

Types of Piles: Their Characteristics and General Use

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This paper presents a review of the current practice and usage of the numerous types of pile in general construction. Information on this subject was obtained from a review of existing literature and from field experience. The paper reviews the purpose of pile foundations and the various factors involved in the selection of a type of pile. Emphasis is placed on the general, physical, and structural characteristics of the piles as well as durability and fabrication. Data are presented on the inherent advantages and disadvantages of the various types of piles and on corresponding optimum pile length and load range. Information and data are presented on the field problems of pile installations and the proper method of handling and treatment to avoid damage or failure of critical pile sections. The fundamental information is supplemented by case histories.

•PILE FOUNDATIONS of timber were in use in ancient times. In its earliest form, a pile foundation consisted of rows of timber stakes driven into the ground. Pile foundations such as these were used by the ancient Aztecs in North America. The Romans made frequent use of pile foundations as recorded by Vitruvius in 59 AD. Pile foundations for ancient Roman dwellings have been found in Lake Lucerne. It is reported that during the rule of Julius Caesar a pile-supported bridge was constructed across the Rhine River.

The durability of timber piles is illustrated in the report of the reconstruction of an ancient bridge in Venice in 1902. The submerged timber piles of this bridge, which were driven in 900 AD, were found in good condition and were reused.

In the years immediately preceding the turn of the twentieth century, several types of concrete piles were devised. These early concrete piles were the cast-in-place type. Further development of the concrete pile led to the precast pile and, relatively recently, to the prestressed concrete pile. The need for extremely long piles with high bearing capacity led to the use of concrete-filled steel-pipe piles about 50 to 60 years ago. More recently, steel H-piles have come into common usage. Their ease of handling, fabrication, splicing, and relatively easy penetration hastened their acceptability in foundation construction.

THE PURPOSE OF A PILE FOUNDATION

The primary function of a pile foundation is (a) to transmit the load of a structure through a material or stratum of poor bearing capacity to one of adequate bearing capacity; (b) in some instances, to improve the load-bearing capacity of the soil; and (c) to resist lateral loads and to function as a fender to absorb wear and shock. In addition, piles are also used in special situations (a) to eliminate objectionable settlement; (b) to transfer loads from a structure through easily eroded soils in a scour zone to a stable underlying bearing stratum; (c) to anchor structures subjected to hydrostatic uplift or overturning; and (d) to serve as a retaining structure when installed in groups or in a series of overlapping (cast-in-place) piles.

NEED FOR SUBSURFACE INVESTIGATIONS

The length of the pile and the method of pile installation are dependent on the nature of the subsurface conditions. Thorough subsurface explorations are necessary to determine the stratification of the foundation elements, including the depth to bedrock and the density of granular materials measured by the number of blows recorded on a standard split spoon sampler, and to obtain undisturbed samples of cohesive strata to evaluate the shearing strength and compressibility characteristics by laboratory testing. The desirable number of exploratory borings depends on the size of the foundation area and the degree of uniformity of the foundation materials. In areas of glacial deposits, the foundation materials tend to be nonuniform, whereas the soil conditions are generally more uniform in marine or alluvial deposits.

Ideally, subsurface explorations should extend to a depth of 100 ft or to a depth of $1\frac{1}{2}$ times the width of the structure, unless bedrock is encountered at a shallower depth.

Groundwater conditions are pertinent in a pile foundation project from the standpoint of the probable permanency of the groundwater level, which is relevant to preserving the permanency of untreated timber piles. The condition of the groundwater is also relevant to steel and concrete piles where acid, alkali, or other injurious solutions may be present.

CHOICE OF PILE TYPE

The initial and primary consideration is the evaluation of the foundation materials and the selection of the substratum that will provide the best pile foundation support. In certain situations involving cohesive subsoils, the pile lengths will be dictated by the necessity to minimize settlement of the foundations rather than the need to develop load capacity. The selection of a type of pile for a given foundation should be made on the basis of a comparative study of cost, permanency, stability under vertical and a horizontal loading, long-term settlement, if any, of the foundation, required method of pile installation, and length of pile required to develop sufficient point bearing and frictional resistance assuming that there is a great depth to bedrock or other hard bottom.

The selection of a pile type and its appurtenances is dependent on environmental factors as, for example, piles in seawater. Environmental factors to be considered are the possibility of marine borer attack, wave action causing alternate wetting and drying and ultimate deterioration, and abrasion due to moving debris or ice. Piles located in strong water currents could be subject to gradual erosion of the pile material due to scouring by abrasive river sediment. Strong chemicals in rivers or streams or alkali soils could adversely affect concrete piles. Steel piles in an electrolytic environment near stray electrical currents could suffer serious electrolysis deterioration.

Foundation materials consisting of loose to medium-dense granular soils would favor a tapered displacement pile for efficient transfer of load along the surface of the pile by friction. If the granular soils were in a very compact state, the piles would probably have to be installed with the aid of water jets. Foundation materials consisting of cohesive soil overlaid by a granular stratum would favor a straight-sided pile to develop the greatest possible skin friction area along the pile and point bearing area at the base of the pile. Piles to be driven through obstructions to bedrock with the least driving effort and soil displacement would favor a steel H-pile or open-end pipe pile. Foundations subject to large lateral forces such as pier bents in either deep or swiftly moving water or both require piles that can sustain large bending forces. Precast, prestressed concrete piles are suitable for such load conditions. The large-diameter Raymond cylindrical prestressed piles have large vertical load and bending moment capacity and are frequently used in such installations.

TIMBER PILES

Timber piles have a wide range of sizes and strengths. The usual timber pile is a tree with a straight trunk and trimmed of branches. The butt diameter ranges in size

from 12 to 20 in. and the tip diameter from 5 to 10 in. Their availability depends on transportation facilities and distance from lumbering regions. In North America the most commonly used trees for piles are southern yellow pine, Douglas fir, spruce, and oak. Southern cypress from the Atlantic and Gulf coasts are also extensively used in piling. Cedar piles, although decay resistant, do not find extensive use because of their relatively low strength. From Central America, some greenheart and angelique are used. They are hardwoods and have considerable resistance to marine borers.

Physical Characteristics

The maximum obtainable length of timber piles is of the order of 110 ft, but lengths over 80 ft are scarce. The normal length of available timber piles is 30 to 60 ft. The elasticity of timber makes wooden piles easy to handle. Timber is well adapted for use in dolphins and fenders for the protection of structures in water because of its resilience, wearing qualities, and ease of replacement. Timber piles are comparatively light for their strength, and they can absorb normal driving stresses to develop their design load. However, they are vulnerable to damage in hard driving. Timber piles are also vulnerable to deterioration and to destruction by marine organisms as described later.

Durability of Timber Piles

Timber piles are subject to deterioration caused by decay, insect attack, marine borer attack, and abrasive wear. Decay is caused by growth of fungi that need moisture, air, favorable temperature, and food. Decay can be prevented if wood can be kept dry, rendered unsuitable for food, or entirely embedded in earth and cut off below groundwater level or submerged in fresh water. Thus, untreated timber piles are subject to decay and insect attack where they project above the water table or above the ground surface, and to marine borer attack where they project above channel bottom in saltwater.

Reasonable protection against decay and insect attack, such as termites, can be attained by poisoning the pile by impregnating the wood with pentachlorophenol or with creosote. Treatment with pentachlorophenol is not recommended for marine piles. Creosote treatment by a pressure process is the most effective method of poisoning wood piles for long-term protection. However, this treatment will not prevent ultimate damage by certain species of marine borers, notably the liminora.

Mechanical protection of wood piles in waterfront structures has been used successfully to protect new piles and to repair piles damaged by abrasion or by marine borers. Mechanical devices include Gunit encasements and precast concrete jackets grouted to the piles. Intrusion-Prepakt concrete placed inside of forms fitted to timber piles has also been used. Such encasements generally extend from a few feet below the mud line to some distance above the high water level.

Fabrication

It is the general practice to remove the bark from wood because timber piles generally carry load by skin friction. A decomposed weak film ultimately develops between the bark and the wood creating a plane of weakness.

The butts of timber piles are cut square and the edges chamfered. The chamfering tends to reduce the tendency to split during pile-driving. When piles are to be driven without the aid of water jets, it is standard practice to trim the pile tips to about a 4-in. diameter when driving through relatively firm foundation materials. In driving through gravelly soils, it is frequently the practice to point the pile tips and clad them with steel shoes to prevent brooming.

Timber piles can be spliced when long piles are unavailable; however, it is time-consuming and rather difficult. Sleeve joint splices have been fabricated with 8-in. and 10-in. diameter pipe, 3 to 4 ft long. Bolted splices have been made by using timber and steel splice bars. Gunit splices 6 ft long have been made by utilizing spiral reinforcement surrounding $\frac{3}{4}$ -in. diameter longitudinal reinforcing bars covered

with a 5-in. thick mortar section. In current practice, splicing of timber piles is an infrequent occurrence.

Structural Characteristics

The normal design load for a timber pile is 15 to 25 tons with a maximum permissible load of 30 tons. A number of load tests on timber piles embedded for their full length have indicated a safe load capacity of 40 tons. Timber piles are vulnerable to damage in hard driving, and a water jet is frequently utilized in the installation of piles in dense granular materials. A single jet pipe strapped to the pile is generally used to install the pile to within 2 to 3 ft of the desired tip elevation, and the pile is driven to its final position to the prescribed driving resistance.

Timber piles, designed to develop their load by end bearing, are sometimes driven butt down to utilize the larger end bearing area. Timber piles installed as dolphins are occasionally driven butt down to take advantage of the larger pile section in the zone of maximum bending produced by lateral loads.

In fender pile systems, it is good practice to avoid the use of bolted connections between piles, sheeting, bracking, and struts, because such fixed restraints tend to be destroyed when deflected by lateral impact.

STEEL PILES

Durability of Steel Piles

Steel piles embedded in relatively impervious earth, at least 2 ft below ground surface, will generally be free of corrosive effects because of insufficient atmospheric oxygen. Embedded steel piles may be subject to corrosion if the surrounding medium consists of coal, alkaline soils, cinder fills, or wastes from mines or manufacturing plants. Steel piles protruding from the ground are subject to rusting at and somewhat below the ground line. Steel piles protruding into fresh water are generally subject to little deterioration but usually experience severe deterioration in seawater. Corrosion is severest in the splash zone.

Corrosion of steel piles by electrolytic action is uncommon. Local electrolytic action and subsequent corrosion may occur in a saltwater environment where the steel pile forms one pole of a battery with the other pole in a dissimilar metal in close proximity. However, when steel piles are embedded in a concrete footing, and thereby insulated from stray electric currents from the superstructure, electrolysis is generally not a problem. Electrolytic deterioration of steel piles can be minimized or prevented by the application of a protective coating such as epoxy coal tar paint or by positive cathodic protection using either electrolytic or galvanic anodes.

Steel piles can be protected against corrosion failure at critical zones by an increase in the steel cross section, or by encasements. Steel pile encasements have been made of poured-in-place concrete, precast concrete jackets, or Gunitite applied before or after pile-driving.

Steel H-Pile

Steel H-piles are rolled steel sections with wide flanges so that the depth of the section and width of the flanges are of about equal dimension. The cross-sectional area and volume displacement of the H-pile are relatively small; consequently, they are well adapted to driving through compacted granular materials and into soft rock. Steel H-piles, because of their small volume displacement, have little or no effect in causing ground swelling or rising of adjacent piles.

The maximum length of steel H-piles is relatively unlimited. Unspliced pile lengths of 140 ft and spliced lengths of more than 230 ft have been driven. The optimum pile length is 40 to 100 ft. The recommended design stress for fully supported piles is 9,000 psi. The normal load range is 40 to 120 tons. Piles with heavy reinforced flanged sections have been driven to design loads of 200 tons and test loaded to 400 tons.

Steel H-piles are easy to splice. Splices can be either riveted, bolted, or welded, the latter being the most common procedure followed. It is desirable to keep splice material on the inner faces to avoid creating a hole in the ground larger than the pile section. This may result in a loss of frictional resistance. For hard driving conditions, splices should develop one-third the full strength of the section. Splices, in long piles with no lateral support, should develop the full strength of the section.

Caps are not usually required for steel H-piles embedded in concrete. Comprehensive tests conducted by the Ohio Department of Highways in 1947 indicated that uncapped H-piles embedded for only 6 in. into concrete proved as effective in transferring load as H-piles with cap plates.

The points of steel H-piles are sometimes tapered and generally reinforced when hard driving is anticipated or when they are to be driven to bedrock. Points are usually reinforced by welding plates to increase the thickness of the original section by a factor of $2\frac{1}{2}$ to 3.

Devices can be attached to a steel H-section to increase the bearing capacity of the pile to be driven into firm materials. Some devices that have been used consist of short sections of straight or wedge-shaped H-piling welded to the sides of the pile to increase the cross-sectional area at or just above the point.

Steel Rail Pile

Old rails have been used as piles by welding 3 rails together at heads or bases. The usual length of rail piles is about 30 ft. Sections of these rail piles have been butt-welded to fabricate a pile 90 ft in length. Rail piles are generally made of abandoned steel rails and are not considered normal steel production piles.

Steel Box Pile

Box piles have been fabricated from sections of steel sheeting in the form of a closed rectangular section. Because of their relatively large exterior dimensions, such piles can sustain large lateral loads and have been used to stabilize sliding banks. Box piles can be cleaned out and filled with concrete for additional bending strength.

Disk Pile

Disk piles have been fabricated of cast-iron pipe with a plate or casting of enlarged size connected to the base of the pipe. A disk pile has been fabricated with a pipe size of 9 in. and a disk diameter of 36 in. Such piles are usually jettied into position for end bearing on a firm stratum. Disk piles are rarely used today.

Screw Pile

Screw piles were used more extensively in the past than they are at present. The pile consists of an open-end pipe section to which is attached a number of turns of a helical shaft or screw at the base of the pipe. The pile is screwed or augered into the ground. Water jets are generally used to facilitate the advancement of the screw pile into the ground. A relatively recent screw pile installation involved a 42-in. diameter and $\frac{7}{8}$ -in. thick shell to which was attached an 8-ft diameter helix at the tip of the pile. The steel shell was fitted with a conical point. Such piles were installed mechanically in 20 to 65 ft lengths. Screw piles can be installed with little or no disturbance to existing structures.

CONCRETE PILES

Concrete piles fall into 2 basic categories: precast and cast-in-place. Precast piles can be divided into the 2 general classes of normally reinforced piles and prestressed piles. Cast-in-place piles can be further subdivided into piles with casing and piles without casing. There are a number of variations of both of these basic types including a variation of cross-sectional area and longitudinal shape. Concrete piles are essentially unaffected by biological organisms or decay as are timber piles. They

are thus used in foundations where the piles extend above groundwater or are immersed in river water or seawater. Depending on the foundation conditions and the type of concrete pile selected, the load carrying ability of the pile can be developed in either skin friction or point bearing or a combination of the two. Concrete cast-in-place piles, and more particularly prestressed concrete piles, can sustain high bending stresses and are frequently used in viaducts and trestle type of structures with the pile extending above ground or channel bottom level.

Durability of Concrete Piles

Plain or reinforced concrete piles embedded in earth are generally considered not subject to deterioration. The water table, if free from deleterious substances, does not affect their durability. In extremely infrequent situations, there is the possibility that concrete piles embedded in permeable soils may be damaged by groundwater saturated by either acids, alkalis, or chemical salts. These commercial agents can result from wastes discharging from manufacturing plants, sewer leakage, leaching from alkali soils, or leaching of acidic compounds from coal or cinder fill. The use of dense rich concrete with sulfate-resisting cement is a means of minimizing the effects of a deleterious environment. Concrete piles should not be used where severe deterioration could possibly result.

Concrete piles extending above the surface of a body of water are subject to damage from the abrasive action of floating objects, from ice where such exists, and from sand scouring. Damage can also result from frost action, particularly in the splash zone, and from internal corrosion of the reinforcement causing spalling of the concrete. The principal factors involved in these frequent types of failures are (a) composition and density of the concrete, (b) porosity of the aggregates, and (c) concrete cover over the reinforcing steel. Normally reinforced concrete piles are more vulnerable to spalling failure than prestressed piles because of inherent fine cracks in the concrete that develop from shrinkage, from handling of the piles, and from tension and shear loads.

The deterioration of concrete piles can be minimized by careful formulation of the concrete mix, use of sound, hard aggregates, and proper mixing, placing, consolidating, and curing to achieve hard dense concrete. The reinforcing steel should have a minimum cover of 2 in., and the use of galvanized reinforcing is advisable where economically permissible. Prestressing reduces cracks in concrete and should be used whenever possible.

Piles can be protected against some agents of deterioration by use of coatings and jackets applied to vulnerable areas. On a project under way in New Jersey where prestressed cylinder piles will be exposed to seawater, the interior and exterior surface of the piles are to be coated with an epoxy bonding compound immediately following sandblasting of the surface. The epoxy bonding compound is to provide a tight seal on the pile surfaces.

On a recently completed project in Long Island involving the use of prestressed concrete pile bents, the pile surfaces in the tide zone were protected by wrought-iron pile jackets grouted to the piles. Right-angle sections of $\frac{1}{4}$ -in. thick wrought iron were bolted together to form a square jacket, and the $1\frac{1}{2}$ -in. annular space between the jacket and pile was filled with grout put into place by a tremie.

CAST-IN-PLACE CONCRETE PILES

In general foundation work, the cast-in-place pile is more commonly used than the precast pile. Cast-in-place concrete piles generally need no storage space, are made in place to correct length, do not require special handling, and are not subject to damage from handling. Cast-in-place piles can be subdivided into 2 basic types: those that are formed in a steel shell in the ground and those that are uncased. Cased piles are the more positive type in that they permit an inspection of the pile prior to placing concrete, and allow for more accurate control in placing concrete. Uncased piles are generally more economical; however, they bear a great inherent risk in their installation.

Cast-in-Place Uncased Concrete Pile

Cast-in-place uncased concrete piles are load-carrying elements formed in the ground wherein the concrete is in direct contact with the soil. Such piles are recommended for use where soil or water will not fill or squeeze into the formed hole following the withdrawal of the forming mandrel or shell prior to the placement of concrete, or where the installation of adjacent piles may eventually damage the green concrete of piles already in place.

The following are types of cast-in-place uncased concrete piles that have been used in the past in this country and abroad but that are not often used at the present time.

1. MacArthur compressed concrete pile—The pile apparatus consists of temporary casing and solid mandrel that are driven together to the desired penetration, displacing the full cross section of the casing. The mandrel is then withdrawn and the casing filled with concrete. With the mandrel placed in direct contact with the concrete, the casing is withdrawn. Such piles are known as the MacArthur straight shaft pile and have been made in diameters ranging from 14 to 24 in. and in lengths up to 60 ft.

This pile can be formed with a mushroom base where it is advantageous to increase the bearing area of the pile. The mushroom base is formed by placing a charge of concrete in the casing, placing the mandrel on top of the concrete charge, raising the casing to the bottom level of the mandrel, redriving the casing and mandrel through the deposited concrete, and forcing the concrete into the surrounding soil to form an enlarged base. The placement of the concrete in the shaft of the pile is accomplished in the same manner as for the straight shaft pile.

2. Simplex concrete pile—The pile is formed by driving a casing with a heavy detachable conical point, displacing the full cross section of the casing. The shaft is filled with concrete, and the casing is withdrawn. Piles with 16- and 18-in. diameters have been so installed with load capacities ranging from 45 to 60 tons.

Tamped simplex piles are similar to the standard type except that the casing is struck with the hammer at short intervals as it is withdrawn, vibrating or tamping the concrete for its full length.

3. Francois express pile—These piles are formed by driving an 18-in. diameter steel casing with a removable point to the required penetration and charging it with concrete. The casing is raised, and the concrete is compressed by driving on a solid ram in contact with the concrete. Additional concrete is added, the casing is raised, and the concrete is compacted in stages producing a pile of varying diameter in accordance with the displacement of the soil as the concrete is laterally compacted.

4. Vibra pile—These piles are formed by driving a steel casing with a removable cast-iron shoe of slightly larger dimension than the casing to the required penetration. Concrete is placed in the casing, and the casing is alternately driven upward to extract it and downward to compact the concrete, which flows beyond the casing to the soil limits. This tends to produce a concrete shaft with a corrugated surface. These piles are currently used in Europe in diameters of 13 to 17 in. and carry loads of 40 to 60 tons. Piles up to 70 ft in length have been installed in this manner.

5. Ridley pile—These piles are formed with a steel casing and removable shoe essentially as described in paragraph 4. The casing is partially filled with grout, and a precast concrete pile, with a shoulder designed to a close tolerance with the inside diameter of the tube, is placed inside the casing and driven as the casing is withdrawn. The grout is forced out against the walls of the soil as the tube is withdrawn, filling the annular space between the precast concrete section and the soil surface.

Cast-in-Place Cased Concrete Pile

Cast-in-place cased concrete piles are formed by pouring concrete into a tapered or cylindrical form previously driven into the ground. The form or encasement could be a light-gage metal shell driven with a mandrel, or a steel shell heavy enough to be driven directly without a mandrel. Reinforcement is generally used in the upper section of the pile to take small bending forces that may develop. The use of the thin-shell pile should be carefully evaluated so that it is used in soils that will collapse or in

places where it will deform because of soil displaced while adjacent piles are driven. The cased piles have an advantage in that the pile can be examined before it is filled with concrete. The placement of concrete, particularly in tapered piles, should be carefully inspected and controlled. There have been cases where such piles have been improperly filled, resulting in intermittent voids along the pile. Deformities or distortions in the pile shell could constrict the flow of concrete into the pile leading to the formation of intermittent voids.

The following is a description of the various mandrel driven cast-in-place cased piles in general use.

1. Raymond pile (standard type)—This tapered pile with a thin corrugated shell is driven with a solid mandrel bearing on the boot of the pile. The shell sections come in 8-ft lengths, with available shell thicknesses varying from 10 to 24 gage depending on the nature of the foundation materials. The optimum pile length is 35 ft, and the optimum load range varies from 30 to 60 tons. The pile is best suited as a friction pile.

2. Raymond step-tapered pile—This pile embodies the same fundamentals as the standard type with the exception that sections of the pile increase in diameter forming a series of steps. This permits increasing the length of the pile up to a maximum of about 100 ft without an excessive increase in the butt diameter. The piles are driven with a stepped solid mandrel.

3. Monotube pile—This is a fluted pile with a tapered steel shell and is best suited for friction piles of medium length. The shells are furnished in gages ranging from 3 to 11, and sustain direct driving with hammers of comparable size to those used for driving timber piles. The optimum length of these piles ranges from 30 to 80 ft with a load range of 50 to 70 tons. This type of pile cannot take excessive driving because the relatively light-gage steel shell will deform at the head. However, these piles can sustain lateral pressures from adjacent driving considerably better than the thin-shell piles.

4. Cobi pile—The casing of this pile is a thin-gage corrugated shell of uniform diameter driven in lengths up to 60 ft. This pile is driven with a Cobi pneumatic mandrel, which, when inflated, expands to a diameter slightly larger than that of the shell. The mandrel and shell are driven as a unit to the desired depth without a tendency to curve during driving. In this respect, the Cobi pneumatic mandrel-driven pile has an advantage over the standard mandrel-driven pile.

5. West's Rotinoff shell pile—The pile consists of a series of precast reinforced concrete shell sections joined together by steel bands and connected to a concrete shoe. The pile is driven by means of a mandrel bearing on the concrete shoe. Following removal of the mandrel, the pile is inspected and filled with concrete. The pile can be driven at locations with restricted headroom because the pile is assembled in sections. Piles of this type have been installed in lengths up to 100 ft. This pile was developed in Great Britain and has been used primarily in Europe.

6. Button-bottom cased concrete pile—This pile is installed by driving a thick-walled steel casing, usually 14 in. in diameter, plugged with a heavy concrete button having a diameter 1 in. larger than that of the casing, to a stratum of firm bearing. A corrugated shell with a flat plate at its base is placed inside the pipe. The flat plate has a center hole that fits over a bolt cast into the concrete button. To prevent floating or heaving during placement of concrete, the shell is anchored to the bottom by threading a nut over the bolt by means of a long socket wrench. The steel casing is withdrawn, and the shell is filled with concrete. These piles can take heavy driving through obstructions and derive their support primarily by point bearing. Piles 76 ft in length have been installed with design loads in the order of 50 tons.

7. Swage pile—This pile is formed by forcing a light steel casing, usually 11 in. in diameter and $\frac{1}{8}$ in. thick, over a tapered precast concrete plug so that the pipe is swaged out by the taper of the plug, forming a watertight joint. The pile is driven by means of a ram bearing on the plug inside the pipe, pulling the swaged pipe with the concrete plug. Following the removal of the ram, the casing is filled with concrete. These piles have been found to be advantageous in extremely hard driving conditions.

8. Closed-end steel pipe pile—This pile is formed by driving a steel pipe into the ground to the desired penetration, and filling it with concrete. The cylindrical steel pipe is of relatively heavy-gage wall thickness, generally ranging from $\frac{5}{16}$ to $\frac{1}{2}$ in. The pipe diameter ranges from 8 to 36 in. Seamless pipe is furnished in diameters up to 24 in., with spiral welded pipe available in larger diameters. Lap-welded pipe is sometimes used but is not recommended in driving through obstructions. The piles are driven with a flat plate or with a tapered cast-iron or steel point welded to the bottom of the pipe. Additional sections of pipe can be added by means of a cast-steel drive sleeve, permitting easy installation of piles of variable length. The optimum pile length ranges from 40 to 120 ft. The optimum load range is usually 80 to 120 tons. The piles are structurally capable of carrying large loads above ground level; the shell participates in carrying the load. The piles also provide high bending resistance under lateral loading. Pipe piles provide alignment control during installation and are capable of hard driving. This type of pile is used extensively in underpinning work because it can be installed in short sections by jacking. The advantages of this type of pile are offset by its relatively high cost.

9. Open-end steel pipe pile—These piles are similar to the closed-end pipe piles except that no closure is used at the tip of the pile. These piles are capable of being extended through obstructions because interferences can be broken or removed through the open pipe. The piles are used where soil displacements would be objectionable or where driving vibrations should be minimized. The open-end piles can be sunk to great depths to reach bedrock; piles more than 300 ft long have been driven. The open-end pipe piles are usually cleaned out with the aid of water jets and compressed air and then filled with concrete.

On a recently completed long-span bridge project in New Orleans involving very heavily loaded piers, 18-in. diameter open-end pipe piles were driven to a depth of 145 ft through clay strata in order to achieve settlement of the foundations. On this project, the settlement of the piers rather than the design loading on the piles dictated the required length of the open-end pipe piles. Only the upper 75 ft of the pile was cleaned and filled with concrete. The results of a series of pile load tests revealed that the piles were carrying load in skin friction and point bearing, indicating that the soil in the pile acted as a plug.

10. Pretest pile—This pile, which is used extensively in underpinning work, is a closed-end steel pipe that is jacked into the ground in sections by using the existing foundation as a reaction. When the pile has been jacked to the required penetration, it is inspected and filled with concrete. While maintaining the jacking pressure on the pile, the load is transferred to struts that are wedged between the top of the pile and the foundation. The transfer of the foundation load to the pile in this manner eliminates movement of the foundation comparable to the combined elastic deformation of the pile and the soil.

Rammed-in-Place Pile

The rammed-in-place pile is also referred to as the compressed concrete pedestal pile or pressure injected footing. The formation of this pile involves the installation of a casing with a temporary closed bottom to the desired penetration, the placement of a charge of concrete at the bottom of the casing, the lifting of the casing about 18 in., and the ramming out of the concrete to form a bulb or pedestal at the base. The casing is then withdrawn as concrete is placed to form the shaft. Where soft soil conditions exist to prevent the proper formation of the shaft, the casing can be left in place, or a thin corrugated shell can be placed inside the casing to contain the shaft concrete and to permit the withdrawal of the heavier casing. The MacArthur compressed concrete pedestal pile is of this type as is the cased pedestal concrete pile. The rammed-in-place pile is advantageous where it is desired to spread load on a relatively thin bearing stratum. The Franki pile is also of this type and is extensively used in Europe, Canada, and the United States.

The Franki pile is installed somewhat differently from that described earlier. The casing is set on the ground, and a charge of dry concrete is placed in it. The concrete

is compacted by means of a drop ram forming a dense plug that drags the casing into the ground to the desired penetration. The casing is held by cables, and the concrete is pounded, forcing it down and out of the casing to form a bulb. The shaft is formed by adding charges of concrete and ramming each concrete charge while gradually withdrawing the casing. This tends to form a corrugated surface along the concrete shaft. Piles of this type have been installed with shaft diameters ranging from 17 to 26 in. and for lengths of 10 to 60 ft. The optimum pile load ranges from 60 to 120 tons. The base of the pile cannot be formed in cohesive soils, and careful control is required in forming the shaft in soft soils to avoid discontinuities.

Formed-in-Place Pile

Formed-in-place piles are a relatively recent innovation and are generally installed by augering techniques. This type of pile is utilized in emergency repairs, in installations where it is not feasible or economical to utilize a pile-driving rig, or in installations where quarters are too cramped for using standard piles. The formed-in-place pile is currently gaining acceptance on large-scale projects. The advantages of this type of pile are speed and economy of installation. The following are descriptions of several formed-in-place piles.

1. Drilled pile—These piles are formed by augering to the desired depth. Where soil and groundwater conditions permit, the auger is withdrawn and the open hole is filled with concrete. In noncohesive soils and as otherwise required, the hole is formed as described, and the walls of the excavation are maintained by drilling fluid consisting of a mixture of bentonite and water. Such piles can be readily advanced past obstructions by means of chopping or coring with rock roller bits. The hole is filled with tremie concrete deposited through the drilling fluid. Piles of this type are usually 16 to 24 in. in diameter and generally extend to depths ranging from 40 to 60 ft.
2. Intrusion-Prepakt pile—These piles are formed by coring holes with an auger to the desired depth. In soft ground, the hole is lined with casing during augering. A $\frac{3}{4}$ -in. grout injection pipe is centered in the augered hole, and $2\frac{1}{2}$ - to $\frac{3}{8}$ -in. aggregate is placed and tamped in the hole. Grout is injected through the grout pipe to solidify the aggregate mass. These piles have diameters of 12 to 24 in. and extend to a depth of 60 ft.
3. Intrusion grout mixed-in-place pile—This pile is formed in sandy soils by injecting grout through a rotating hollow drill rod with vanes attached at the bottom. The rotating rod mixes the grout with the granular soil as it penetrates the ground to the desired depth. Reinforcing bars can be pushed through the grouted soil mass after removal of the drill. These piles also have diameters of 12 to 24 in. and extend to a depth of 60 ft.
4. Augercast pile—This pile is formed by a continuous hollow-shaft auger rotated into the ground to the specified pile depth. High-strength mortar is pumped through the hollow shaft as the auger is withdrawn. Reinforcement can be placed while the mortar is still fluid. Twelve-in. diameter piles have been so installed to a depth of 60 ft to support a design load of 40 tons.

PRECAST CONCRETE PILES

Precast concrete piles find frequent use in marine installations and in foundations, bents, and viaducts where the piles need to extend above water or ground level. Precast concrete piles are generally cast in square or octagonal shapes. Circular (normally reinforced) precast concrete piles have been manufactured in the past, but are not currently in common use in this country. Precast piles can be manufactured of uniform cross section or tapered. The tapered piles are usually limited in length to about 40 ft. The uniform section piles are generally made with the lower few feet of the pile sharply tapered. Piles of larger cross section are frequently manufactured with a hollow interior to reduce weight. Pile reinforcement consists of longitudinal steel tied to spiral reinforcement or rectangular bars depending on the circular or square configuration of the longitudinal steel. The spiral and tie-bar reinforcement

is generally placed at a closer spacing at the tip and head of the pile, relative to the middle section of the pile. The required longitudinal reinforcement is generally governed by the stresses resulting from handling of the pile. When the precast pile serves as a column or is subject to lateral forces, the amount of reinforcement is generally governed by the structure loads. Where jetting is anticipated in the installation of the pile, it has frequently been the practice to form a 3- to 4-in. diameter jet hole along the central axis of the pile.

Precast piles are available in sizes ranging from 12 to 24 in. and in lengths up to about 100 ft. The optimum pile load ranges from 40 to 60 tons and extends beyond 100 tons per pile for the larger sections. Among the disadvantages in the use of precast piles are the difficulty in handling, the cutting off of excess length, and the relatively high initial cost. The primary advantages include their suitability in marine installations, their ability to tend above groundwater level without inherent deterioration, and their ability to carry relatively high working loads.

COMPOSITE PILES

Composite piles were developed about 60 years ago to provide an economical pile of relatively long length. Composite piles consist of a lower section of one material joined with an upper section of another material. Each of the materials selected should be suited to the conditions of the in situ medium. Typical combinations of materials include (a) a timber section embedded in the ground below the permanent groundwater level and an upper section of concrete, and (b) a concrete-filled steel pipe or a lower steel H-section and an upper concrete section. All of the various cast-in-place concrete piles can be combined with timber or steel to form composite piles. Composite piles have also been fabricated with precast concrete upper sections. The precast section is cast with a recess in its lower end to receive the stub of the wood pile.

The following is an outline of the method of forming and installing a typical cased concrete and wood composite pile. The butt of a timber pile is tapered to form a tenon, which is wrapped with spiral wire. A casing and solid core are simultaneously driven to a depth well below groundwater level, and the solid core is removed. The wood pile with the wire-wrapped tenon is inserted in the open casing and driven close to the casing bottom by means of a follower. A corrugated metal shell with a reinforcing cage connected to its base is lowered in the casing and placed over the tenon of the wood pile. The shell is held to prevent uplift, and concrete is placed to fill the shell to ground level. The outer casing is removed, leaving in place a cased concrete and wood composite pile.

The optimum length of composite piles is in the range of 60 to 120 ft. Lengths of up to 180 ft have previously been driven. The optimum load range is 30 to 80 tons with a maximum load limited to about 150 tons. The primary disadvantage of the composite pile is the difficulty to attain a good joint between the 2 materials. Its major advantage is its comparatively low cost for the long pile lengths attainable. However, the extra labor involved in the fabrication of a composite pile somewhat neutralizes its economic advantage in this country.

PRESTRESSED CONCRETE PILES

The prestressed concrete pile is used extensively in this country and abroad and is rapidly replacing the standard reinforced precast concrete pile because of its many advantages. Prestressing essentially eliminates open cracks in a concrete pile, and this is most significant in seawater installations. Prestressing permits considerable ease in handling and reduces the tendency to spall during driving. The compression induced in the pile because of prestressing permits such piles to sustain considerable bending stresses.

Physical Characteristics

The design and manufacturing details of square and octagonal prestressed concrete piles and prestressed concrete hollow cylinder piles have been standardized by a joint

committee of the American Association of State Highway Officials and the Prestressed Concrete Institute. The square and octagonal piles are made in sizes ranging from 10 to 24 in. The piles can be manufactured with a center void for sizes larger than 18 in. The cylinder piles are manufactured with outside diameters of 36, 48, and 54 in. and with wall thicknesses of 5 and 6 in.

The pile reinforcement consists of high-strength wire in a circular or square pattern, enveloped in mild spiral steel wire or tie-bar reinforcement. The prestressing wire is pretensioned prior to the placement of concrete, and the prestressing force is released when the concrete has reached a strength of 4,000 psi. The 28-day concrete strength usually ranges from 5,000 to 7,000 psi. Concrete hardening is usually accelerated by steam-curing for economy of manufacture. For installations involving extremely long piles, sections of piles can be spliced. One type of splice that has been used involves joining the adjacent pile sections with a group of 6 dowels embedded 2 ft into each end. A fast-setting plasticized cement fills the dowel holes and the space between the pile sections.

Another type of frequently used prestressed pile is the Raymond cylinder pile. This pile is manufactured by joining together a series of hollow cylindrical precast sections, each section reinforced with a small amount of longitudinal and spiral steel to facilitate handling. Longitudinal holes for the prestressing wires are cored in the walls of the sections. These piles are fabricated to the desired length by joining the sections and post-tensioning them by stressing the cables running through the cored holes. The ends of the sections are previously sealed with a plastic joint compound, and the cable holes are subsequently pressure-grouted with cement. Stress is transferred to the pile by releasing the external cable-pull after the cement grout surrounding the cables has attained the proper strength. The tensioning cables usually consist of twelve 6-gage, high-tensile strength wires. However, the number of tensioning cables and wire strands in each cable can be varied to suit the design loading. The piles can be manufactured in diameters ranging from 24 to 90 in. and with wall thickness ranging from 4 to 7 in. The standard pile diameters are 36 and 54 in. Piles of this type have been made in lengths exceeding 200 ft. The piles are generally driven open-end and can carry loads exceeding 200 tons. The piles can be subjected to bending moments of considerable magnitude and find extensive use in structural bents over land and water.

An unusual pile installation in New Jersey involves the use of 36-in. diameter Raymond cylinder piles in a fender system. The piles are joined together by a heavily reinforced cap, and the connection between the cap and piles is designed as a flexible system. Thus, the fender system permits the participation of all the piles in resisting lateral load and in dissipating the impact energy by deflection of the entire system.

Problems in Installations of Prestressed Piles

Prestressed concrete piles are inherently weak with respect to radial stresses, with resulting tensile stresses being carried only by the nominal spiral reinforcement. An illustration of this occurred on a project where the contractor elected to use a sonotube (cardboard) form to create a 4-in. tubular jetting void in the interior of a 24-in. square pile. In the steam-curing of the piles, the sonotube distorted, producing a non-uniform opening. In the jetting process, the form collapsed and caused a sudden blockage of water resulting in internal tensile stresses that cracked the pile longitudinally. This problem was eliminated with the substitution of metal pipe for forming the void. The internal jetting of the piles worked very well, achieving accurate alignment control in the installation of vertical and batter piles.

The possibility of developing internal tensile stresses applies also to the Raymond prestressed cylinder piles and similar types of thin-walled concrete piles. Care needs to be exercised in the installation of these piles in that jetting and driving operations need to be controlled to prevent the buildup of excessive internal pressure.

An unusual failure has occurred in a pile splice, similar to the one just described, because of excessive driving energy in advancing a long pile through relatively soft foundation materials. The splice failed as the pile was driven by the full driving energy of the hammer through soft materials. The resulting substantial compression wave in

the pile not meeting sufficient resistance at the pile tip produced a tensile wave in the pile as the driving energy traveled out of the pile tip. The resulting tensile stress caused failure of the pile at the splice. This problem was eliminated by substantially reducing the driving energy in extending the pile through the soft foundation materials.

CAISSON PILES

Caisson piles can be generalized as large-diameter, cast-in-place, open-end, cased concrete piles. The pile diameters can range from 12 to 36 in., and the casing may or may not remain as a part of the load-carrying element. Casing, where used, is usually thick-walled. Caissons are designed to carry extremely heavy loads to extreme depths. A description of some caisson piles that typify those in current use follows.

1. Western caisson pile—These caisson piles are installed by driving an open-end heavy steel pipe to bedrock or to a firm stratum of high bearing value. The pipe is cleaned and filled with concrete if dry, or by the tremie method if water is present. The pipe is pulled for reuse.

2. Calweld drilled foundation—This caisson pile is formed by a self-contained boring rig that can drill holes 10 to 72 in. in diameter up to 200 ft deep. In advancing through submerged granular materials, drilling mud is utilized to keep the hole open. Where soil conditions permit, bells up to 80 in. in diameter can be cut into the soil above the founding level by a bell bucket. The shaft is filled with concrete in the dry or by means of a tremie pipe through the drilling mud.

3. Drilled-in-caisson—This type of installation comprises a steel casing, steel H-pile core section, and concrete shaft. The drilled-in-caisson is a composite fixed-end column terminating in a rock socket, transferring load by direct bearing and bond to solid bedrock. An open-end casing is advanced to bedrock, and a churn drill is used to remove rock to form a socket. The depth of the socket is related to the magnitude of the load to be carried and the bearing and shear values of the rock. A concrete seal is placed at the base of the socket, the steel H-pile core section is centered in the socket, and the casing is filled with concrete. Drilled-in-caissons are usually 24 or 30 in. in diameter and have been installed in lengths of more than 140 ft. The composite section of steel casing, steel H-pile core, and concrete carry loads of the magnitude of 1,500 tons.

SUMMARY

Only the more significant details of the various types of piles available could be reviewed in this paper. The types of piles discussed do not by any means constitute a complete and comprehensive review of the subject. They are considered, however, to be a generalized representation. An economic comparison of the various types of piles has not been presented because of the variables involved with respect to time, place, availability of materials, and other pertinent factors. A relative economic comparison among types of piles was presented whenever possible.

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