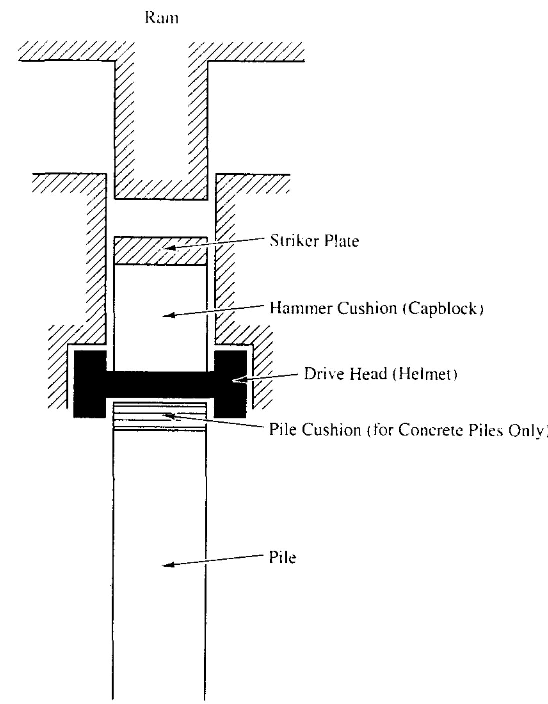


Figure 11.22 Pile-driving appurtenances.

Predrilling, Jetting, and Spudding

All piles are subject to damage during driving, especially in very hard ground or ground that contains boulders. Figure 11.23 shows an example of pile damage. One way to reduce the potential for damage and increase the contractor's production rate is to use predrilling, jetting, or spudding.

Predrilling means drilling a vertical hole, and then driving the pile into this hole. The diameter of the predrill hole must be less than that of the pile to assure firm contact with the soil. Predrilling also reduces the heave and lateral soil movement sometimes associated with pile driving. The predrill hole does not necessarily need to extend for the entire length of the pile.

To use *jetting*, the contractor pumps high-pressure water through a pipe to a nozzle located at the pile tip. This loosens the soil in front of the pile, thus allowing it to advance with very few or no hammer blows. Jetting is useful in sandy and gravelly soils, but is ineffective in clays. It is most often used to quickly penetrate through sandy layers to reach deeper bearing strata.

Spudding consists of driving hard metal points into the ground, and then removing them and driving the pile into the resulting hole. This method is much less common than predrilling or jetting, and is most often used to punch through thin layers of hard rock.

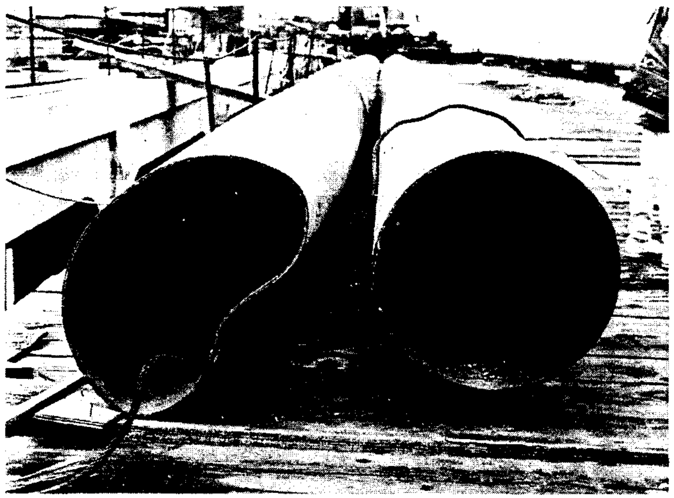


Figure 11.23 These steel pipe piles were used to support a temporary pier while the permanent pier (on the left) was under construction. Afterwards, they were extracted. The pile on the left experienced damage during driving, probably as a result of hitting an underground obstruction.

Pile Arrangements and Geometries

Usually each member of the superstructure that requires a foundation (for example, each column in a building) is supported on a group of three or more piles. *Pile groups* are used instead of single piles because:

- A single pile usually does not have enough capacity.
- Piles are *spotted* or located with a low degree of precision, and can easily be 150 mm (6 in) or more from the desired location, as shown in Figure 11.24. If a column for a building, which is located with a much greater degree of precision, were to be supported on a single pile, the centerlines would rarely coincide and the resulting eccentricity would generate unwanted moments and deflections in both the pile and the column. However, if the column is supported on three or more piles, any such eccentricities are much less significant.

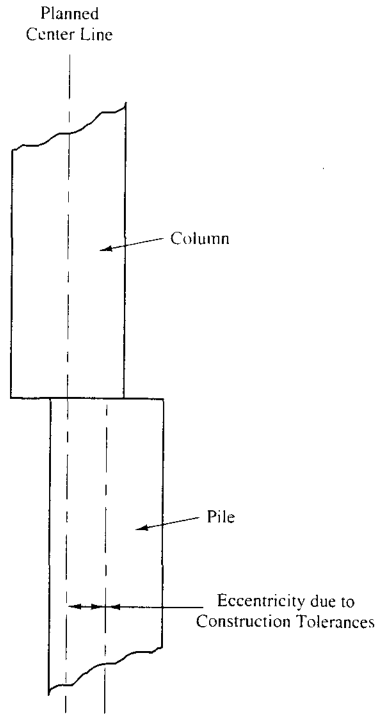


Figure 11.24 Unanticipated eccentricities between columns and single piles caused by construction tolerances.

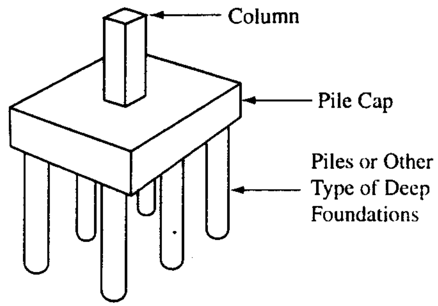


Figure 11.25 A pile cap is a structural member that connects the piles in a group.

- Multiple piles provide redundancy, and thus can continue to support the structure even if one pile is defective.
- The lateral soil compression during pile driving is greater, so the side friction capacity is greater than for a single isolated pile.

Each group of piles is connected with a *pile cap*, as shown in Figure 11.25, which is a reinforced concrete member that is similar to a spread footing. Its functions are to distribute the structural loads to the piles, and to tie the piles together so they act as a unit. The design of pile caps varies with the number of piles and the structural loads. Figure 11.26 shows typical pile cap layouts. Sometimes the individual pile caps are connected with *grade beams*, which are structural beams embedded in the ground. During construction, grade beams resemble continuous footings, but their purpose is significantly different.

QUESTIONS AND PRACTICE PROBLEMS

11.1 Explain the difference between axial loads and lateral loads.

11.2 Discuss some of the primary advantages and disadvantages of the following types of piles and suggest a potential application for each:
- Timber
- Steel
- Prestressed concrete

11.3 What is predrilling and when might it be used? What might happen if the predrill diameter or length was excessive?

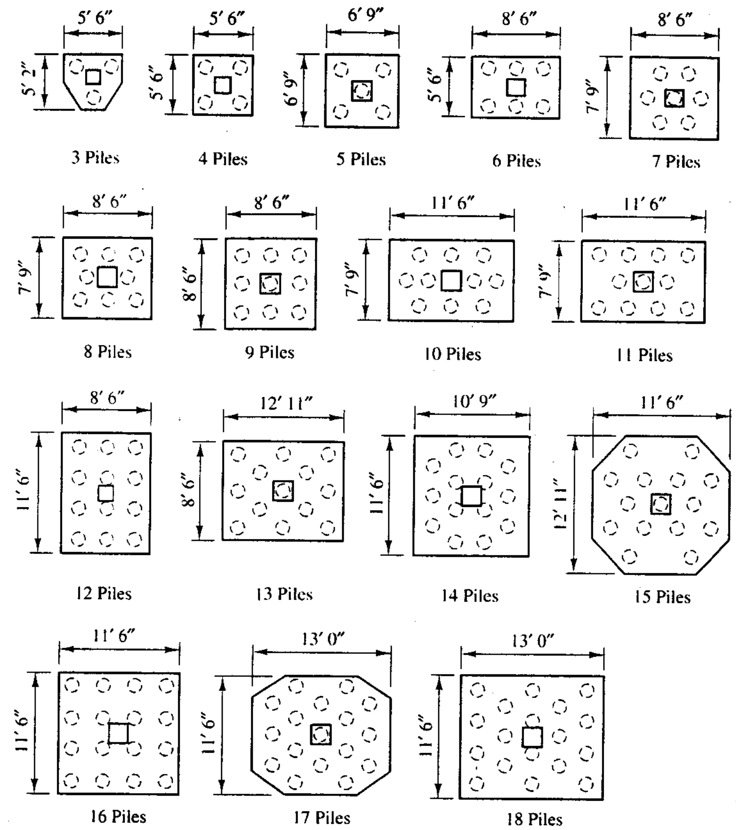


Figure 11.26 Typical configurations of pile caps (Adapted from CRSI, 1992).

11.4 What type or types of piles would be appropriate to support a heavy structure on an undulating bedrock surface located 25 to 40 m below the ground surface? Assume the side friction in the overlying soils provides less than 20 percent of the total axial load capacity. Explain the reasons for your choice.

11.5 Why are most concrete piles prestressed instead of being conventionally reinforced?

11.6 In the context of pile construction, what are cushions, when are they used, and what is their purpose?

11.7 Pile foundations that support buildings usually have at least three piles for each column. Why?

11.8 Pile driving in loose sands without predrilling tends to densify these soils. What effect does this densification have on the load bearing capacity of such piles?

11.4 DRILLED SHAFTS

Drilled shafts are another common type of deep foundation. The fundamental difference between piles and drilled shafts is that piles are prefabricated members driven into the ground, whereas drilled shafts are cast-in-place.

The construction procedure in competent soils, known as the *dry method*, is generally as follows:

1. Using a *drill rig*, excavate a cylindrical hole (the *shaft*) into the ground to the required depth, as shown in Figure 11.27a.
2. Fill the lower portion of the shaft with concrete as shown in Figure 11.27b.
3. Place a prefabricated reinforcing steel cage inside the shaft as shown in Figure 11.27c.
4. Fill the shaft with concrete as shown in Figure 11.27d.

Alternative construction procedures for use in difficult soils are discussed later in this chapter.

Engineers and contractors also use other terms to describe to this type of deep foundation, including the following:

- *Pier*
- *Drilled pier*
- *Bored pile*
- *Cast-in-place pile*
- *Caisson*
- *Drilled caisson*
- *Cast-in-drilled-hole (CIDH) foundation*

However, drilled shafts are not the same as certain other methods that also involve cast-in-place concrete, such as *auger-cast piles*, *pressure injected footings*, *step-taper piles*, and *grouted anchors*. They are covered later in this chapter.

History

The quality of soils usually improves with depth, so it often is helpful to excavate through weak surface soils to support structures on deeper bearing materials. Even the ancient Greeks understood the value of removing poor quality soils (Kerisel, 1987).

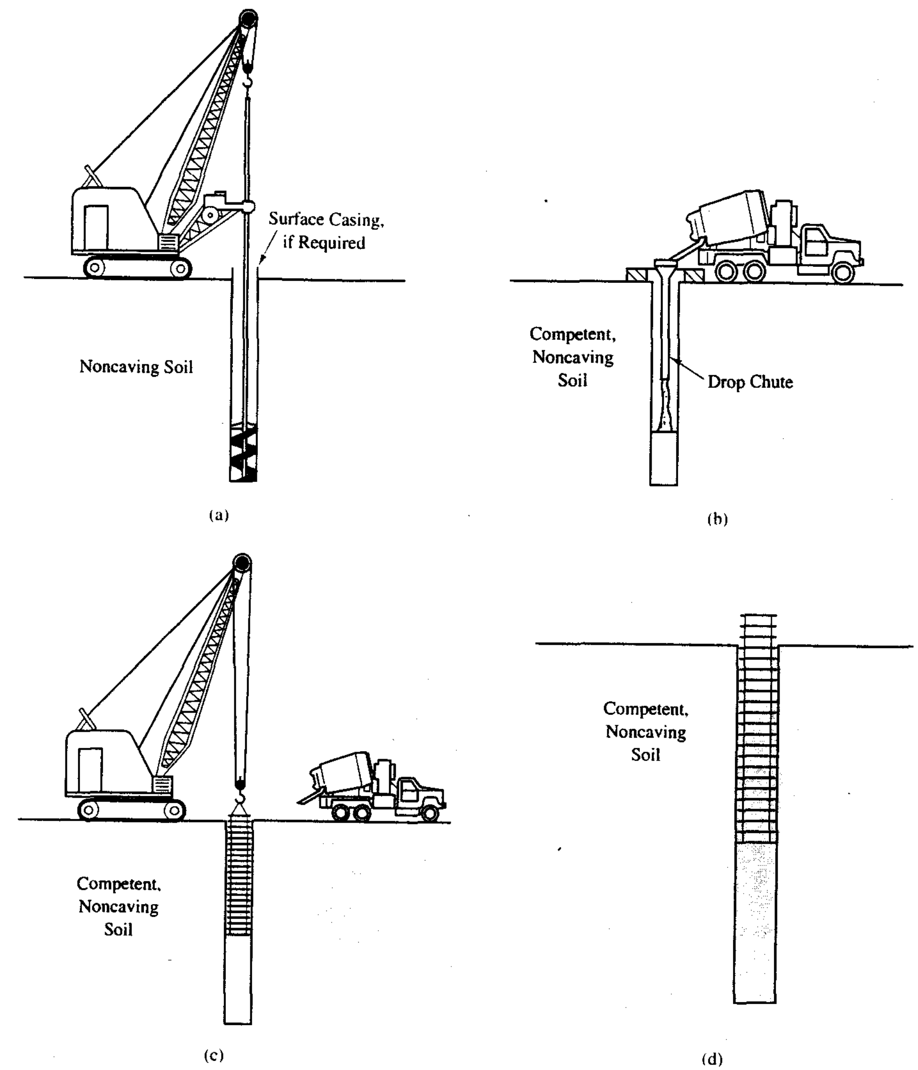


Figure 11.27 Drilled shaft construction in competent soils using the dry method: (a) Drilling the shaft; (b) Starting to place the concrete; (c) Placing the reinforcing steel cage; and (d) Finishing the concrete placement (Reese and O'Neill, 1988).

During the late nineteenth and early twentieth centuries, builders began to modify the traditional techniques of reaching good bearing soils. Many of the greatest advances occurred in the large cities of the Great Lakes region. As taller and heavier buildings began to appear, engineers realized that traditional spread footing foundations would no longer suffice. Following many years of problems with excessive settlements, they began to use foundation systems consisting of a single hand-dug shaft below each column.

General William Sooy-Smith was one of the pioneers in this new technology. His *Chicago Well Method*, developed in 1892, called for the contractor to hand-excavate a cylindrical hole about 1 m (3 ft) in diameter and 0.5 to 2 m (2–6 ft) deep, as shown in Figure 11.28. To prevent caving, they lined its wall with vertical wooden boards held in place with steel rings, and then repeated the process until reaching the bearing stratum. Finally, they enlarged the base of the excavation to form a bell and filled it with concrete up to the ground surface.

Hand excavation methods were slow and tedious, so the advent of machine-dug shafts was a natural improvement. The early equipment was similar to that used to drill oil wells, so much of the early development occurred in oil-producing areas, especially Texas and California. A few examples of horse- and engine-driven drills appeared between 1900 and 1930, but they had very limited capabilities. By the late 1920s, manufacturers were building practical truck-mounted engine-driven drill rigs, such as the one in Figure 11.29, thus bringing drilled shaft construction into its maturity.

During the next thirty five years, manufacturers and contractors developed larger and more powerful equipment along with a variety of cutting tools. They also borrowed construction techniques from the oil industry, such as casing and drilling mud, to deal with difficult soils. By the 1960s, drilled shafts had become a strong competitor to driven piles.

Today, drilled shafts support structures ranging from one story wood frame buildings to the largest skyscrapers. For example, the Sears Tower in Chicago is supported on 203 drilled shafts, some of them 30 m (100 ft) deep.

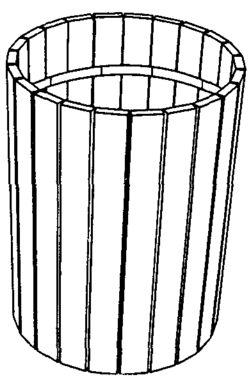


Figure 11.28 Early shaft construction using the Chicago Well Method. This is one set of wooden shores; the excavation would continue with additional sets until reaching the desired depth.

Figure 11.29 Early truck mounted drill rig and crew, circa 1925 (ADSC: The International Association of Foundation Drilling).

The advantages of drilled shaft foundations include the following:

- The costs of mobilizing and demobilizing a drill rig are often much less than those for a pile driver. This is especially important on small projects, where they represent a larger portion of the total costs.
- The construction process generates less noise and vibration, both of which are especially important when working near existing buildings.
- Engineers can observe and classify the soils excavated during drilling and compare them with the anticipated soil conditions.
- Contractors can easily change the diameter or length of the shaft during construction to compensate for unanticipated soil conditions.
- The foundation can penetrate through soils with cobbles or boulders, especially when the shaft diameter is large. It is also possible to penetrate many types of bedrock.
- It is usually possible to support each column with one large shaft instead of several piles, thus eliminating the need for a pile cap.

The disadvantages include the following:

- Successful construction is very dependent on the contractor's skills, much more so than with spread footings or even driven piles. Poor workmanship can produce weak foundations that may not be able to support the design load. Unfortunately, most of these defects are not visible. This is especially important because a single drilled shaft does not have the benefit of redundancy that is present in a group of driven piles.

- Driving piles pushes the soil aside, thus increasing the lateral stresses in the soil and generating more side friction capacity. However, shaft construction removes soil from the ground, so the lateral stresses remain constant or decrease. Thus, a shaft may have less side friction capacity than a pile of comparable dimensions. However, this effect is at least partially offset by rougher contact surface between the concrete and the soil and the correspondingly higher coefficient of friction.
- Pile driving densifies the soil beneath the tip, whereas shaft construction does not. Therefore, the unit end bearing capacity in shafts may be lower.
- Full-scale load tests are very expensive, so the only practical way to predict the axial load capacity is to use semiempirical methods based on soil properties. We typically have no independent check. However, the Osterberg load test device and high-strain dynamic impact tests, discussed in Chapters 12 and 15, may overcome this problem.

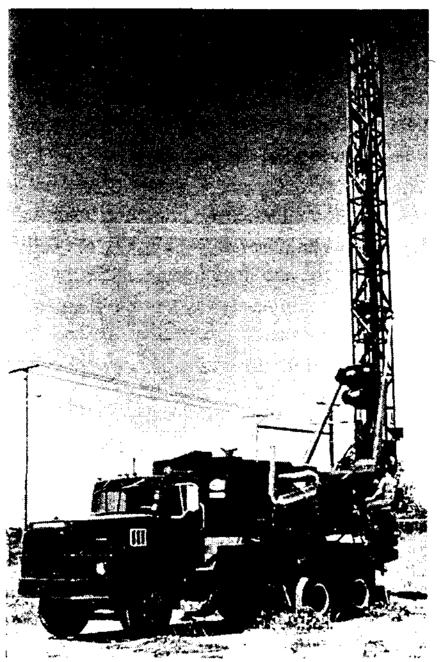


Figure 11.30 Typical drilling rig for constructing drilled shafts. This rig is able to drill shafts up to 1800 mm (72 inches) in diameter and 24 m (80 ft) deep. (ADSC: The International Association of Foundation Drilling).

Modern Construction Techniques

Contractors use different equipment and techniques depending on the requirements of each project (Greer and Gardner, 1986). The design engineer must be familiar with these methods to know when and where drilled shafts are appropriate. The construction method also influences the shaft's load capacity, so the engineer and contractor must cooperate to assure compatibility between the design and construction methods.

Drilling Rigs

Most drilled shafts are 500 to 1200 mm (18–48 inches) in diameter and 6 to 24 m (20–80 ft) deep. A typical modern truck-mounted drilling rig, such as the one shown in Figure 11.30, would typically be used to drill these shafts. Specialized rigs, such as those in Figures 11.31 and 11.32, are available for difficult or unusual projects. Some rigs are capable of drilling shafts as large as 8 m (26 ft) in diameter and up to 60 m (200 ft) deep.

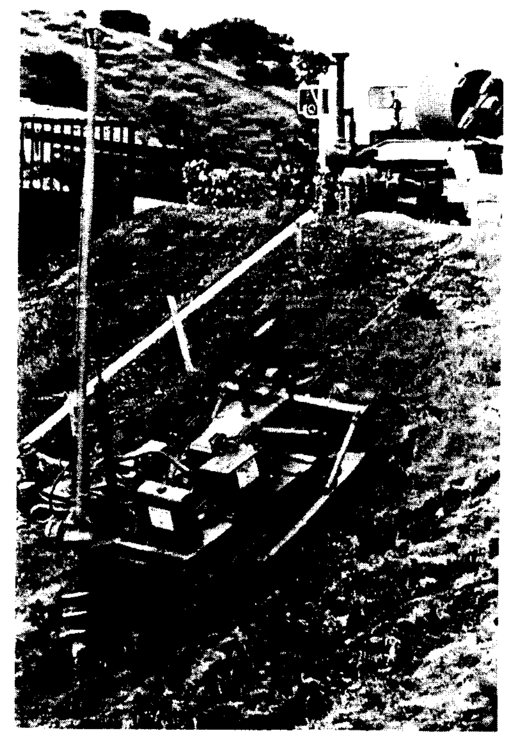


Figure 11.31 Small track-mounted drilling rig capable of working on a hillside (ADSC: The International Association of Foundation Drilling).

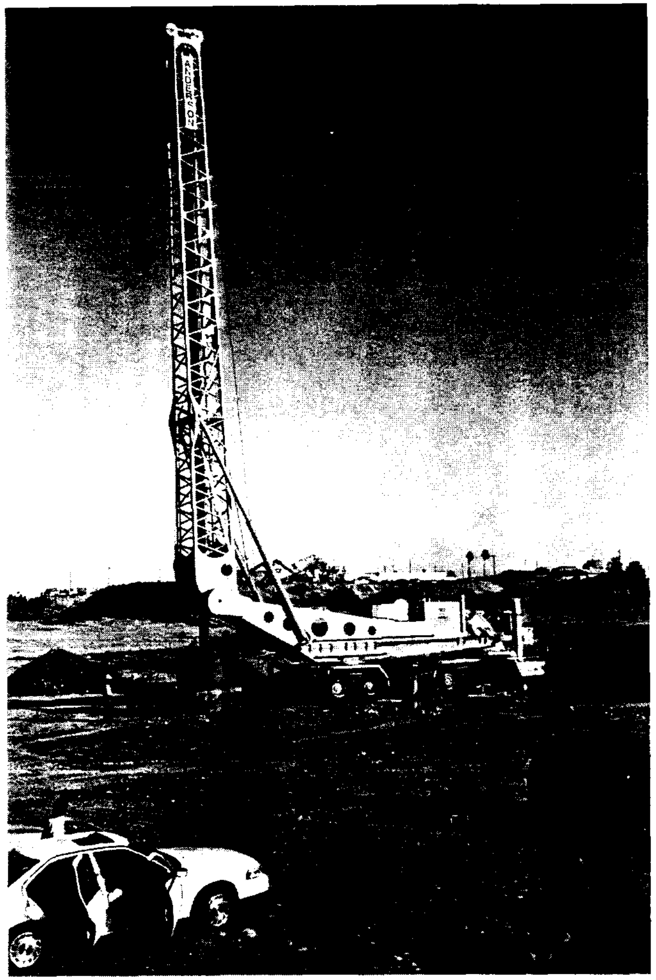


Figure 11.32 Extremely large drill rig capable of drilling 8 m (26 ft) diameter holes to depths of 60 m (200 ft) (Anderson Drilling Co.)

Drilling Tools

Contractors have different drilling tools, each suited to a particular subsurface condition or drilling technique. The helix-shaped *flight auger*, shown in Figure 11.33, is most common.

The drill rig rotates the auger into the ground until it fills with soil. Then, it draws the auger out and spins it around to remove the cuttings, as shown in Figure 11.34. This process repeats until the shaft reaches the desired depth.

Conventional flight augers are effective in most soils and soft rocks. However, when encountering difficult conditions, the contractor has the option of switching to special augers or other tools. For example, augers with hardened teeth and pilot *stingers* are effective in hardpan or moderately hard rock. Spiral-shaped rooting tools help loosen cobbles and boulders, thus allowing the hole to advance under conditions that might cause refusal in a driven pile. Some of these special tools are shown in Figure 11.35.

Other drilling tools include:

- *Bucket augers* that collect the cuttings in a cylindrical bucket that is raised out of the hole and emptied. They are especially useful in running sands.
- *Belling buckets* that have extendable arms to enlarge the bottom of the shaft. These enlargements are called *bells* or *underreams*.
- *Core barrels* that cut a circular slot, creating a removable cylindrical core. They are especially useful in hard rock.
- *Multiroller percussion bits* to cut through hard rock.
- *Cleanout buckets* to remove the final cuttings from a hole and produce a clean bottom suitable for end bearing.

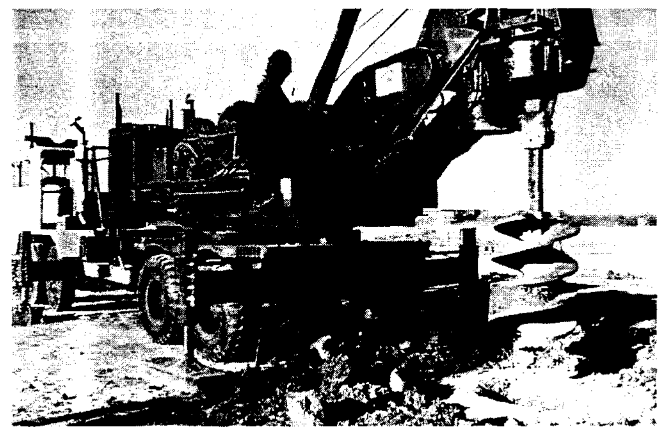


Figure 11.33 Typical flight auger (ADSC: The International Association of Foundation Drilling).

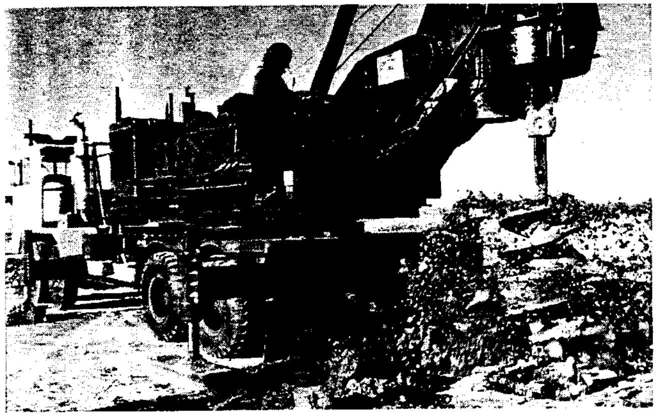
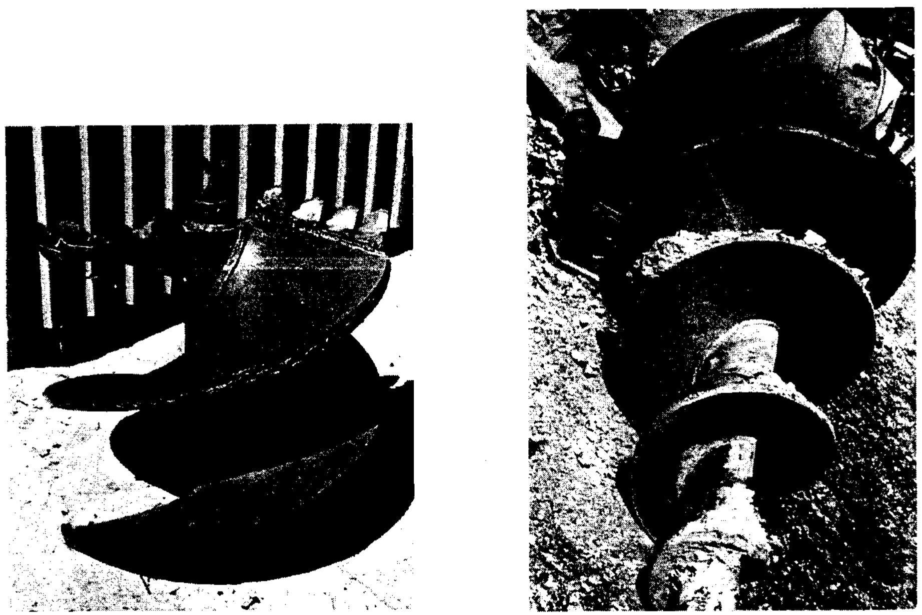
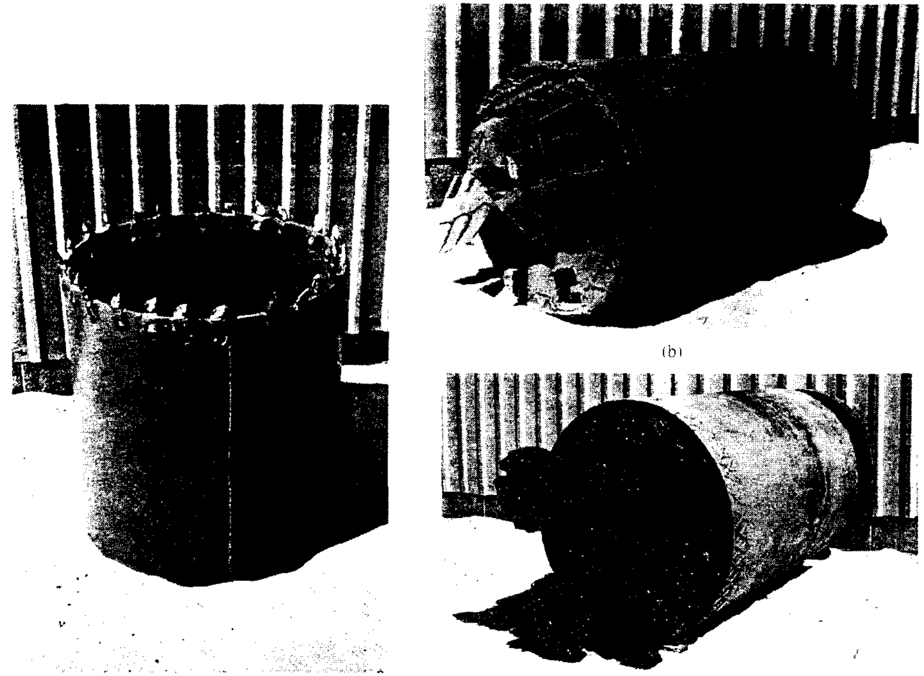


Figure 11.34 Spinning the auger to remove the cuttings (ADSC: The International Association of Foundation Drilling).



(a) (b)

Figure 11.35 Special flight augers for difficult subsurface conditions (a) Auger with hardened teeth and a stinger; (b) Spiral-shaped rooting auger (ADSC: The International Association of Foundation Drilling).



(a) (b) (c)

Figure 11.36 Special drilling tools (a) Core barrel; (b) Bucket auger; (c) Multiroller percussion bits (ADSC: The International Association of Foundation Drilling).

Some of these tools are shown in Figure 11.36.

Drilling Techniques in Firm Soils

In firm soils, contractors use the *dry method* (also known as the *open-hole method*) to build the shaft, as shown in Figure 11.27. These holes usually advance quickly using conventional flight augers and remain open without any special support. After checking the open hole for cleanliness and alignment, it is a simple matter to insert the steel reinforcing cage and dump concrete in from the top. Some contractors use a tremie or a concrete pump to deliver the concrete. Open-hole shafts in firm soils are very common because of their simplicity and economy of construction and their good reliability.

It also is possible to excavate stiff soils below the groundwater table using the open-hole method. Usually, the contractor simply pumps the water out as the hole advances and places the concrete in the dewatered shaft.

Drilling Techniques in Caving or Squeezing Soils

A hole is said to be *caving* when the sides collapse before or during concrete placement. This is especially likely in clean sands below the groundwater table. *Squeezing* refers to the sides of the hole bulging inward, either during or after drilling, and is most likely in soft clays and silts or highly organic soils. Either of these conditions could produce *necking* in the shaft (a local reduction in its diameter) or soil inclusions in the concrete, as shown in Figure 11.37, both of which could have disastrous consequences.

The two most common construction techniques for preventing these problems are the use of *casing* or the use of *drilling fluid*.

The casing method, shown in Figure 11.38, uses the following procedure:

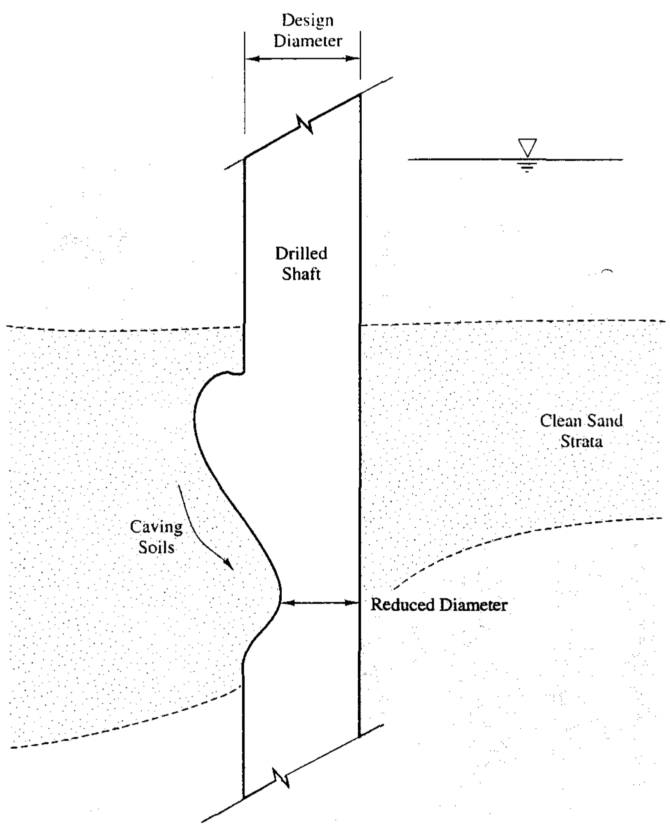


Figure 11.37 Possible consequences of caving or squeezing soils.

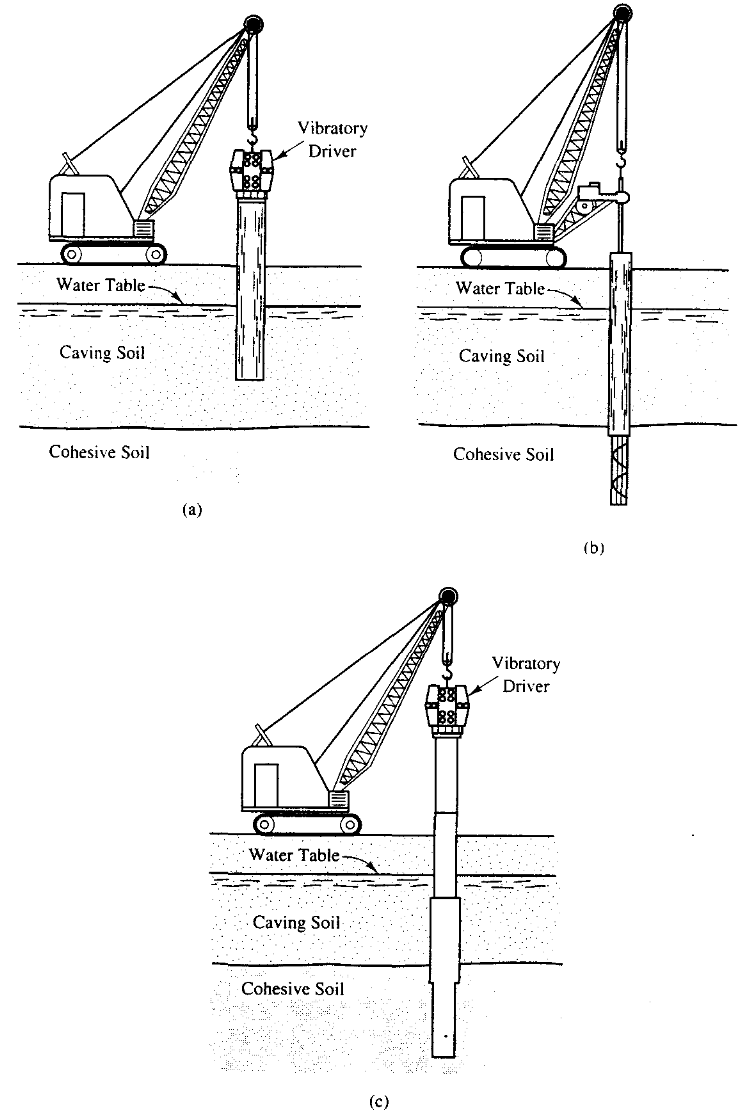


Figure 11.38 Using casing to deal with caving or sqeezing soils: (a) Installing the casing; (b) Drilling through and ahead of the casing; and (c) Placing the reinforcing steel and concrete, and removing the casing (Reese and O'Neill, 1988).

1. Drill the hole using conventional methods until encountering the caving strata.
2. Insert a steel pipe (the casing) into the hole and advance it past the caving strata as shown in Figure 11.38a and 11.39. Contractors do this using vibratory hammers such as the one in Figure 11.21. The diameter of this casing is usually 50 to 150 mm (2–6 in) less than the diameter of the upper part of the shaft.
3. Drill through the casing and into the non-caving soils below using a smaller diameter auger as shown in Figure 11.38b.
4. Place the reinforcing steel cage and the concrete through the casing and extract the casing as shown in Figure 11.38c. This is a very critical step, because premature extraction of the casing can produce soil inclusions in the shaft.

Figure 11.39 The contractor at this site is using casing. The first casing, visible at the bottom of the photograph, is already in place. However, its length is limited by the height of the rig. When casing must extend to greater depths, a second smaller casing is installed by passing it through the first casing, as shown here.

There are many variations to this method, including the option of leaving the casing in place and combining the casing and slurry methods.

The drilling fluid method (also known as the *slurry method*) is shown in Figure 11.40. It uses the following procedure:

1. Drill a *starter hole*, perhaps 3 m (10 ft) deep.
2. Fill the starter hole with a mixture of water and bentonite clay to form a *drilling mud* or *slurry*. When sea water is present, use attapulgite clay instead of bentonite. When properly mixed, the drilling mud has the appearance of very dirty water and keeps the hole open because of the hydrostatic pressure it applies to the soil.
3. Advance the hole by passing the drilling tools through the slurry as shown in Figure 11.39a. Continue to add water and bentonite as necessary.
4. Insert the reinforcing steel cage directly into the slurry as shown in Figure 11.39b.
5. Fill the hole with concrete using a *tremie pipe* that extends to the bottom as shown in Figure 11.39c. The concrete pushes the slurry to the ground surface, where it is captured.

Do not be concerned about the quality of the bond between the rebar and the concrete. Although the rebar is first immersed in slurry, research has shown that the bond is satisfactory. However, the slurry can form a cake on and in the surrounding soil, thus reducing the side friction resistance. Some specifications require the contractor to "scour" the sides of the holes to remove the slurry cake before placing the concrete.

Underreamed Shafts

An *underreamed shaft* (also known as a *belled shaft*) is one with an enlarged base, as shown in Figure 11.41. Usually, the ratio of the underream diameter to the shaft diameter (B_b/B_s) should be no greater than 3. Contractors build underreams using special belling buckets, such as the one shown in Figure 11.42.

The larger base area of underreamed shafts increases their end bearing capacity, and thus they are especially useful for shafts bottomed on strong soils or rock. However, the displacement required to mobilize the full end bearing is typically on the order of 10 percent of the base diameter, which may be more than the structure can tolerate. Underreamed shafts also have greater uplift capacities due to bearing between the ceiling of the underream and the soil above.

Unfortunately, the construction of underreamed shafts can be hazardous to the construction workers. In addition, the bottom of the underream must be cleaned of loose soil before placing concrete, and this process can be difficult and expensive.

Underreamed shafts are not being built as often as they were in the past, primarily because it is often more cost-effective to simply drill a deeper straight shaft and rely on the additional side friction. However, underreamed shafts are still built, especially when a firm bearing stratum is available.

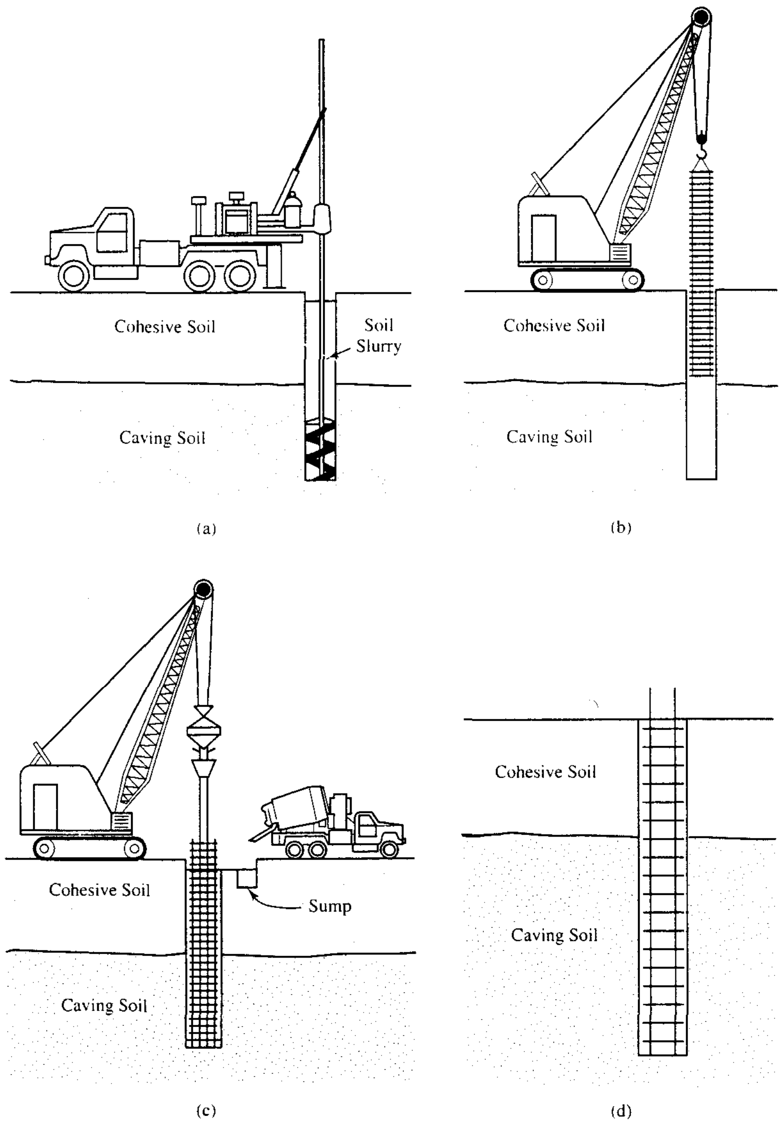


Figure 11.40 Using drilling fluid to deal with caving or squeezing soils: (a) Drilling the hole using slurry; (b) Installing the reinforcing steel cage through the slurry; (c) Placing the concrete using a tremie pipe and recovering slurry at the top; and (d) The completed foundation (Reese and O'Neill, 1988).

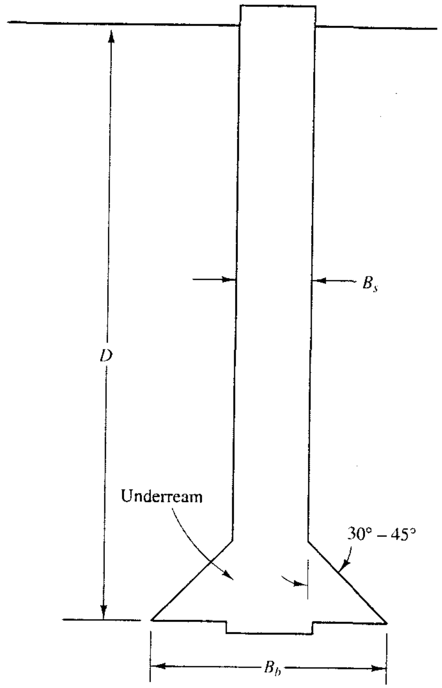


Figure 11.41 An underreamed drilled shaft.

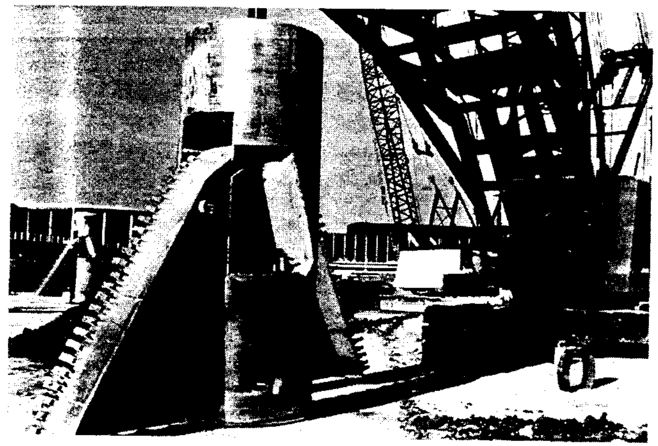


Figure 11.42 A belling bucket used to produce a bell or underream at the bottom of a shaft (ADSC: The International Association of Foundation Drilling).

Concrete

Concrete for drilled shafts must have sufficient slump to flow properly and completely fill the hole. Using concrete that is too stiff creates voids that weaken the shaft. Typically, the slump should be between 100 and 220 mm (4–9 in), with the lower end of that range being most appropriate for large-diameter dry holes with widely spaced reinforcement and the high end for concrete placed under drilling fluid. Sometimes it is appropriate to include concrete admixtures to obtain a high slump while retaining sufficient strength.

Some people have experimented with expansive cements in drilled shaft concrete. These cements cause the concrete to expand slightly when it cures, thus increasing the lateral earth pressure and side friction resistance. So far, this has been only a research topic, but it may become an important part of future construction practice.

QUESTIONS AND PRACTICE PROBLEMS

11.9 Describe two situations where a drilled shaft would be preferable over a driven pile, then describe two situations where the reverse would be true.

11.10 In what circumstances would you expect caving or squeezing conditions to be a problem? What construction methods could a contractor use to overcome these problems?

11.11 The dry method of drilled shaft construction is most suitable for which types of soil conditions?

11.5 CAISSONS

The word *caisson* is derived from the French *caisse*, which means a chest or box. When applied to foundation engineering, it describes a prefabricated hollow box or cylinder that is sunk into the ground to some desired depth and then filled with concrete, thus forming a foundation.[1] Caissons have most often been used in the construction of bridge piers and other structures that require foundations beneath rivers and other bodies of water because the caissons can be floated to the job site and sunk into place.

Open Caissons

An *open caisson* is one that is open to the atmosphere, as shown in Figure 11.43. They may be made of steel or reinforced concrete, and normally have pointed edges at the bottom to facilitate penetration into the ground.

[1]The word "caisson" also is sometimes used to describe drilled shaft foundations because they were originally developed as "machine-dug caissons." However, this use of the term is confusing and should be avoided.

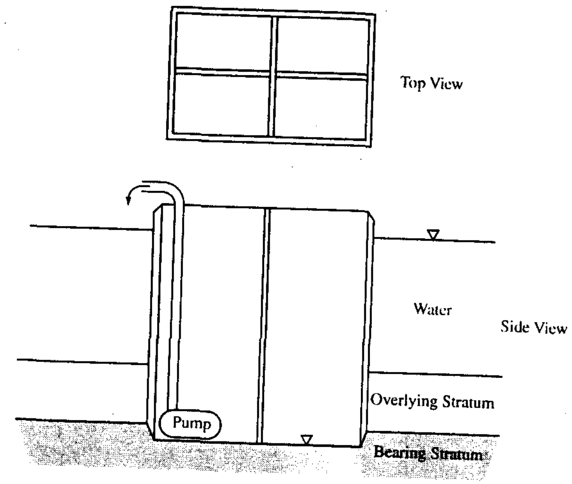


Figure 11.43 An open caisson.

Sometimes the site of the proposed foundation is dredged[2] before the caisson arrives on site. The dredging operation can be an economical way to remove some of the upper soils, thus reducing the quantities that must be excavated through the caisson. Then the caisson is floated into place and sunk into the soil. As it descends, the soil inside is removed and hauled out of the top and water that accumulates inside is pumped out. This process continues until the caisson sinks to the required depth and reaches the bearing stratum. It then is filled with concrete to form the foundation.

Caissons must be designed to resist the various loads imparted during construction, as well as the structural and hydrodynamic loads from the completed structure. In addition, it must have sufficient weight to overcome the side friction forces as it descends into the ground.

Pneumatic Caissons

When the excavation inside open caissons extends well below the surrounding water level, water flowing into the bottom can produce a quick condition in the soils as shown in Figure 11.44. This is most likely to occur in clean sands and is caused by the upward seepage forces of the flowing water.

One way to counteract this problem is to seal the bottom portion the caisson and fill it with compressed air, as shown in Figure 11.45. If the air pressure equals or exceeds the

[2]Dredging is the process of removing soil from the bottom of a body of water. This is normally done using specially-equipped ships, normally for the purpose of providing sufficient water depth for larger ships.

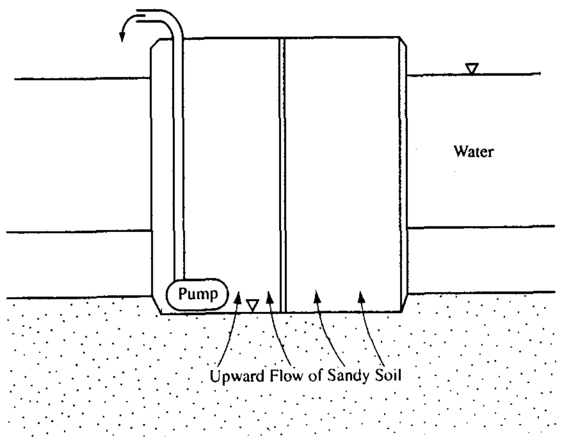


Figure 11.44 Development of a quick condition beneath an open caisson.

pore water pressure, very little water enters the excavation, thus eliminating the seepage forces and the potential for quick conditions. In addition, the required pumping costs then become minimal. This method was first used around 1850 by the British engineer Isambard Kingdom Brunel (1806–1859) during construction of the Chepstow Bridge across the Thames River in London. Many bridge foundations in North America also have been

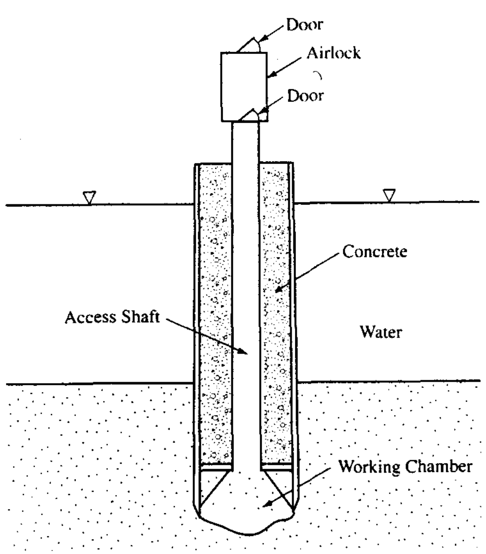


Figure 11.45 A pneumatic caisson uses compressed air to halt the flow of groundwater.

built using this method, including the Brooklyn and Williamsburg Bridges in New York City.

For example, an excavation 50 ft below the groundwater table would require a pressure, p, of about:

$$p \approx u = \gamma_w z_w = (62.4\ \text{lb/ft}^3)(50\ \text{ft})\left(\frac{1\ \text{ft}^2}{144\ \text{in}^2}\right) = 22\ \text{lb/in}^2$$

This is the same pressure a diver would encounter 50 ft below the water surface in a lake. Construction personnel, who are called *sandhogs*, can work for three-hour shifts under such pressures. In some cases, air pressures up to 48 lb/in^2 (35 kPa) may be used, but the shift time drops to only thirty minutes (White, 1962).

Workers enter these excavations by passing through an air lock, which is an intermediate chamber with doors connected to the outside and to the working chamber. The workers enter through the outside door, then both doors are closed and the chamber is slowly filled with compressed air. When the pressure reaches that in the working chamber, the workmen open the connecting door and enter the working chamber. The process is reversed when exiting.

If the air pressure in the air lock is lowered too quickly, nitrogen bubbles form inside the workers bodies, causing *caisson disease*, also known as *the bends*. It causes severe pains in the joints and chest, skin irritation, cramps, and paralysis. Fourteen men died of caisson disease during construction of the Eads Bridge in St. Louis. Divers can experience the same problem if they rise to the surface too quickly.

Because of the hazards of working under compressed air, the large expense of providing the necessary safety precautions for the workers, and the availability of other foundation types, pneumatic caissons are rarely used. However, in some circumstances they can be economically viable. For example, foundations for the proposed Great Belt Bridge in Denmark are to be built using pneumatic caissons (Prawit and Volmerding, 1995).

11.6 MANDREL-DRIVEN THIN-SHELLS FILLED WITH CONCRETE

One method of combining some of the best features of driven piles and cast-in-place drilled shafts is to use a mandrel-driven thin shell, as shown in Figure 11.46. Alfred Raymond developed an early version of this method in 1897 and later refined it to create the *step-taper pile*.

This type of foundation is built as follows:

1. Hold a steel mandrel in the leads of the pile driver. This mandrel is cylindrical and matches the inside of the thin shell. The purpose of the mandrel is to transmit the driving stresses from the hammer to the sides and bottom of the shell.
2. Pull the thin shell (which resembles corrugated steel drain pipe) onto the mandrel.
3. Drive the mandrel and shell into the ground using a pile hammer.

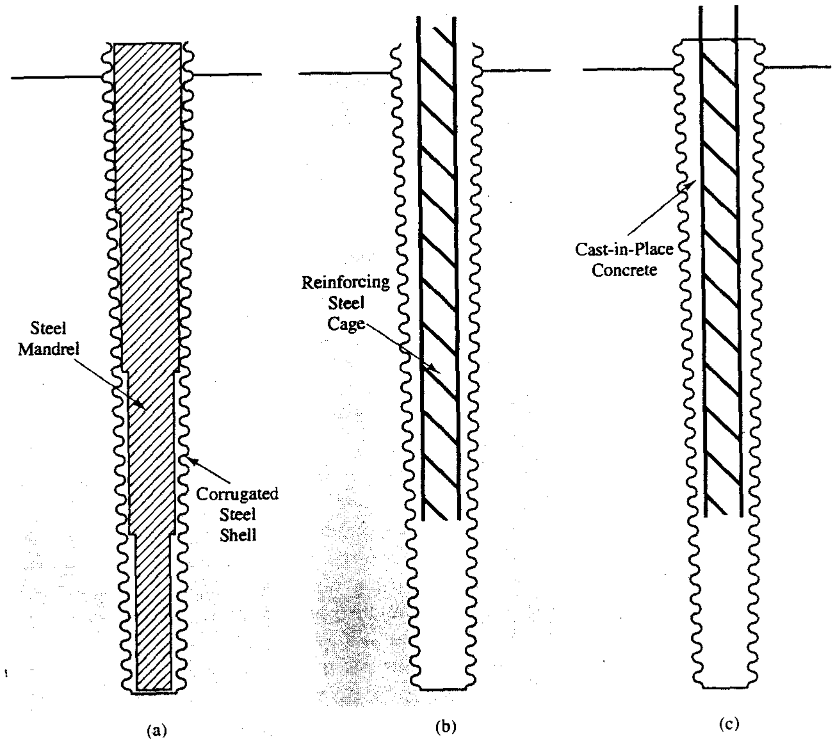


Figure 11.46 Construction of mandel-driven thin-shell pile filled with concrete: (a) drive the thin shell into the ground using a steel mandrel; (b) Remove the mandrel and insert a cage of reinforcing steel; and (c) fill the shell with concrete.

4. Remove the mandrel and inspect the shell.
5. (optional) Place a cage of reinforcing steel into the shell.
6. Fill the shell with concrete.

The advantages of this design include:

- The shell provides a clean place to cast the concrete, so the structural integrity may be better than a drilled shaft.
- The displacement developed during driving and the corrugations on the shell produce high side friction resistance.

- The shells and mandrel can be shipped to the job site in pieces and assembled there, so it is possible to build long piles.

However, it also has disadvantages:

- It is necessary to mobilize a pile driver and other equipment, so the cost per pile will be at least as high as that for conventional driven piles.
- They cannot be spliced, so the total length is limited by the height of the pile driver.

11.7 AUGER-CAST PILES

The *auger-cast pile* is a type of cast-in-place pile developed in the United States during the late 1940s and early 1950s (Neate, 1989). They are known by many names (DFI, 1990), including:

- Augered pressure grouted (APG) pile
- Augered cast-in-place pile
- Continuous flight auger pile
- Intruded mortar piles
- Augerpress pile
- AugerPile
- Grouted bored pile
- Augered grout-injected pile

Specialty contractors build auger-cast piles as described below and as shown in Figure 11.47:

1. Using a hollow-stem auger with a temporary bottom plug, drill to the required depth. In the United States, 300, 350, or 400 mm (12, 14, or 16 inch) diameter augers are most common. Japanese contractors have built piles as large as 1 m (39 inches) in diameter. This equipment is similar to, but larger than, the hollow-stem augers used for soil exploration purposes. These augers are suspended from a crane and driven by a pneumatic or hydraulic motor. The depth of the pile may be as great as 27 m (90 ft), but lengths of 6 to 15 m (20–50 ft) are more typical.
2. Inject cement grout (sand, portland cement, and water) under high pressure through the middle of the auger. This grout forces the bottom plug out and then begins to flow out of the bottom of the auger.
3. While the grout is being injected, slowly and smoothly raise and rotate the auger to form the pile while bringing the soil cuttings to the ground surface.
4. Upon reaching the ground surface, remove the auger and insert reinforcing steel into the grouted hole. This may consist of a single centrally located bar or a prefab-

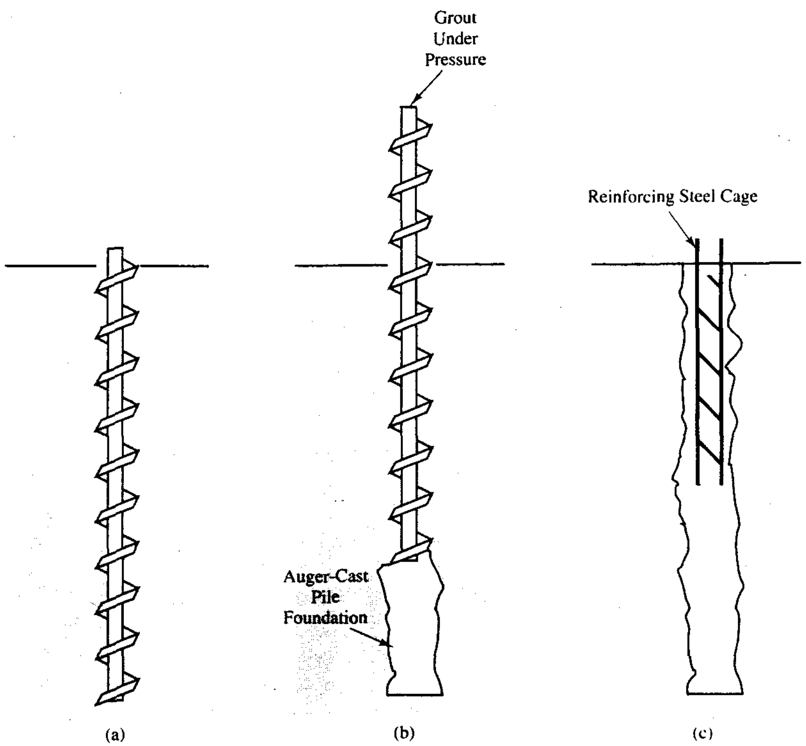


Figure 11.47 Construction of an auger-cast pile: (a) Drill to the required depth using a hollow-stem auger; (b) Withdraw the auger while injecting cement grout; (c) Install steel rebars (optional).

ricated steel cage. Because the grout has a very high slump and no gravel, it is possible to insert the steel directly into the newly grouted pile.

The advantages of this method include:

- The cost of construction is low, partly because the crane can be rented locally, thus reducing mobilization costs.
- The noise and vibration levels are much lower than those with driven piles.
- The auger protects the hole from caving, thus reducing the potential for ground movements during drilling.

- The grout is injected under pressure, so it penetrates the soil and provides and good bond. The pressure also provides some compaction of the soil.
- The technique is usable in a wide variety of soils, including some of those that might cause difficulties with driven piles or drilled shafts.

However, it also has disadvantages (Massarsch et al., 1988; Brons and Kool, 1988):

- The quality and integrity of the completed pile are very dependent on the skills of the contractor. For example, if the auger is raised too quickly or not rotated sufficiently, the concrete may become contaminated with soil. It is also difficult for the equipment operator to judge the correct grout pressure to use.
- In certain conditions, the augering process can draw up too much soil, thus causing a reduction in the lateral stresses in the ground. For example, if an auger passes through a loose sand, and then encounters a stronger strata, the auger will not advance as quickly, and continued rotation may bring too much of the sand to the surface.
- The construction process is very sensitive to equipment breakdowns. Once grouting has begun, any significant breakdown becomes cause for abandoning the foundation.
- Placement of reinforcing steel cages can be difficult, especially if heavy reinforcement is required. This may limit the pile's ability to resist lateral loads (resist uplift loads by placing a single large bar in the middle of the auger before grouting).
- These piles can not be used in soils that contain cobbles or boulders (the auger will not excavate them) or in thick deposits of highly organic soils (they compress under the grout pressure and thus require excessively large grout volumes).
- Unlike driven piles, there is no hammer blow count to use as an independent check on the pile capacity (the auger torque does not appear to be a good indicator).

Although auger-cast piles typically do not have as great a load capacity as conventional driven piles of comparable dimensions, they are often much less expensive. Because the equipment mobilization costs are much less than those for driven piles, and the technique works well in caving soils, auger-cast piles are most often used on small to medium-size structures on sandy soils.

11.8 PRESSURE-INJECTED FOOTINGS

Edgard Frankignoul developed the pressure-injected footing (PIF) foundation in Belgium before the First World War. This technique uses cast-in-place concrete that is rammed into the soil using a drop hammer. This ramming effect compacts the surrounding soil, thus increasing its load bearing capacity. PIF foundations are often called *Franki piles*. Other names include *bulb pile*, *expanded base pile*, *compacted concrete pile*, and *compacto pile*.

The construction techniques used to build PIFs are described below and shown in Figure 11.48.

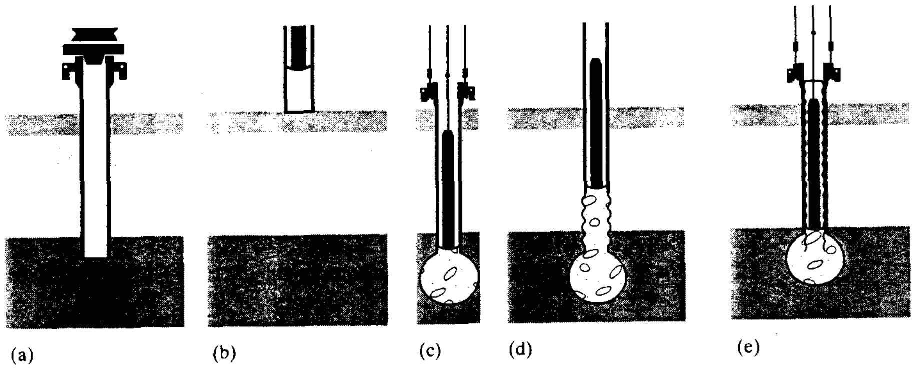


Figure 11.48 Construction of a PIF foundation: (a) top driving; (b) bottom driving; (c) finished base; (d) uncased shaft; and (e) cased shaft (Adapted from brochure by Franki Northwest Co., used with permission.)

Phase 1: Driving

The process begins by temporarily inserting the *drive tube* into the ground. This tube is a specially built 300–600 mm (12–24 in) diameter steel pipe. The contractor does so using one of the following methods:

- *Top driving method*: Install a temporary bottom plate on the drive tube, and then drive the tube to the required depth using a diesel pile hammer. The plate will later become detached when the concrete is pounded through the drive tube.
- *Bottom driving method*: Place a plug of low-slump concrete in the bottom of the tube and pack it in using the drop hammer. Then, continue to strike this plug, thus pulling the tube into the ground.

Phase 2: Forming the Base

Once the drive tube reaches the required depth, hold it in place using cables, place small charges of concrete inside the tube, and drive them into the ground with repeated blows of the drop hammer. This hammer has a weight of 1400 to 4500 kg (3–10 kips) and typically drops from a height of 6 m (20 ft). If the top driving method was used, this process will expel the temporary bottom plate. Thus, a bulb of concrete is formed in the soil, which increases the end-bearing area and compacts the surrounding soil. This process continues until a specified number of hammer blows is required to drive out a certain volume of concrete.

Phase 3: Building the Shaft

The shaft extends the PIF base to the ground surface. Two types of shafts are commonly used:

- To build a *compacted shaft*, raise the drive tube in increments while simultaneously driving in additional charges of concrete. This technique compacts the surrounding soil, thus increasing the side friction resistance. It also increases the end-bearing resistance by providing a stronger soil over the base.
- To build a *cased shaft*, insert a corrugated steel shell into the drive tube, place and compact a zero-slump concrete plug, and withdraw the tube. Then fill the shell with conventional concrete. Although this method does not develop as much load capacity, it is often more economical for piles that are longer than about 9 m (30 ft). A cased shaft may be mandatory if very soft soils, such as peat, are encountered because these soils do not provide the lateral support required for the compacted shaft method.

The contractor can reinforce either type of shaft to resist uplift or lateral loads. For the compacted shaft, the reinforcing cage fits between the drop hammer and the drive tube, thus allowing the hammer to fall freely.

PIF foundations may be installed individually or in a group of two or more and connected with a pile cap. Table 11.1 gives typical dimensions and typical capacities of PIF foundations. The actual design capacity must be determined using the techniques described in Chapter 14. Figure 11.49 shows a "mini" PIF that was extracted out of the ground.

TABLE 11.1 TYPICAL PIF DIMENSIONS AND CAPACITIES

	Typical Allowable Downward Capacity		Base Diameter[a]		Nominal Shaft Diameter			
					Compacted		Cased	
PIF Type	(k)	(kN)	(in)	(mm)	(in)	(mm)	(in)	(mm)
Mini	100	450	24–30	600–750	n/a	n/a	10.6–11.1	270–280
Medium	200	900	34–40	850–1000	17	430	12.2–14	300–360
Standard	400	1800	34–40	850–1000	22	560	16–17.6	400–450
Large	500	2200	34–40	850–1000	23	580	19	480
Maxi	600	2700	34–40	850–1000	25	630	22	560

Adapted from a brochure by Franki Northwest Company. Used with permission.

[a]In very loose soils, the base diameter may be larger than listed here. Conversely, when PIFs are installed in groups, it may be slightly smaller.

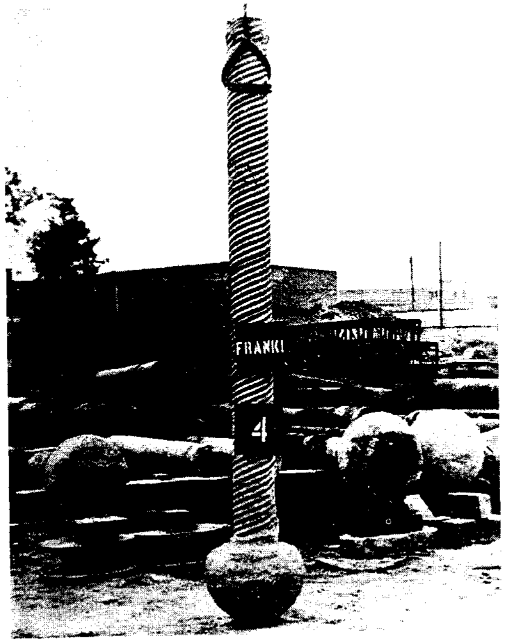


Figure 11.49 This "mini" PIF was extracted from the ground. It had a base diameter of 600 mm (24 in). (Photo courtesy of William J. Neely.)

The advantages of PIF foundations include:

- The construction process compacts the soil, thus increasing its strength and load-bearing capacity. This benefit is most pronounced in sandy or gravelly soils with less than about 15 percent passing the #200 sieve, so PIFs are best suited for these kinds of soils.
- When compacted shafts are used, the construction process produces a rough interface between the shaft and the soil, thus further improving the side friction resistance.
- It is possible to build PIFs with large bases (thus gaining the additional end bearing area) in soils such as loose sands where belled drilled shafts would be difficult or impossible to build.

Disadvantages include:

- The side friction resistance for cased PIFs is unreliable because of the annular space between the casing and the soil. Although this space is filled with sand after the drive tube is lifted, we cannot be certain about the integrity of the connection between the shaft and the soil.

- The construction process generates large ground vibrations and thus may not be possible near sensitive structures. These vibrations also can damage wet concrete in nearby PIFs.
- The construction equipment is bulky and cumbersome, and thus requires large work areas.
- Compacted shafts cannot include large amounts of reinforcing steel.
- Although each PIF will have a higher load capacity than a pile or drilled shaft of comparable dimensions, it also is more expensive to build. Therefore, the engineer must evaluate the alternatives for each project individually to determine which type is most economical.
- They are generally economical only when the length is less than about 9 m (30 ft) for compacted PIFs or about 21 m (70 ft) for cased PIFs.

PIFs with Auger-Cast Shafts

Some contractors have combined a PIF base with an auger-cast shaft (Massarsch et al., 1988). The side friction resistance of this type of foundation will be much greater and more reliable than that of a conventional cased PIF, but not as large as that of a compacted shaft PIF. However, an auger-cast shaft could be built more quickly and at less cost than a compacted shaft PIF, thus providing reasonably high capacity at a moderate cost. Very few of these foundations have been built.

11.9 PILE-SUPPORTED AND PILE-ENHANCED MATS

Most mat foundations are supported directly on the underlying soils, as discussed in Chapter 10. However, when the net bearing pressure is too high or the soil is too compressible, such mats may experience excessive settlements. One option for such situations is to use a *pile-supported mat*, as shown in Figure 11.50. The piles are distributed across the mat, which then acts as a very large pile cap. "Pile"-supported mats also may be built using drilled shafts or other types of deep foundations.

Many pile-supported mats have been designed to transfer all of the structural loads to the deep foundations. However, others partially rely on the bearing pressure between the bottom of the mat and the underlying soil, and use the deep foundations to carry the balance of the load. This later design, which can be called a *pile-enhanced mat* can be much less expensive, and will probably be used more frequently in the future.

11.10 ANCHORS

The term *anchor* generally refers to a foundation designed primarily to resist uplift (tensile) loads. Although most foundations are able to resist some uplift, anchors are designed specifically for this task and are often able to do so more efficiently and at a lower cost.

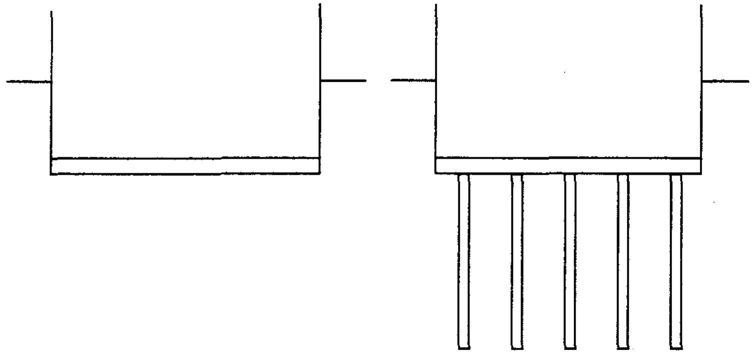


Figure 11.50 A conventional mat foundation and a pile-supported (or pile-enhanced) mat foundation.

Lightweight structures often require anchors because the lateral wind and earthquake loads on the structure often produce uplift loads on some of the foundations. These structures include power transmission towers, radio antennas, and mobile homes. Some of these structures are stabilized with guy wires, which are then connected to the ground using anchors.

Anchors also can be installed horizontally (or nearly so) to provide lateral support to earth retaining structures. These are called *tieback anchors*. They eliminate the need for bracing outside the wall, and thus provide more space for construction and permanent structures.

Kulhawy (1985) divided anchors into three categories, as shown in Figure 11.51. These include:

- *Spread anchors* are specially designed structural members that are driven or inserted into the ground, then expanded or rotated to form an anchor.
- *Helical anchors* are steel shafts with helices that resemble large screws. They are screwed into the ground using specialized equipment, as shown in Figure 11.52.
- *Grouted anchors* are drilled holes filled with a steel tendon and grout. The tendon transmits the tensile loads into the anchor, then the grout transmits them to the surrounding ground through side friction.

The design load capacities may be computed from the geometry and soil type. For helical anchors, the torque required to install the anchor also can be an indicator of load capacity. In critical applications, such as tieback anchors, engineers often load test the installed anchors using hydraulic jacks.

Some anchors also can resist nominal downward, shear, and moment loads, and thus may be used in other foundation applications. For example, helical anchors similar to

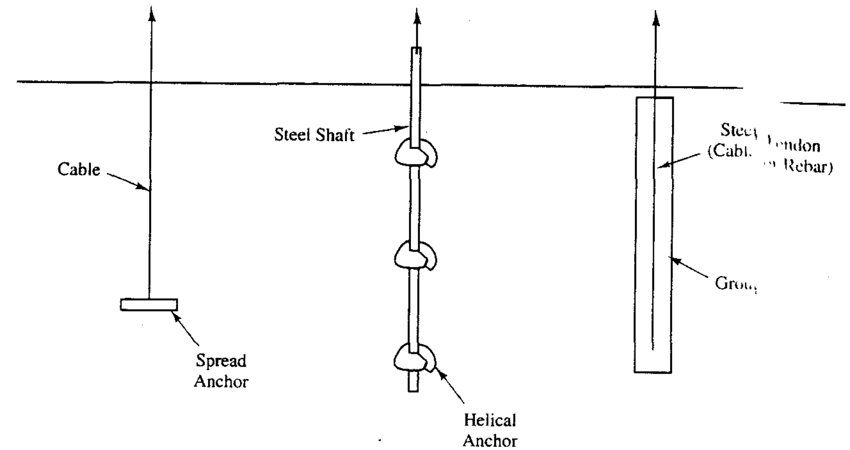


Figure 11.51 Types of anchors (Adapted from Kulhawy, 1985; Used with permission of ASCE).

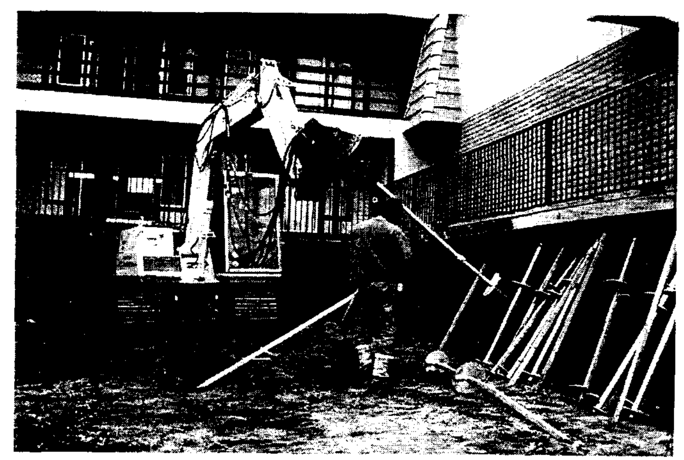


Figure 11.52 Installation of a helical anchor to be used as a tieback for a sheet pile wall. Once these anchors are installed, the soil in the foreground will be excavated (Photo courtesy of A. B. Chance Company).

those in Figure 11.52 may be used to support streetlight standards, signs, cellphone antennas, and other similar structures. In some cases these foundations may be constructed without any concrete, which can be a significant advantage in remote locations. Helical anchors also may be used to underpin spread footings that have experienced excessive settlement.

QUESTIONS AND PRACTICE PROBLEMS

11.12 There are many ways to build midstream foundations for bridges that cross rivers and other bodies of water. One of them is to use a caisson, as described in this section. Another is to drive piles from a barge. Suggest some advantages and disadvantages of these two methods.

11.13 Suggest some critical items that a construction inspector should watch for during the construction of auger-cast piles.

11.14 Pressure-injected footings are best suited for sandy or gravelly soils with less than about 15 percent fines. Why would this construction method be less effective in a stiff saturated clay?

SUMMARY

Major Points

1. Deep foundations are those that transfer some or all of the structural loads to deeper soils.
2. We can classify deep foundations based on the method of construction. Major classifications include
   - piles
   - drilled shafts
   - caissons
   - mandrel-driven thin shells filled with concrete
   - auger-cast piles
   - pressure-injected footings
   - anchors
3. Load transfer analyses normally divide the applied loads into two categories: axial loads (tension and compression) and lateral loads (shear and moment).
4. Deep foundations transfer axial loads to the ground through two mechanisms: side friction and toe bearing.
5. Piles are prefabricated members that are driven or otherwise inserted into the ground. They are made of wood, concrete, steel, and other materials. Each has its advantages and disadvantages, and is best suited for particular applications.
6. Piles are installed using a pile-driving rig equipped with a pile hammer. Once again, a wide range of equipment is available to accommodate various field conditions.

7. Drilled shafts are constructed by drilling a cylindrical hole and casting the concrete in-place. Various methods are available for drilling the hole and for keeping it open until the concrete is placed.
8. An underreamed shaft is one that has an enlarged base. This design increases the allowable toe bearing load.
9. A caisson is a prefabricated box or cylinder that is sunk into the ground to form a foundation. They are most often used for bridges and other structures that require foundations beneath rivers or other bodies of water.
10. Mandrel-driven thin shells filled with concrete are a cross between piles and drilled shafts. These are also known as step-taper piles.
11. Auger-cast piles are constructed by injecting cement grout at high pressure through a hollow-stem auger. They generally have lower capacity than piles or drilled shafts, but also are generally less expensive, especially in squeezing or caving soil conditions.
12. Pressure-injected footings (also known as Franki piles) are made by pounding stiff concrete into the ground to form a bulb. These are high-capacity foundations and are generally used to support high loads in certain kinds of soil profiles.
13. Pile-supported or pile-enhanced mats consist of a mat foundation underlain by a deep foundation. These are often designed so the mat supports some of the load, and the deep foundations support the balance.
14. Anchors are special deep foundations designed primarily to resist tensile forces.

Vocabulary

Anchor	Head	Pressure-injected footing
Appurtenances	Helmet	Prestressed concrete
Auger-cast pile	Hydraulic hammer	Refusal
Axial load	Jetting	Side friction resistance
Caisson	Large displacement pile	Single-acting hammer
Casing method	Lateral load	Slurry method
Caving soil	Mandrel-driven thin shell filled with concrete	Small displacement pile
Closed-end pipe pile		Soil plug
Composite pile	Open caisson	Spudding
Cushion	Open-end pipe pile	Squeezing soil
Deep foundation	Pile cap	Steam hammer
Diesel hammer	Pile hammer	Steel pipe pile
Double-acting hammer	Pile driver	Steel H-pile
Drilled shaft	Pile	Step-taper pile
Drilling rig	Pile-enhanced mat	Toe
Drop hammer	Pile-supported mat	Toe bearing resistance