Module 8
(Lectures 29 to 34)

PILE FOUNDATIONS

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PILE FOUNDATIONS

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1.2 INTRODUCTION
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  ➢ Steel Piles
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1.4 ESTIMATING PILE LENGTH
  ➢ Point Bearing Piles
  ➢ Friction Piles
  ➢ Compaction Piles

1.5 INSTALLATION OF PILES
INTRODUCTION

Piles are structural members that are made of steel, concrete, and/or timber. They are used to build pile foundations, which are deep and which cost more than shallow foundations (chapters 3 and 4). Despite the cost, the use of piles often is necessary to ensure structural safety. The following list identifies some of the conditions that require pile foundations (Vesic, 1977).

1. When the upper soil layer(s) is (are) highly compressible and too weak to support the load transmitted by the superstructure, piles are used to transmit the load to underlying bedrocks or a stronger soil layer, as shown in figure 8.1a. When bedrock is not encountered at a reasonable depth below the ground surface, piles are used to transmit the structural load to the soil gradually. The resistance to the applied structural load is derived mainly from the frictional resistance developed at the soil-pile interface (figure 8.1b).

![Figure 8.1 Conditions for use of pile foundations](image-url)
2. When subjected to horizontal forces (see figure 8.1c), pile foundations resist by bending while still supporting the vertical load transmitted by the superstructure. This type of situation is generally encountered in the design and construction of earth-retaining structures and foundations of tall structures that are subject to high wind and/or earthquake forces.

3. In many cases, expansive and collapsible soils (chapter 11) may be present at the site of a proposed structure. These soils may extend to a great depth below the ground surface. Expansive soils swell and shrink as the moisture content increases and decreases, and the swelling pressure of such soils can be considerable. If shallow foundations are used in such circumstances, the structure may suffer considerable damage. However, pile foundations may be considered as an alternative when piles are extended beyond the active zone, which swells and shrinks (figure 8.1d).

Soils such as loess are collapsible in nature. When the moisture content of these soils increases, their structures may break down. A sudden decrease in the void ratio of soil induces large settlements of structures supported by shallow foundations. In such cases, pile foundations may be used in which piles are extended into stable soil layers beyond the zone of possible moisture change.

4. Foundations of some structures, such as transmission towers, offshore platforms, and basement mats below the water table, are subjected to uplifting forces. Piles are sometimes used for these foundations to resist the uplifting force (figure 8.1e).

5. Bridge abutments and piers are usually constructed over pile foundations to avoid the possible loss of bearing capacity that a shallow foundation might suffer because of soil erosion at the ground surface (figure 8.1f).

TYPES OF PILES AND THEIR STRUCTURAL CHARACTERISTICS

Different types of piles are used in construction work, depending on the type of load to be carried, the subsoil conditions, and the location of the water table. Piles can be divided into the following categories: (a) steel piles (b) concrete piles, (c) wooden (timber) piles, and (d) composite piles.

Steel Piles

*Steel piles* generally are either *pile piles* or *rolled steel H-section piles*. Pipe piles can be driven into the ground with their ends open or closed. Wide-flange and I-section steel beams can also be used as piles. However, H-section piles are usually preferred because their web and flange thicknesses are equal. In wide-flange and I-section beams, the web thicknesses are smaller than the thicknesses of the flange. Table D.1 (Appendix D) gives the dimensions of some standard H-section steel piles used in the United States. Table D.2 (Appendix D) shows selected pile sections frequently used for piling purposes. In many cases, the pile piles are filled with concrete after driving.
The allowable structural capacity for steel piles is

$$Q_{\text{all}} = A_s f_s$$  \[8.1\]

Where

$$A_s = \text{cross-sectional area of the steel}$$

$$f_s = \text{allowable stress of steel}$$

Based on geotechnical considerations (once the design load for a pile is fixed) determining whether $Q_{(\text{design})}$ is within the allowable range as defined by equation 1) is always advisable.

When necessary, steel piles are spliced by welding or by riveting. Figure 8.2a shows a typical condition of splicing by welding for an H-pile. A typical case of splicing by welding for a pipe is shown in figure 8.2b. Figure 8.2c shows a diagram of splicing an H-pile by rivets or bolts.

![Diagram of steel piles splicing](image)

Figure 8.2 Steel piles: (a) splicing of H-pile by welding; (b) splicing of pile by welding; (c) splicing of H-pile rivets and bolts; (d) flat driving point of pipe pile; (e) conical driving point of pipe pile
When hard driving conditions are expected, such as driving through dense gravel, shale, and soft rock, steel piles can be fitted with driving points or shoes. Figure 8.2d and 8.2e are diagrams of two types of shoe used for pipe piles.

Steel piles may be subject to corrosion. For example, swamps, peats, and other organic soils are corrosive. Soils that have a pH greater than 7 are not so corrosive. To offset the effect of corrosion, an additional thickness of steel (over the actual design cross-sectional area) is generally recommended. In many circumstances, factory-applied epoxy coatings on piles work satisfactorily against corrosion. These coatings are not easily damaged by pile driving. Concrete encasement of steel piles in most corrosive zones also protects against corrosion.

**Concrete Piles**

Concrete piles may be divided into two basic categories: (a) precise piles and (b) case-in-situ piles. Precast piles can be prepared by using ordinary reinforcement, and they can be square or octagonal in cross section (figure 8.3). Reinforcement is provided to enable the pile to resist the bending moment developed during pickup and transportation, the vertical load, and the bending moment caused by lateral load. The piles are cast to desired lengths and cured before being transported to the work sites.

Precise piles can also be prestressed by the use of high-strength steel prestressing cables. The ultimate strength of these steel cables is about 260 ksi ($\approx 1800$ MN/m$^2$). During casting of the piles, the cables are pretensioned to about $130 - 190$ ksi ($\approx 900 - 1300$ MN/m$^2$), and concrete is poured around them. After curing, the cables are cut, thus producing a compressive force on the pile section. Table D3 (Appendix D) gives additional information about prestressed concrete piles with square and octagonal cross sections.

Cast-in-situ, or cast-in-place, piles are built by making a hole in the ground and then filling it with concrete. Various types of cast-in-place concrete pile are currently used in construction, and most of them have been patented by their manufactures. These piles
may be divided into two broad categories: (a) cased and (b) uncased. Both types may have a pedestal at the bottom.

_Cased piles_ are made by driving a steel casing into the ground with the help of a mandrel placed inside the casing. When the pile reaches the proper depth, the mandrel is withdrawn and the casing is filled with concrete. Figure 8.4a, b, c, and d show some examples of cased piles without a pedestal. Table 1 gives additional information about these cased piles. Figure 8.4 shows a cased pile with a pedestal. The pedestal is an expanded concrete bulb that is formed by dropping a hammer on fresh concrete.

![Diagram of cased piles](image)

Figure 8.4 Cast-in-place concrete piles (see table 1 for descriptions)

Figure 8.4f and 8.4g are two types of uncased pile, one with a pedestal and the other without. The uncased piles are made by first driving the casing to the desired depth and then filling it with fresh concrete. The casing is then gradually withdrawn.

The allowable loads for cast-in-place concrete piles are given by the following equations,

**Cased Pile**

\[ Q_{all} = A_s f_s + A_c f_c \]  

[8.2a]

Where
\[ A_s = \text{area of cross section of steel} \]
\[ A_c = \text{area of cross section of concrete} \]
\[ f_s = \text{allowable stress of steel} \]
\[ f_c = \text{allowable stress of concrete} \]

**Uncased Pile**

\[ Q_{\text{all}} = A_c f_c \quad [2b] \]

**Table 1 Description of the Cast-in-Place Piles Shown in figure 8.4**

<table>
<thead>
<tr>
<th>Part in figure 8.4</th>
<th>Name of pile</th>
<th>Type of casing</th>
<th>Maximum usual depth of pile</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>(ft)</td>
</tr>
<tr>
<td>a</td>
<td>Raymond Step-Taper</td>
<td>Corrugated, thin, cylindrical casing</td>
<td>100</td>
</tr>
<tr>
<td>b</td>
<td>Monotube or Union Metal</td>
<td>Thin, fluted, tapered steel casing driven without mandrel</td>
<td>130</td>
</tr>
<tr>
<td>c</td>
<td>Western cased</td>
<td>Thin sheet casing</td>
<td>100-130</td>
</tr>
<tr>
<td>d</td>
<td>Seamless pile or Armco</td>
<td>Straight steel pipe casing</td>
<td>160</td>
</tr>
<tr>
<td>e</td>
<td>Franki cased pedestal</td>
<td>Thin sheet casing</td>
<td>100-130</td>
</tr>
<tr>
<td>f</td>
<td>Western uncased without pedestal</td>
<td>-</td>
<td>50-65</td>
</tr>
<tr>
<td>g</td>
<td>Franki uncased pedestal</td>
<td>-</td>
<td>100-130</td>
</tr>
</tbody>
</table>

**Timber Piles**

*Timber piles* are tree trunks that have had their branches and bark carefully trimmed off. The maximum length of most timber piles is 30-65 ft (10-20 m). To qualify for use as a pile, the timber should be straight, sound, and without any defects. The American Society
of Civil Engineers’ *Manual of Practice*, No. 17 (1959), divided timber piles into three classifications:

1. *Class A piles* carry heavy loads. The minimum diameter of the butt should be 14 in. (356 mm).
2. *Class B piles* are used to carry medium loads. The minimum butt diameter should be 12-13 in. (305-330 mm).
3. *Class C piles* are used in temporary construction work. They can be used permanently for structures when the entire pile is below the water table. The minimum butt diameter should be 12 in. (305 mm).

In any case, a pile tip should not have a diameter less than 6 in. (150 mm).

Timber piles cannot withstand hard driving stress; therefore, the pile capacity is generally limited to about 25-30 tons (220 – 270 kN). Steel shoes may be used to avoid damage at the pile tip (bottom). The tops of timber piles may also be damaged during the driving operation. The crushing of the wooden fibers caused by the impact of the hammer is referred to as *brooming*. To avoid damage to the pile top, a metal band or a cap may be used.

Splicing of timber piles should be avoided, particularly when they are expected to carry tensile load or lateral load. However, if splicing is necessary, it can be done by using *pile sleeves* (figure 8.5a) or *metal straps and bolts* (figure 8.5b). The length of the pile sleeve should be at least five times the diameter of the pile. The butting ends should be cut square so that full contact can be maintained. The spliced portions should be carefully trimmed so that they fit tightly to the inside of the pile sleeve. In the case of metal straps and bolts, the butting ends should also be cut square. Also, the sides of the spliced portion should be trimmed plane for putting the straps on.

![Figure 8. 8.5 Splicing of timber piles: (a) use of pipe sleeves; (b) use of metal straps and bolts](image)
Timber piles can stay undamaged indefinitely if they are surrounded by saturated soil. However, in a marine environment timber piles are subject to attack by various organisms and can be damaged extensively in a few months. When located above the water table, the piles are subject to attack by insects. The life of the piles may be increased by treating them with preservatives such as creosote.

The allowable load-carrying capacity of wooden piles is

\[ Q_{\text{all}} = A_p f_w \]  \hspace{1cm} [8.3]

Where

\( A_p \) = average area of cross section of the pile

\( f_w \) = allowable stress for the timber

The following allowable stresses are for pressure-treated round timber piles made from Pacific Coast Douglas fir and Southern pine, when used in hydraulic structures (ASCE, 1993).

<table>
<thead>
<tr>
<th>Allowable stress</th>
<th>Pacific coast Douglas fir</th>
<th>Southern pine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compression parallel to gain</td>
<td>875 lb/in² (6.04 MN/m²)</td>
<td>825 lb/in² (5.7MN/m²)</td>
</tr>
<tr>
<td>Bending</td>
<td>1700 lb/in² (11.7 MN/m²)</td>
<td>1650 lb/in² (11.4 MN/m²)</td>
</tr>
<tr>
<td>Horizontal shear</td>
<td>95 lb/in² (0.66 MN/m²)</td>
<td>90 lb/in² (0.62 MN/m²)</td>
</tr>
<tr>
<td>Compression perpendicular to grain</td>
<td>190 lb/in² (1.31 MN/m²)</td>
<td>205 lb/in² (1.41 MN/m²)</td>
</tr>
</tbody>
</table>

**Composite Piles**

The upper and lower portions of composite piles are made of different materials. For example, composite piles may be made of steel and concrete or timber and concrete. Steel and concrete piles consist of a lower portion of steel and an upper portion of cast-in-place concrete. This type of pile is the one used when the length of the pile required for adequate bearing exceeds the capacity of simple cast-in-place concrete piles. Timber and concrete piles usually consist of a lower portion of timber pile below the permanent water table and an upper portion of concrete. In any case, forming proper joints between two dissimilar materials is difficult, and, for that reason, composite piles are not widely used.

**Comparison of Pile Types**
Several factors affect the selection of piles for a particular structure at a specific site. Table 2 gives a brief comparison of the advantages and disadvantages of the various types of pile based on the pile material.

### Table 2 Comparison of Piles Made of Different Materials

<table>
<thead>
<tr>
<th>Pile type</th>
<th>Usual length of piles</th>
<th>Maximum length of pile</th>
<th>Usual load</th>
<th>Approximate maximum load</th>
<th>Comments</th>
</tr>
</thead>
</table>
| Steel     | 50-200 ft (15-60 m)   | Practically unlimited  | 67 - 270 kip (300 - 1200 kN) | Equation (1) | **Advantages**
|           |                       |                        |            |                          | a. Easy to handle with respect to cutoff and extension to the desired length  
|           |                       |                        |            |                          | b. Can stand high driving stresses  
|           |                       |                        |            |                          | c. Can penetrate hard layers such as dense gravel, soft rock  
|           |                       |                        |            |                          | d. High load-carrying capacity |

**Disadvantages**
- a. Relatively costly material
- b. High level of noise during pile driving
- c. Subject to corrosion
- d. H-piles may be damaged or deflected
<table>
<thead>
<tr>
<th></th>
<th>Precast conrete</th>
<th>Precast: 30-50 ft (10-15 m)</th>
<th>Prestressed: 30-150 ft (10-35 m)</th>
<th>67 – 675 kip (300 – 3000 kN)</th>
<th>Prestressed: 1700 – 1900 kip (7500 – 8500 kN)</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Precast: 100 ft (30 m)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>a. Can be subjected to hard driving</td>
</tr>
<tr>
<td></td>
<td>Prestressed: 200 ft (60 m)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>b. Corrosion resistant</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>c. Can be easily combined with concrete superstructure</td>
</tr>
<tr>
<td>Cased cast-in-place concrete</td>
<td>15-50 ft (5-15 m)</td>
<td>100-130 ft (30-40 m)</td>
<td>45 115 kip (20 – 50 kN)</td>
<td>180 kip (800 kN)</td>
<td></td>
<td>a. Relatively cheap</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>b. Possibility of inspection before pouring concrete</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>c. Easy to extend</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>a. Difficult to splice after</td>
<td></td>
</tr>
</tbody>
</table>
### Uncased Cast-In-Place Concrete

<table>
<thead>
<tr>
<th>Depth</th>
<th>Range</th>
<th>Load Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-15 ft</td>
<td>15-50 ft (5-15 m)</td>
<td>160 kip (700 kN)</td>
</tr>
<tr>
<td>100 ft</td>
<td>100-130 ft (30-40 m)</td>
<td>65 – 115 kip (300 – 500 kN)</td>
</tr>
</tbody>
</table>

**Advantages**
- Economical
- Can be finished at any elevation

**Disadvantages**
- Voids may be created if concrete is placed rapidly
- Difficult to splice after concreting
- In soft soils, the sides of the hole may cave in, thus squeezing the concrete

### Wood Piles

<table>
<thead>
<tr>
<th>Depth</th>
<th>Range</th>
<th>Load Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-15 ft</td>
<td>30-50 ft (10-15 m)</td>
<td>60 kip (270 kN)</td>
</tr>
<tr>
<td>100 ft</td>
<td>100 ft (30 m)</td>
<td>2245 kip (100 – 200 kN)</td>
</tr>
</tbody>
</table>

**Advantages**
- Economical
- Easy to handle
- Permanently submerged piles are fairly resistant to decay

**Disadvantages**
- Decay above water table
ESTIMATING PILE LENGTH

Selecting the type of pile to be used and estimating its necessary length are fairly difficult tasks that require good judgment. In addition to the classification given in section 2, piles can be divided into three major categories, depending on their lengths and the mechanisms of load transfer to the soil: (a) point bearing piles, (b) friction piles, and (c) compaction piles.

**Point Bearing Piles**

If soil-boring records establish the presence of bedrocks or rocklike material at a site within a reasonable depth, piles can be extended to the rock surface. (Figure 8.6a). In this case, the ultimate capacity of the piles depends entirely on the load bearing capacity of the underlying material; thus the piles are called point bearing piles. In most of these cases, the necessary length of the pile can be fairly well established.

![Diagram of Point Bearing Piles](image)

**Figure 8.6** (a) and (b) Point bearing piles; (c) friction piles
If, instead to bedrock, a fairly compact and hard stratum of soil is encountered at a reasonable depth, piles can be extended a few meters into the hard stratum (figure 8.6b). Piles with pedestals can be constructed on the bed of the hard stratum, and the ultimate pile load may be expressed as

\[ Q_u + Q_p + Q_s \]  

[8.4]

Where

\[ Q_p = \text{load carried at the pile point} \]
\[ Q_s = \text{load carried by skin friction developed at the side of the pile (caused by shearing resistance between the soil and the pile)} \]

If \( Q_s \) is very small,

\[ Q_u \approx Q_p \]  

[8.5]

In this case, the required pile length maybe estimated accurately if proper subsoil exploration records are available.

**Friction Piles**

When no layer of rock or rocklike material is present at a reasonable depth at a site, point bearing piles become very long and uneconomical. For this type o subsoil condition, piles are driven through the softer material to specified depths (figure 8.6c). The ultimate load of these piles may be expressed by equation (4). However, if the value o \( Q_p \) is relatively small,

\[ Q_u \approx Q_s \]  

[8.6]

These piles are called *friction piles* because most of the resistance is derived from skin friction. However, the term *friction pile*, although used often in the literature, is a misnomer: in clayey soils, the resistance to applied load is also caused by *adhesion*.

The length of friction of piles depends on the shear strength of the soil, the applied load and the pile size. To determine the necessary lengths of these piles, an engineer needs a good understanding of soil-pile interaction, good judgment, and experience. Theoretical procedures for the calculation of load-bearing capacity of piles are presented later in this chapter.

**Compaction Piles**

Under certain circumstances, piles are driven in granular soils to achieve proper compaction of soil close to the ground surface. These piles are called *compaction piles*. The length of compaction piles depends on factors such as (a) relative density of the soil before compaction, (b) desired relative density of the soil after compaction, and (c) required depth of compaction. These piles are generally short; however, some field tests are necessary to determine a reasonable length.
INSTALLATION OF PILES

Most piles are driven into the ground by means of hammers or vibratory drivers. In special circumstances, piles can also be inserted by jetting or partial augering. The types of hammer used for pile driving include the (a) drop hammer, (b) single acting air or steam hammer, (c) double-acting and differential air or steam hammer, and (d) diesel hammer. In the driving operation, a cap is attached to the top of the pile. A cushion may be used between the pile and the cap. This cushion has the effect of reducing the impact force and spreading it over a longer time; however, its use is optional. A hammer cushion is placed on the pile cap. The hammer drops on the cushion.

Figure 8.7 illustrated various hammers. A drop hammer (figure 8.7a) is raised by a winch and allowed to drop from a certain height $H$. It is the oldest type of hammer used for pile driving. The main disadvantage of the drop hammer is the slow rate of hammer blows. The principle of the single-acting air or steam hammer is shown in figure 8.7b. In this case, the striking part, or ram, is raised by air or steam pressure and then drops by gravity. Figure 8.7c shows the operation of the double-acting and differential air or steam hammer. For these hammers, air or steam is used both to raise the ram and to push it downward. This increases the impact velocity of the ram. The diesel hammer (figure 8.7d) essentially consists of a ram, an anvil block, and a fuel-injection system. During the operation, the ram is first raised and fuel is injected near the anvil. Then the ram is released. When the ram drops, it compresses the air fuel mixture, which ignites it. This action, in effect, pushes the pile downward and raises the ram. Diesel hammers work well under hard driving conditions. In soft soils, the downward movement of the pile is rather large, and the upward movement of the ram is small. This differential may not be sufficient to ignite the air-fuel system, so the ram may have to be lifted manually.
Figure 8.7 Pile-driving equipment: (a) drop hammer; (b) single-acting air or seam hammer; (c) double-acting and differential air or steam hammer; (d) diesel hammer; (e) vibratory pile driver
The principles of operation of a vibratory pile driver are shown in figure 8.7e. This driver essentially consists of two counter-rotating weights. The horizontal components of the centrifugal force generated as a result of rotating masses cancel each other. As a result, a sinusoidal dynamic vertical force is produced on the pile and helps drive the pile downward.

*Jetting* is a technique sometimes used in pile driving when the pile needs to penetrate a thin layer of hard soil (such as sand and gravel) overlying a softer soil layer. In this
technique, water is discharged at the pile point by means of a pile 2-3 in. (50-75 mm) in diameter to wash and loosen the sand and gravel.

Piles driven at an angle to the vertical, typically $14^\circ$ to $20^\circ$, are referred to as batter piles. Batter piles are used in group piles when higher lateral load-bearing capacity is required. Piles also may be advanced by partial augering, with power augers (chapter 2) being used to predrill holes part of the way. The piles can then be inserted into the holes and driven to the desired depth.

Based on the nature of their placement, piles may be divided into two categories: displacement piles and nondisplacement piles. Driven piles are displacement piles because they move some soil laterally; hence there is a tendency for densification of soil surrounding them. Concrete piles and closed-ended pile piles are high-displacement piles. However, steel H-piles displace less soil laterally during driving, and so they are low-displacement piles. In contrast, bored piles are nondisplacement piles because their placement causes very little change in the state of stress in the soil.