AN INVESTIGATION OF PILE FOUNDATIONS, THEIR USES AND COSTS

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TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd)

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INTRODUCTION

The use of piles in deep foundations dates from primitive times. Piles are efficient foundations for various purposes and for a variety of structures. Though piles are not new in foundation engineering, the author has not found any comprehensive work on various types of piles, including the newer prestressed concrete piles. The purpose of this report is to present various aspects of piles: their types, uses, and an approximate analysis of cost for the various types.

Piles are basically part of the substructure unit, by means of which loads are transmitted from the superstructure and the remainder of the substructure through weak unsuitable soils, water, or air to a lower stratum that has sufficient bearing value to support the completed structure and all the loads that are expected to be applied to it. Piles may be used to spread these loads through and over relatively weak soils to enable it to support the structure safely.

Piles have been found as foundations in prehistoric dwellings in Lake Lucerne in Europe. The villages of prehistoric tribes on the lakes of Switzerland were almost entirely built on piles. Even the existence of Venice depends on piles. Modern pile driving started with the first steam pile drivers, invented by Nasmyth in 1845, from which the present single-acting steam hammer has been developed. Present day engineering makes use of millions of piles each year.

Formerly, piles were simply trees that were cut off and stuck into the mud, but present day piles may be made up of timber, concrete, steel or a composite of any or all of these, and a large variety of each is available.

Numerous and complex combinations of soil materials and arrangements exist in nature. Full information on soil conditions and experience in interpreting this information are necessary in the sound design of pile foundations. Final design of any important structure should not be made without a loading or driving test.

Piles are generally brought down to their final positions by successive blows delivered to the tops by a pile hammer. They may also be driven by aid of water jets.

The design of pile foundations requires consideration of many factors, geology of site, boring results, pile types, driving equipment in conjunction with a proper dynamic formula, performance of load tests, pile capacity using static formula, driving of test piles, and bearing capacity of soil below the piles.

FUNCTIONS OF PILES

Piles are used as an element of construction, placed either vertically into the ground or nearly so, to increase power to sustain the weight of a structure or to resist a lateral thrust. Piles transfer and distribute the load by either bearing on a hard stratum or by skin friction between the piles' surface and soil. Piles are used to anchor down structures subjected to hydraulic uplift pressure, which causes overturning moments. These piles also provide anchorage against horizontal pull from sheet piling walls in anchor bulkheads. Another common use of piles is for retaining banks of earth and resisting horizontal forces. Sheet piles are used for this purpose and are driven close together. In addition, there are several less common purposes for which piles are used, for instance, in all kinds of marine structures, piles are often used as fenders.

TYPES OF PILES

A summarized statement of pile types is made in Figure 1. Piles could be classified according to function, as point bearing, friction, and composite types.

A point bearing pile is one in which the load is transferred to the stiffer strata at the bottom through the bearing only. A point bearing condition occurs when the pile is driven through soft material to or into a stratum of firm or unyielding material, the pile being designed as a bearing pile. This pile can be round, square, octagonal, annular, or H-shaped in section, depending upon the material.

In a friction pile, the transfer of load is through the friction between the earth and the pile skin. This type is used when a sufficiently strong structure is not available at a reasonable distance below the surface and when the soil has a high coefficient of friction. The efficiency of such a pile depends upon the contact area available for friction between the soil and the pile. A point

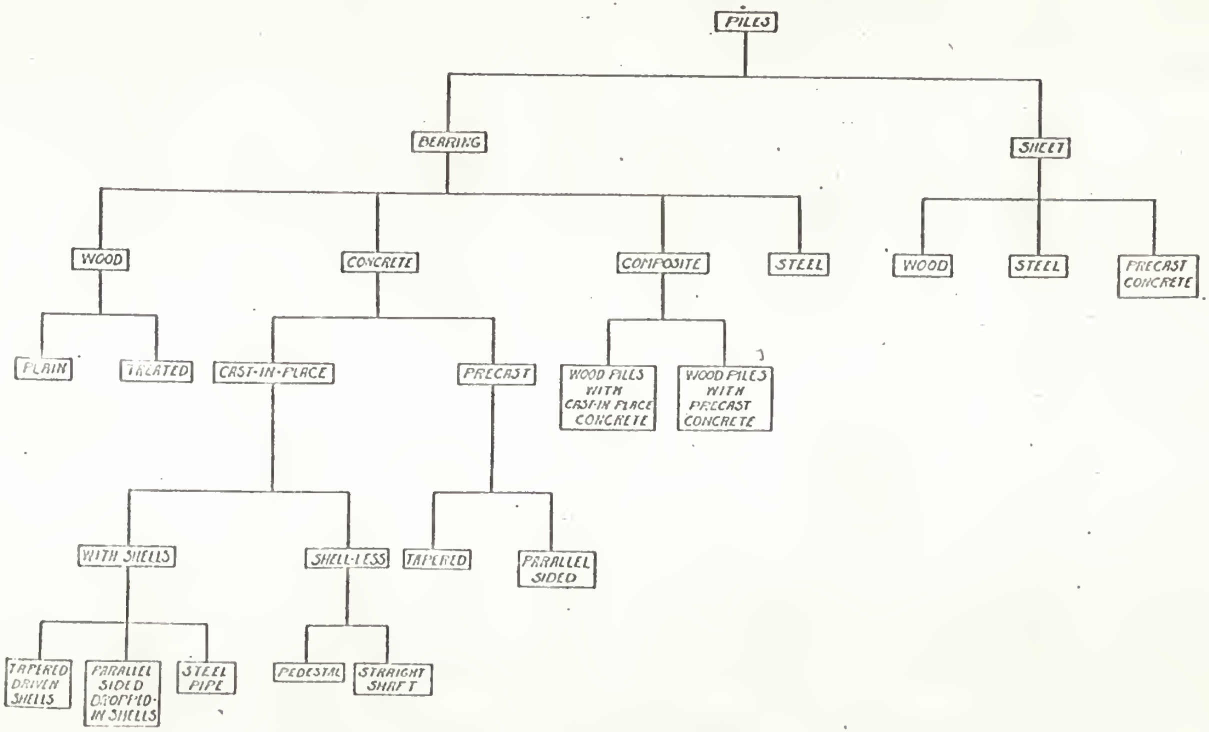


Figure 1. Pile Classification

worth noting is that the friction should not diminish in presence of water as may happen in cases of clayey soils.

In practice it is usually impossible to find cases when piles transfer the loads fully through bearing or friction, but they usually transfer the load as a combined effect of both. These piles are called composite piles.

The bearing capacities of different types of rocks and frictional resistances of different types of soils to be used as pile bearing material can be had from any standard book. However, test bearings should be made to establish these values.

Timber Piles

Scope. A timber pile is, in essence, the trunk of a tree with its branches trimmed, as was done in primitive days. The following are the characteristics of a good timber pile:

A timber pile should be of sound quality, free from sharp bends, large or loose knots, splits, and decay. It should be free from short or reverse bends and from crooks greater than one-half the diameter of the pile at the middle of the bend. It should be straight and have a uniform taper. A straight line drawn between the centre of the butt and the centre of the tip should lie entirely within the pile. The general requirements of timber pile are described in the ASCE Manual No. 17 entitled "Timber Piles and Construction Timber."

Classification. According to the ASCE manual, the following are listed for convenience in specifying piles for structures of varying quality of timber and dimensions of the pile:

Class A pile. To be used for heavy loads or large unsupported length.

Class B pile. To be used for medium loads; they are smaller in diameter.

Class C pile. To be used below permanent water level and for the temporary work where treatment is not required for protection.

Preservative Treatment. Durability is one of the grave problems connected with the use of the wooden piles. Their usefulness may be destroyed by fungi, marine borers and mechanical action. Untreated piles entirely embedded below the ground water table are considered permanent, provided marine borers are not present. When piles are above the water table, they are subjected to decay by fungi and attack by insects and borers.

A most effective method of preventing piles from decay is to poison the food supply of the fungi, marine borers, and termites. The piles to be treated are loaded on train cars which run into a large cylinder. A preliminary vacuum is created to remove as much air as practicable from the wood cells. After the cylinder door is closed, preservative and pressure is applied until the required absorption has been obtained. A final vacuum is commonly applied immediately after the cylinder has been emptied of preservative to free the charge from dripping preservative.

The pile is then ready for use and after being driven to the final depth, it is sawed square to appear undamaged. Before wood receives a pile cap, the treated piles should be protected by zinc coat, lead paint, or by wrapping the pile heads with fabric upon which hot pitch is applied.

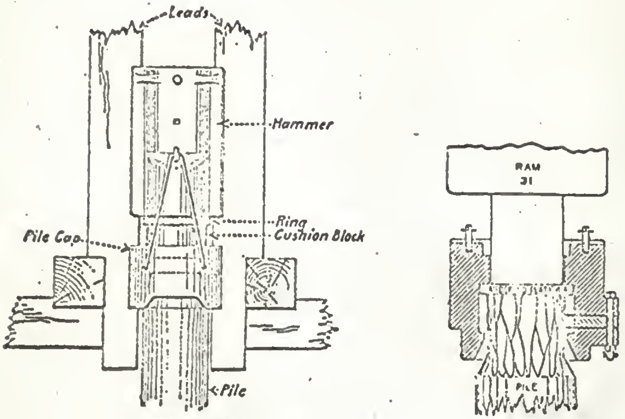
Strength of Timber Piles. Timber piles are good as friction piles. The compressive strength of the timber is small and they are not good for the end-bearing ones. Ordinarily, timber pile should not have to support more than 30 to 35 tons under the best conditions.

Accessories of Timber Piles.

Rings. When pressure on the pile fibers exceeds ultimate resistance in compressions, they yield and the hammer tends to injure the fibers farther down. This breaking down is called brooming. The crushing of the fiber is frequently followed by splitting of the pile. This tendency is promoted by failing to cut off enough of the butt as it comes from the forest to cover the entire section area of the pile, for if the hammer hits only one-half of the area it will force that part down into the head and split it. To reduce the effect of brooming and prevent splitting, the head may be hooped by a pile ring as shown in Figure 2. The sizes of rings range from 2 inches by 3/8 inches to 4 inches by 1 inch. The diameter varies to suit the different sizes of piles. They are made of wrought iron and can be used repeatedly.

An ingenious mechanical device is used to remove rings. When the pile has been driven, a lever is placed on the top of the pile and the hammer is allowed to drop, as shown in Figure 3.

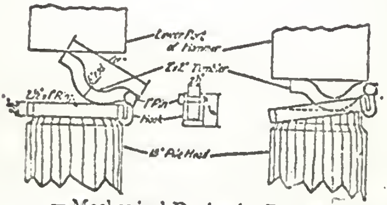
Caps. A more effective and less expensive method of protecting the head of a timber pile is the pile cap. A casting with a taper recess fits over the chamfer head of the pile with a tough, hard wooden block fitted into it as a cushion. The cap has jaws which engages



Casgrain's Pile Cap.

—McDermid Base.

Figure 2. Pile Caps and Rings



—Mechanical Device for Removing Rings.

Figure 3. Mechanical Device for Removing Rings

the leads and guides the pile driving. The cap is hooked to the hammer by ropes and pins and raised with it.

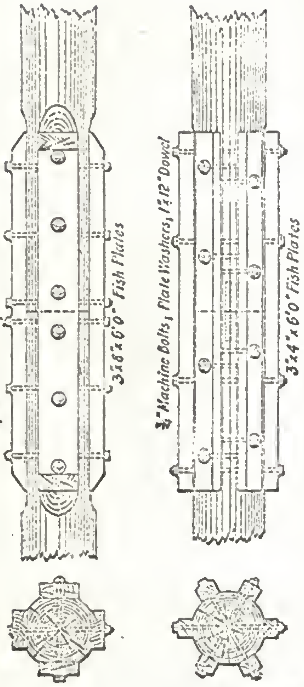
Followers. When the pile has to be driven below the lead or ground or water surface, a follower is employed. This is a member interposed between the hammer and the pile to transmit the blows to the latter. This can be a short pile of any material with extra reinforcement at the base or at the top, if necessary.

Points and Shoes. When driving is hard for most of the penetration, as in stiff clay or in material that is but slightly compressible and hence must be displaced, the piles are pointed to separate the material at the foot like a wedge. To guard the strength of fibers against brooming, a square of 4 inches to 6 inches is kept as the tip of the point. Pointing increases the rate of penetration and reduces the energy required.

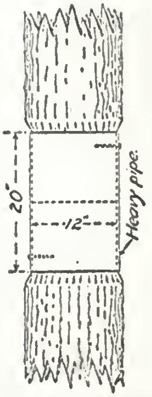
Shoes are often used instead of points. Shoes are not made of very strong material as are rings or caps, as shoes cannot be reused.

Splices of Timber Piles. Splicing timber piles is poor practice except in firm laterally supporting soil. If the pile is very long and strong, the splice is used at the middle portion of the unsupported piles. Splice should be avoided when piles are subjected to uplift or lateral forces.

One of the methods of splicing is to use a section of a pipe sleeve with a length of approximately 4 to 5 times the diameter of the pile which is sawed square to ensure full contact, as shown in Figure 4. After being driven, the splice portions are then trimmed smooth and fitted tightly into the pipe sleeve. This type of splice is simple to make, but it has ability to transmit uplift forces.



–Fishplate Splices for Timber Piles.



.—Tubular Splice for Timber Pile.

Figure 4. Splices for Timber Piles

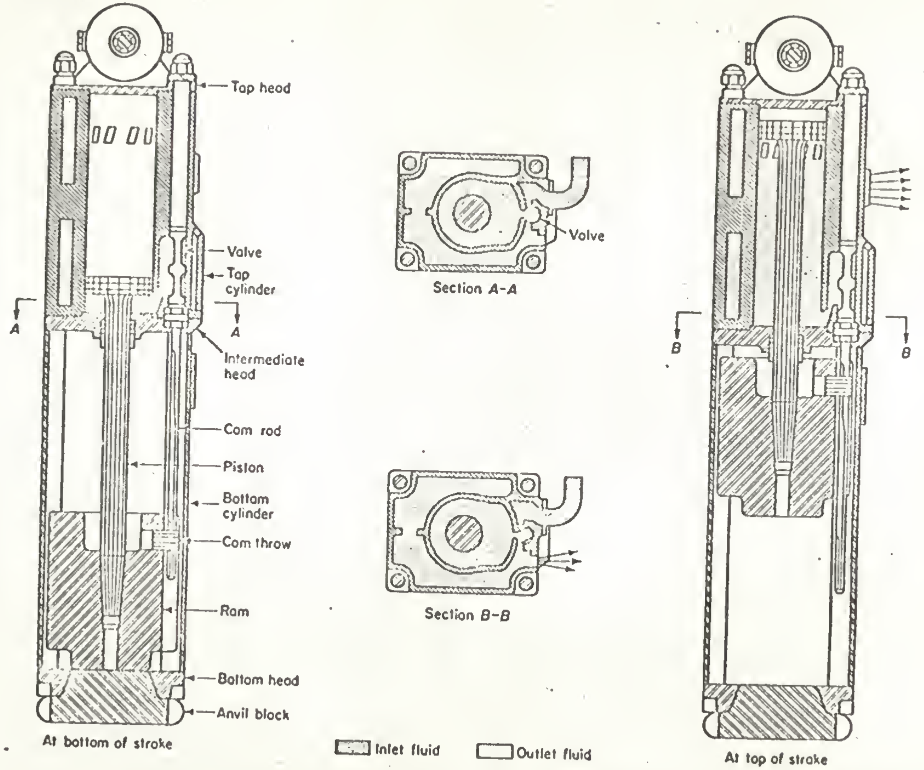
In the other method of splicing, steel straps and bolts are used. Four sides of the piles are planed flat to receive the splicing. The straps are then bolted, as shown in Figure 4. This type of splice can resist some uplift and lateral forces.

Hard driving is likely to broom the butt of wooden piles, and the tips may be crushed when driven through or into dense, gravelly materials. Therefore, the design capacity of timber piles is limited empirically to about 25 tons in order to avoid possible damages due to the necessity of hard driving.

Driving Phenomena. The oldest method of driving piles is by drop hammer. This consists of a heavy ram in between the leads. The ram is hoisted up to a certain height and released to drop on the pile.

A single-acting hammer is a long stroke machine consisting of a heavy ram which is lifted by and dropped by its own weight. The double-acting hammer employs steam or air for lifting the ram and for accelerating the downward stroke. It operates with a succession of rapid blows. Photographs and sections of the single-acting and the double-acting hammer are shown in the Figure 5 and Figure 6.

Thus, by transferring the potential energy of hammer to the pile, pile driving is achieved. Another advanced method of pile driving is by water jet. The water jet displaces the earth at the foot of the pile and, used in conjunction with a hammer, results in an efficient driving. Pile driving can be still improved upon by prebored holes. The alignment of the pile is maintained by a guide along the leads. By successive striking of the hammer, the desired



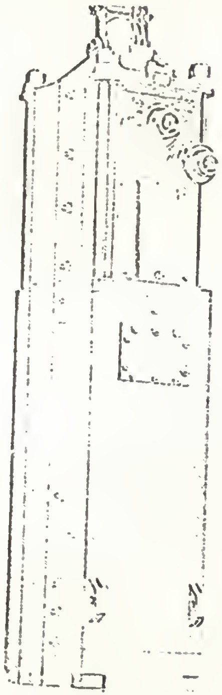
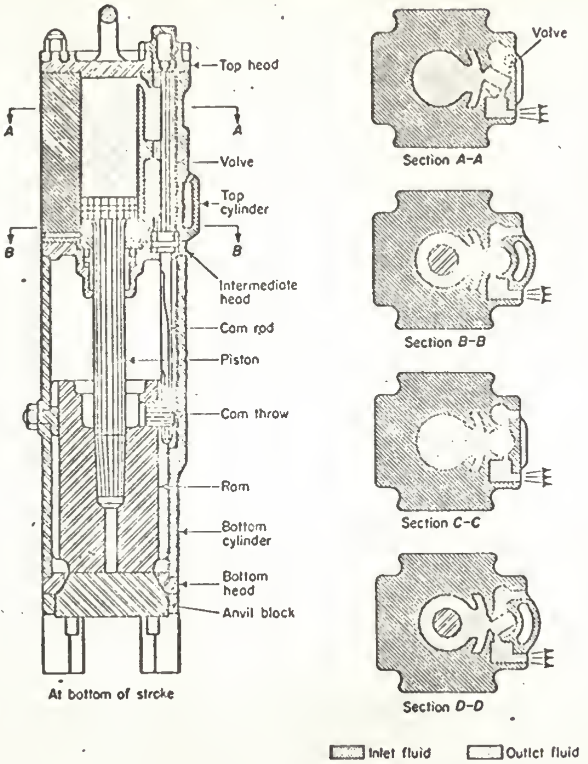
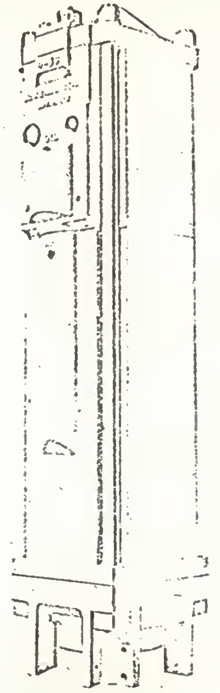

Single-acting hammer.
McKiernan-Terry Corp.

Figure 5. Single-acting Hammer and Its Working





Double-acting hammer.
McKiernan-Terry Corp.

Figure 6. Double-acting Hammer and Its Working

penetration of pile or, indirectly, the desired bearing capacity of pile is achieved.

Concrete Piles

Scope. When wooden piles are limited in their use because of fire hazard or ground water table, need for waterproofness and where high strength and long life are required, concrete piles become the most suitable piles. Reinforced concrete piles in waterfront structures are called upon to meet very unfavorable exposure conditions in harbors. Even these are guarded against by selecting the proper quality of aggregates, by composition of cement cover, for reinforcement, and by mixing and placing operation. A group of concrete piles behaves as a better spaceframe because of its mode of construction. Extra precautions need not be taken against marine bores, or salt water.

There are two kinds of concrete piles: the precast and the cast-in-place pile.

Precast. Precast piles are of reinforced concrete and prestressed concrete.

Reinforced Concrete. A reinforced concrete pile is cast round, square or octagonal in section. It may be of uniform cross-section or it may be tapered. It can be hollow or of full section. It can be used where decay would prevent the use of the wood piles. It is useful in carrying fairly heavy loads through soft material to firmer strata. Constructing concrete piles requires equipment for handling and large storage space. Predetermining length of piles is hard and may then involve cutting off extra length or building up.

Concrete piles can be used even in a location of water table if the concrete is properly made. Precast concrete piles are generally built with a tapered bottom. The taper does not materially change the capacity of end-bearing but generally eases the tendency of the pile to move during driving. The taper is desirable for soils without cohesion such as sand or gravel and where hard strata is to be penetrated. For plastic soils, a blunt point is most suited. The metal shoes are not generally used but may be used where the driving is hard or where boulders are present. It is essential to provide a head, so that piles do not get damaged by the hammer blows. The head should be a true plane, at right angles to axis of the pile, and lateral reinforcement should be provided for a minimum distance equal to the diameter of the pile. The protective cover is designed to resist the stresses due to service loads, handling and driving. Reinforcement consists of longitudinal bars with hoops or spirals. Jet pipes to be used in sinking are cast at the center of the pile.

Manufacturing of Precast Piles. The fundamentals of design and control of concrete mixture recognized as good practice are equally applicable to piles as to all other concrete construction. The equipment and facilities provided may either be temporary and "homemade" or the most modern suitable for long time operation. Piles are manufactured either near the site or at a remote location. The size and location of the job will determine the place of the casting yard, the layout of its facilities, the type of forms and the handling and loading arrangement.

Piles are cast in forms placed either horizontally or vertically, the former practice being more common. Forms are made up of wood or steel or both. They should be substantial for construction and should be designed for easy assembling and dismantling to permit reuse.

Concrete should be made in accordance with the provision of specification ASTM designation C-150 and C-175. A uniform quality of concrete should be taken to ensure well compacted strong concrete at the head and the point.

Reinforcement is first assembled in the cages and then is placed in the forms. If the cages are circular, the lateral ties are usually continuous spirals spaced on small steel channels. The longitudinal bars should end in the same plane and be kept back about 3 inches from the head and the point. It is essential to support reinforcement properly in the forms before concrete is placed.

Twenty-four hours after placing the concrete in the forms, they should be removed and the piles should be kept wet for at least 7 days, if normal Portland cement is used; and, if practicable, curing is done by ponding.

Prestressed Piles. Prestressed concrete piles have several properties which make them preferable to other types in many situations.

They withstand severe driving conditions without cracking or spalling. A non-prestressed concrete pile will crack as it recoils from a heavy hammer blow. When the hammer strikes, its force creates compression in the pile, causing an elastic shortening. The pile springs back to its original length, having gathered momentum, causing further elongation which in turn creates tensile stresses in the pile. Under repeated blows these tensile stresses cause cracks, and under repeated blows spalling may develop. Prestressed concrete piles are fabricated with sufficient compressive stress to offset the tensile stresses caused by recoil. Experience indicates that an initial compressive stress of 800 psi is normally sufficient for this purpose.

Prestressed concrete piles are easy to lift and transport. Their compressive stress enables them to resist large bending moments, so that they can be lifted with simple one or two-point picks-ups where reinforced concrete piles of the same dimensions require complicated rigging for multi-point picks-ups.

Prestressed concrete piles are durable because they are crackless. They are seldom cracked by driving or handling, and even if they should be, the compressive stress will keep the cracks tightly closed once the pile is in place.

Types of Prestressed Piles. Prestressed concrete piles have been used to a notable degree in the United States. The types of piles which have been used can be divided into the three following classifications:

1. Post-tensioned, multi-element cylinder piles
2. Pre-tensioned, precast piles
3. Pre-tensioned spun piles.

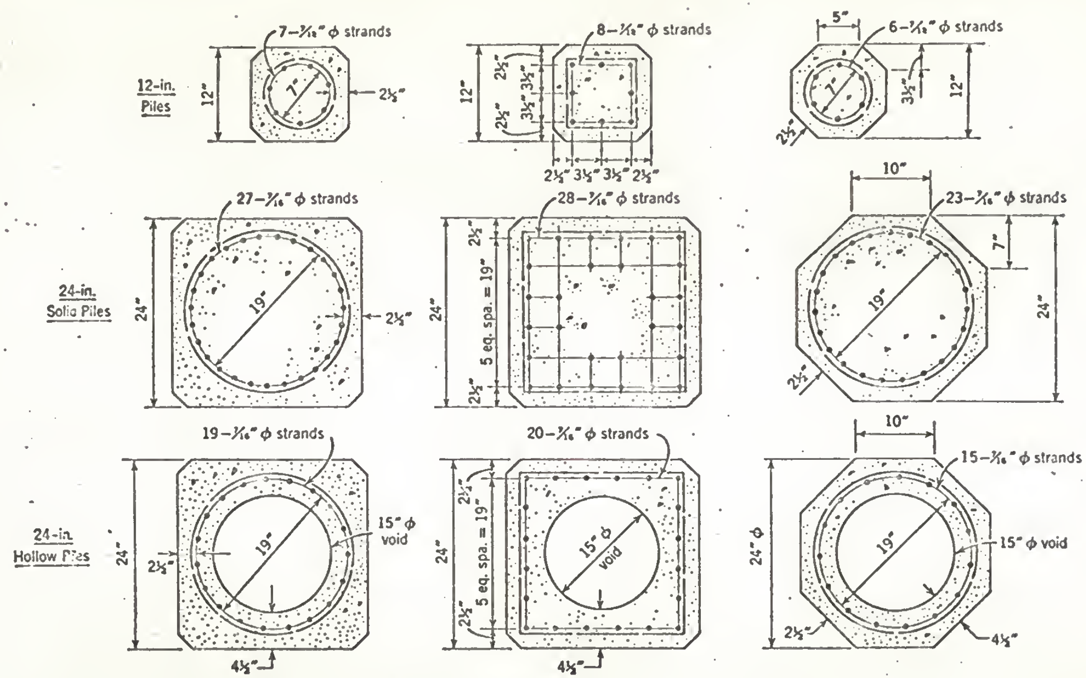
The post-tensioned, multi-element cylinder piles are made by precasting hollow cylinders of concrete in sections about 16 feet long. Each section has a wall thickness of from 4 to 5 inches, and holes are formed longitudinally through the walls at the time the sections are cast. After the precast sections have cured, they are aligned, and post-tensioning tendons are threaded through the holes in the walls, stressed and grouted in place. In this manner, piles up to 150 feet can be made.

The cylinder piles are normally made in diameters from 3 feet to 4 feet 6 inches and have been used with design loads up to 350 tons, although 225 tons is more normal for the large-size piles. The hollow shape is an efficient one for resisting axial loads as well as for resisting bending moments which may be applied from any direction.

Pre-tensioned precast piles have been made with square, octagonal, and round cross-sections, both hollow and solid. This type of pile has been used a great deal in the construction of water-front structures, and is fabricated in the normal manner used in pre-tensioned construction. This type has been used more than the other two types.

Pre-tensioned spun piles are made in individual molds which are designed to resist the pretensioning force during the casting and curing of the pile. The manufacturing procedure consists of placing the tendons and reinforcing cage in steel molds, stressing the tendons, and placing the mold on revolving wheels which turn the mold as the concrete is placed. The centrifugal force compacts the concrete and forces the excess water from the plastic concrete. The pile is then cured and stripped from the mold.

Details and Connections. Some typical pre-tensioned pile are given in Figure 7. These piles are usually pre-tensioned with



Typical pre-tensioned pile sections (AASHO-PCI Standard).

Figure 7. Typical Pre-tensioned Pile Sections

7 wire strands, from 3/8 to 1/2 inch diameter. The spacing of spiral steel also was established by experience. Its design has not been rationalized but it is generally agreed that steel of No. 5 gauge about 0.2 inch in diameter, at a 6 inch pitch, will suffice for the middle part of the pile, while a 3 inch pitch is used for the end portions.

Where the pile tops are encased in a heavy footing, very often no connection other than sufficient embedment is required. If additional anchorage is required, the following type of connection can be used.

The connection of pile to cap is the simple reinforcing bar anchorage similar to that used for many years in conventionally reinforced piles. The reinforcing can be cast in the head of the prestressed pile where the piles can be driven reasonably close to final elevation, but a special driving head or follower must be used. Bars can be grouted into either precast holes or holes drilled after driving.

Driving. Prestressed concrete piles have proven their ability to take an unbelievable amount of punishment without structural damage. They are very strong in bending but are not indestructible. Experience has shown that if the criterion of no tension in the concrete is used for bending and transporting, a sufficient factor of safety against cracking is available to take care of impact and shock loads for all but extreme cases. When no extra loads are expected, tensile stresses may be permitted during handling.

The pile head must be truly perpendicular to the pile axis and reasonably plane. Irregular or inclined heads tend to concentrate the driving blow and may cause spalling or cracking at the head. The wire strands should be burned flush with the pile head. A chamfered edge at the head also helps to prevent spalling. If jetting is required, the internal-type jet has proved superior to the external type in preventing wandering of the pile tip and consequent eccentricity during driving.

One of the most important details in connection with the driving operation is the cushion block. Generally the best performance has been obtained with 4 to 8 inches of laminated softwood, such as Douglas Fir, placed directly between the pile head and the driving helmet. The type of cushion block directly affects the magnitude of the driving stresses. In severe cases, the use of a reduced hammer blow during the soft driving stage may also help.

Cast-in-Place Piles. A cast-in-place pile is constructed by making holes in the ground of required depth. They are formed in various ways, and then filled with concrete. A variety of cast-in-place are available in the U.S.A. and each bears the name of the manufacturer. Reinforcement is usually not required, unless the soil is such that during construction operations heaving tends to distort them, or if they are called upon to resist flexural stresses. Extensions and cut-off are eliminated.

Three major types of cast-in-place piles are shown in Figure 8. Each of these has different characteristics. A few of the characteristics of each type will be discussed here.

Three major types of cast-in-place piles are discussed in the report. These are Shell-less (or Uncased) pile, Shell type pile, and Pedestal Pile.

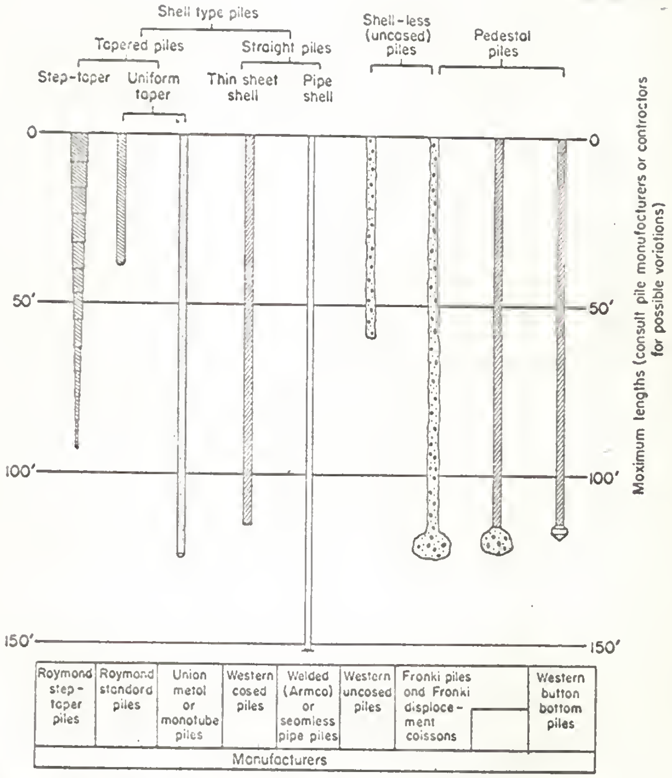


Figure 3. Common Types of Cast-in-place Piles

- Shell-less (Uncased) Pile
    - Western Uncased Pile
    - Franki Pile and Franki Displacement Caisson
- Shell Type Pile
    - Raymond Step-taper Pile
    - Raymond Standard Pile
    - Monotube or Union Metal Pile
    - Western Cased Pile (Thin Sheet Shell)
    - Welded (Armco) or Seamless Pipe Pile (Pipe-Shell)
- Pedestal Pile
    - Franki Pile (Uncased)
    - Franki Pile (Thin Sheet Shell)
    - Western Button Bottom Pile (Swage Pile)

Shell-less Pile. This pile is used when one is certain that there is no water or soil which falls into the hole, or squeezes into and reduces the size of the hole left after withdrawing a driven shell before pouring concrete, or that driving an adjacent pile does not damage the wet concrete. This pile does not require storage space and special equipment for handling. No cutting off excess length is involved.

Method of Forming. Core and casing are required that are approximately of the same size when the core is inserted into the shell. Both of these are driven into the ground until the required penetration is obtained. Then the core is retracted and the casing is filled with concrete of a coarse aggregate. Now the casing is in contact with the concrete replacing the core. The casing is withdrawn leaving the weight of the hammer and plunger on the concrete.

Western Compressed Uncased Pile or MacArthur Compressed Uncased Pile. This type of pile is made up-to 60 feet of length, and 14 inches to 24 inches in diameter. This pile is satisfactory under any soil conditions. Method of driving is as explained above. This type of pile is often driven by the MacArthur Corporation and it is claimed that the weight of the hammer and core, approximately 7 tons, results in a solid dense shaft of concrete.

The western foundation claims that their method prevents any possibility of lifting apart of the concrete column when removing the casing, as it consists of pulling the casing by drawing together the collar on the casing head and the crosshead over the hammer top. This results in a positive compression in the concrete column at all times, obviating breaking or arching of the concrete in the casing.

MacArthur Compressed Concrete Pedestal Pile. This pile is used when the bearing stratum is rough or a sharply inclined rock surface and the pedestal ensures a firm grip on the rock. When the bearing stratum is of limited thickness only and can be received within economical depth, this pile can well be advantageous. The pedestal gives the effect of a spread footing on this comparatively thin bearing stratum. This pile is formed by driving a casing and a core. Before dropping the charge of concrete, the core is removed. Casing is then pulled up 18 inches to 4 feet with pressure of the core and hammer on the concrete. The concrete is rammed to form a pedestal. The core is then removed and the casing is filled with concrete. The core is replaced in contact with the concrete. The casing is steadily withdrawn while the concrete is under the pressure from the weight of the hammer and core. This pile is generally driven by MacArthur Pile Corp. and maximum diameter generally driven is 16 inches.

Cast-in-Place Cased Pile. Generally when support is required for the sides of the hole while pouring the concrete, this pile is used. In driving procedure a temporary heavy outer casing is driven with the hammer and a permanent light shell is inserted. The outer casing is then withdrawn and reused. This pile does not require storage space and cutting off excess lengths, and it does not require special handling. It is used when the soil is too soft and soapy to permit the use of uncased pile.

Raymond Taper Pile. This pile is manufactured by Raymond Concrete Pile Co. It is formed by driving a thin shell, with a taper of 0.4 inch to 1 foot and with circumferential corrugations and a closed foot by means of a tapered mandrel. After driving, the mandrel is withdrawn and the pile is filled with concrete which can be reinforced. This type of pile is used either in end-bearing or in frictions-load-carrying soils. This pile is available in length up to 37 feet with 10 to 22 guage.

Union Metal or Minotube Pile. This type of pile is suitable for any soil. It is tight against inflow of water. The method of forming is by the driving shell which is then filled with concrete and the excess shell cut off. This type of pile is manufactured by Union Metal Mfg. Co.

Western Cased Pile. This pile is made in various diameters varying from 12 inches to 20 inches, with the maximum length available 75 feet. In the driving procedure, core and casing of the same size are used so as to close the casing completely when the core is inserted in it. Both are driven to the required penetration. Then the core is removed and the pile shell is used to serve as the concrete container prior to setting. It is a very light material which is either corrugated or plain, riveted or lock steam. The core is replaced in the casing in contact with the top of the shell. The position of the core is fixed by dogging the hammer. When the lower and upper collars are drawn out, the casing is withdrawn, while the shell is so held that the new pile cannot be disturbed by movement of the casing.

Western Button-Bottom Pile. This pile is primarily an end-bearing pile. This pile could be used where one must penetrate unreliable material overlying a good stratum of dense sand, gravel or hardpan. The large area of button provides adequate bearing for heavy loads. These piles have been driven through 16 feet of dumped rock fill with little delay. Maximum length up to 76 feet may be driven and loads up to 50 tons carried. In driving, a steel pipe, 14 inches diameter with 1/2 inch thick wall with reinforced bore of cast-steel, is set upon a concrete button with diameter 1 inch larger than the pipe diameter. The pipe and button are driven to a special elevation. The casing is then withdrawn, leaving the button in place, and the shell is filled with concrete.

Precautions Against Damages. The green concrete in the case of cast-in-place piles should not be disturbed before it sets. To accomplish this, AREA specifications limit the distance of other pile to be driven near by to 4 1/2 times the average diameter or 5 feet. In the use of shell piles, it is 15 feet. The underground water can wash away, segregate or even separate piles into pieces if it is uncased. Even in the case of cased pile, precautions should be taken to prevent the pulling up of concrete as the casing is lifted.

Chemicals present in ground water attack the concrete and deteriorate it. Treatments are suggested in standard books against all chemicals except acids. Deterioration in sea water is due to chemical and mechanical action. Chemical decomposition of concrete in sea water is promoted by the presence of cracks, thereby rusting the reinforcement. The effect of mechanical action may be due to the freezing of water in the pores or cracks and exposing the reinforcement. If flexural cracks are not allowed to develop, as in prestressed pile, and if reinforcement is provided to account for all the above causes, they can, to a considerable extent, be avoided.

Handling Concrete Piles. Reinforcement in piles is provided to resist stresses due to (1) handling the pile, (2) driving the pile (3) the final load that the pile has to withstand in its final position.

The longitudinal reinforcement bars receive their maximum stresses when piles are picked up at or near the middle, in going to and from the seasoning yard, and must be strong enough to resist flexural stresses to their own weight. When a pile is dragged by one end to reach the pile driver, it must be strong enough to resist flexural strength and also strength to resist impact. The specifications of the AASHO which require the use of concrete that tests 3,000 psi in 28 days, limit the stresses in the reinforcement due to handling to 12,000 psi, allowing 100% of the calculated load for impact and shock.

Handling stresses can be limited as desired by providing the number of suspension points used. Let the weight of the pile be W and L be its length. Then for one point suspension, the maximum moment is 1.5WL in-lb. When the positive moment at the centre equals the negative moments, it leads to the use of two-point of suspension. So for two-point suspension, the points of supports are at 0.207L from ends, and the maximum moment is 0.257W in-lb. In the case of three-point suspension, the best result is obtained by keeping one suspension at the centre and the other two at the 0.138L from the ends. With this position of suspension, the maximum negative moment will be at the first and third supports and the maximum positive moment will be at a distance of L/3 from the ends. These moments will be equal to 0.0523WL in-lb., as shown in Figure 9a and Figure 9b.

Design Chart for Concrete Piles. Figure 10 gives the size and number of longitudinal bars required for such piles for the three methods of handling shown in the Figure 9, based on f_c = 1,400 psi and f_s = 20,000 psi without allowance for impact. A protective cover of 1 3/4 inches to center of steel has been allowed.

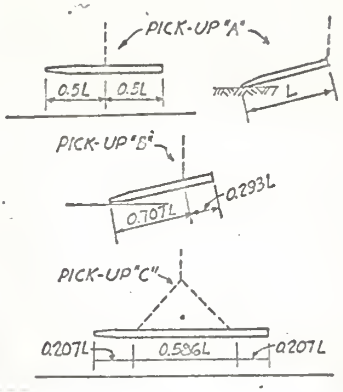


Figure 9-a. Precast Concrete Pile Pickups

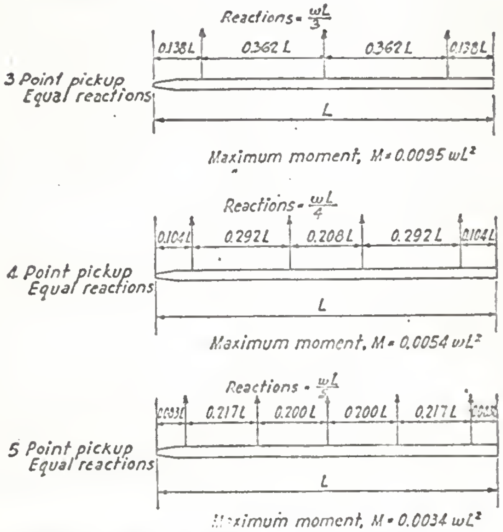
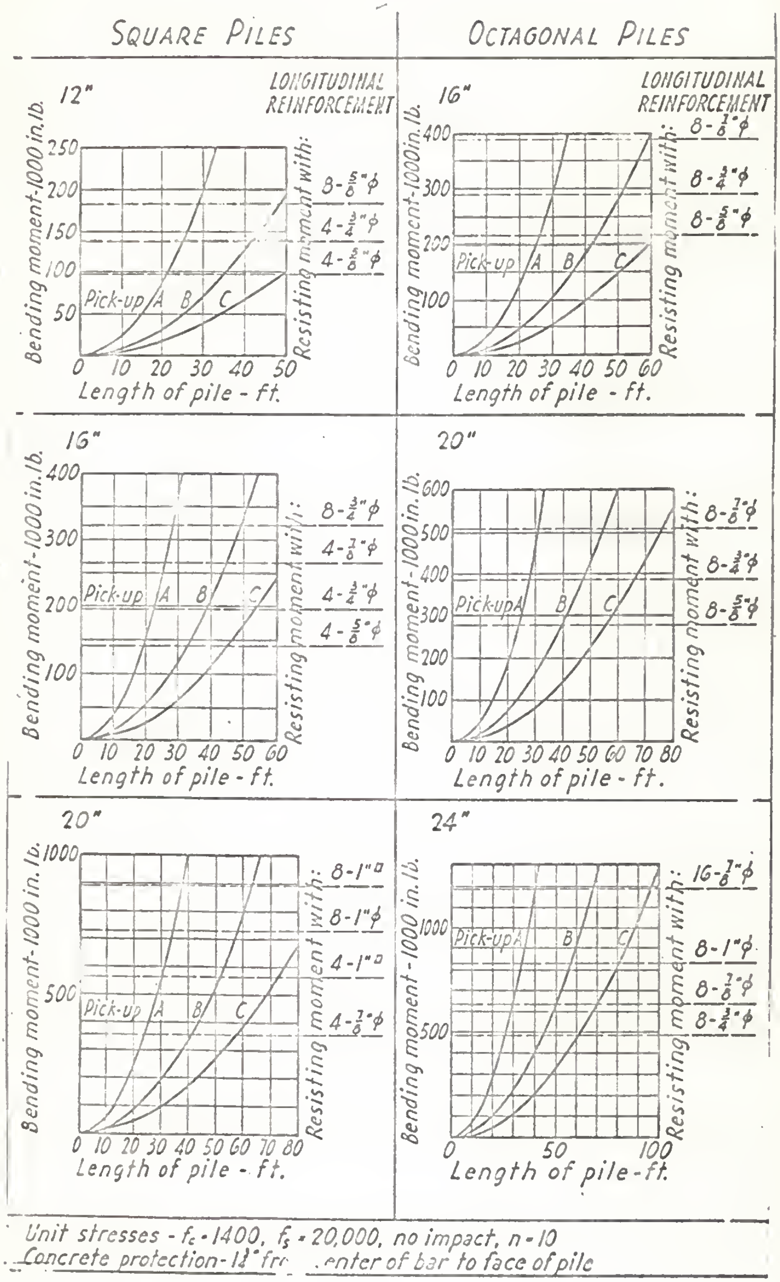


Figure 9-b. Pickup Locations and Moments for Equal Reaction



Unit stresses - f_c - 1400, f_s - 20,000, no impact, n - 10
Concrete protection - 1½" fr[illegible] .enter of bar to face of pile

Figure 10. Design Chart of Piles

To use these charts for an allowable steel unit stress of f_s other than 20,000 psi, multiply the ordinate of the resisting moment by $f_s/20,000$ where f_s is the new unit stress.

If it is necessary to design the pile for impact, reduce the ordinate of the curves by 100/100+I in which I is the percent impact.

The following example illustrates the use of this chart.

1. Determine the reinforcement required for a 20 inch octagonal pile 45 feet long.

Enter the chart, Figure 10 at length of pile equal to 45 feet, and find the intersection of the vertical line at 45 feet with lines A, B and C.

For pickup C, at least eight 5/8 inch round bars are required. For pickup B, at least eight 3/4 inch round bars are necessary. It is not practicable to lift this pile by pickup A.

2. Determine the maximum pile lengths permissible with pickups A, B and C for a 20 inch square pile with four 1 inch square bars.

The intersection of the dash line for this reinforcement with lines A, B and C gives lengths of 30 feet, 52 feet and 73 feet respectively.

Steel Piles

Scope. Steel piles may be of rolled section, fabricated shape of a piece of sheet pile. Two or more sections of sheet piles may be connected together in box shape and driven as one pile. Steel piles have greater capacity per pile than other types. This may be utilized to greatest advantage in locations where piling can be driven into hard ground material such as hard pan and shell or to firm bearing on solid rock.

Thus, extremely high bearing capacities can be developed. In soft soil also they can be used to advantage when a long length of penetration is desired to reach a low lying stratum or to develop required bearing capacity by friction.

Steel piles need less space for shipping and storage. Also, on account of facilities for splicing rolled shape on job, there is practically no limit to the length of pile that can be used. Compared to wood piles that split and the concrete piles that crack, the stresses which develop in steel piles are generally low. Steel piles can withstand very rough handling.

The principal advantage of steel pile, however, lies in its ability to withstand the punishment of the long-continued and hard driving, necessary to obtain required penetration. It has the fortunate characteristic of showing any destruction due to driving at the extreme top of 6 to 12 inches which can be cut off with a torch so that driving can be continued.

Classification. Following are the varieties of the steel piles:

1. H-Pile 2. Pipe Pile 3. Sheet Piles 4. I-Beams and Rail Piles 5. Box Piles.

H-Piles. When it is desired to penetrate to rock through hard material with the least effort and time, H-bearing piles are suitable. Because of their smaller soil displacement, these are often the only piles that can be driven to desired penetration without recourse to jetting, coring, or other similar operations. They have large bending strength and are useful when lateral horizontal forces act on piles. When close spacing is necessary, their small soil displacement is of importance. They do not require special slings or special care in handling unless they are long, in which case they are supported with web vertical. Length up to 127 feet unspliced and 227 feet spliced have been successfully driven. Penetration up to 10 to 20 feet in hard pan and 22 feet in cemented sand has been obtained.

H-piles are used extensively in retaining walls and in bulkheads. In trench cuts they are driven 5 to 8 feet, centers and planks are dropped into the grooves as the excavation proceeds. This construction is useful in driving a sheet piling coffer dam. H-piles are readily withdrawn for reuse.

Pipe Piles. Metal piles filled with reinforced concrete have been used for some bridge foundations and building foundation, especially where under-pinning is involved. The pipe can be of any diameter, according to the manufacturers. The common sizes are 10 inches to 18 inches diameter. Pipe as large as 54 inch diameter has been used, but when a man can enter in the pile for excavation, it is called a caisson. The AREA specifies "pipe shall have an inside diameter of 10 inches or more and thickness not less than 3/8 inch, except that a thickness of 5/16 inch can be used on 10 inch and 12 inch pipe."

Sheet Piles. There are various forms of sheet piling but forms resembling the old Lackawanna sheet piling are most common. Manufacturers give standard specifications for their sheet piling. Sheets can be arranged in various profiles to resist different loads by interlocking. Sometimes box pile, I-beams or space between sheet piles filled with reinforced concrete are used as reinforcement.

I-Beams and Rail Piles. I-beams are used to reinforce the sheet piles. Abandoned rails are extensively used by many companies in different configuration. These are not costly and are strong.

Box Piles. Canadian box piles are formed by welding together sections of Algoma steel sheet piling in various shapes. They can be driven in any type of soft rock and will perform the same function as pile or caisson.

Preservation against Corrosion. Corrosion is a complex electrochemical process in which iron atoms are ionized into positive iron atoms and negative electrons. The electrons are removed or neutralized during continuous process of corrosion. Soil full of swamp, peat, alkali and ingredients such as coal particles, acid materials, cinder, etc., are very corrosive. Moisture and oxygen cause active corrosion. Procedure of corrosivity determination is still in research stage and not much is known yet. For an ordinary project, one of the following methods for reducing corrosion is used:

(1) Concrete Encasement. Near the ground surface where moisture and oxygen are abundant, the piles may be protected by encasing them in concrete. Encasement extending to a great depth is costly, but increases the strength of the pile.

(2) Allowing Extra Thickness. Most codes require extra thickness, usually 1/16 inch in excess of the sectional area required for strength.

Extra thickness may be achieved by reducing 1/16 inch from the section and designing the pile for strength or splicing extra plate where the corrosion is anticipated.

Accessories.

Driver. A driver is a high wooden or steel tower fastened with loads which hold and guide the hammer. The drivers are mounted on skids or rollers for foundation work, on barges for marine work and on special cars for railroad works.

Hammer. This is similar to the hammer used for timber pile but is heavier. Different companies give charts containing size, net weight, weight of ram, stroke energy, and blows per minute.

Cap. As discussed in timber piles, cushioning is provided by using a specially designed cap to reduce the effect of impact on the head of the pile. Caps are also necessary to adopt the base of the hammer to different sizes of pile. For sections like H-pile or I-beam, or rails, a head on top can be prepared by welding plates or angles in any efficient way. In the case of sheet pile, a cap called Helmet is generally employed. Its base contains grooves or socket which fit over the pile to protect the head specially in hard ground.

Splices. In any type of steel pile, whether H, I or sheet pile, the splicing is done by riveting, bolting or welding. If desired, these connections are furnished by the mill. Welded splices are butt, welded, or bar splice. The splice material should be kept in inner faces in case of H or I piles, if the hole forced in the ground is not desired to be larger than the pile. Splicing of adjacent piles should be staggered as far as possible.

Followers. Followers, in the case of all piles, consist of the same section with down standing plates to hold the alignment.

Points. Points are reinforced by welding or riveting plates so that the pressure developed on the rock ranges between 3000 to 6000 psi, the crushing strength achieved in test on small cubes of rock. The thickness is usually built up to about 3 times the original for a height of about 3 times the diameter. This does not account for distribution of load if only one corner rests on rock. For the above reason the rivets and welds are designed for a load due to a stress of 10,000 psi on the section. Some engineers recommend the ends to be left blunt and flat to have straighter penetration farther into soft rock.

Strength and Load Capacity of Steel Piles. Load carrying capacity of a steel pile is determined by designing it as a column. The compressive stress on which is given by the formula: $f = 15{,}000 - 1/3\ (L/R)^2$

Where f = Allowable unit stress in lb. per sq. in.

L = Dist. in in. between points of lateral support

R = Least radius of gyration of cross section in in.

If pile is driven in firm material there will be lateral support throughout its length and f = 15,000 psi. But to be on a safer side, the stress is limited to about 8,000 to 10,000 psi. Total load on pile too is limited to the following values.

For H-Piles.

Size of pile	8	10	12	14
Load in tons	40	45	55	65

Even though the stress on section be easily resisted, the rock on which the pile bears might fail in crushing or get pulverized due to the repeated application of load. Consequently, the pressure must be limited to a reasonable figure, say 6,000 psi. On hard rock and 3,000 psi in case of soft rock. Account should be taken of the friction resistance offered by the considerable contact area while considering bearing on the rock.

Unspliced length is limited to about 40 feet beyond which splices should be made with pile section in full contact and they should be such that they will resist driving shock and maintain perfect alignment. Reduction of 5% is often made in the allowable load for every splice in excess of one.

Composite Pile

The composite pile consists of two portions, each of which is made of different material, the two common types being 1) Timber and Concrete 2) Steel and Concrete. The composite piles were developed on an account of engineers' efforts to make use of advantages of different types of piles in order to produce a very long pile that was the most economical.

Timber and Concrete. This consists of a timber pile topped with cast-in-place concrete pile. The concrete section extends from the permanent ground water level up to pile cut off elevation and the timber pile is used below water level. Such a pile takes advantage of the low cost of the timber pile and at the same time it eliminates the necessity of expensive sheeting, excavation and pumping that would be required to cutt off and cap the timber pile at water level. The upper end of the wood pile is usually cut in the form of tenon which projects up into the concrete section. All of the various types of cast-in-place concrete piles are combined in this manner with timber piles to form composite pile. It is necessary to fasten together two sections of the pile so that they do not separate after they are in the ground. Different fastenings are developed for this purpose. Also it is necessary to provide a seal between the pile shell and the timber pile, so as to exclude water and mud from the joint. Composite piles are also made with precast concrete pile superimposed on wood pile, but here the precast section has a recess unit at the lower end and to receive tenon.

Steel and Concrete. If the required depth of pile is greater than available length of cast-in-place concrete pile, steel piles of H-sections are attached to the lower end of the cast-in-place concrete pile.

RATIONAL PILE-DRIVING FORMULAS

Nomenclature

Using the following nomenclature and expressing forces in pounds and all distances in inches:

R_d = Ultimate resistance of the pile

R_a = Allowable load on the pile

s = Penetration of pile per blow

W_h = Weight of drop hammer or ram of steam hammer

W_p = Weight of pile and pile cap

h = Fall of hammer

e = Efficiency

r = W_h/W_p

n = Coefficient of restitution

E = Modulus of elasticity of pile in psi

A = Mean cross-sectional area of pile

L = Length of pile

C_1 = Elastic compression of pile

C_2 = Rebound of pile due to elasticity of soil

C_3 = Elastic compression of pile cap

$C = C_1 \quad C_2 \quad C_3$

Discussion and Development of Formulae

We have the following energy conditions,

$$eW_hHK_1 = eW_hH \frac{r(1 - n)^2}{(r + 1)^2} = \text{Kinetic Energy of pile}$$

$$eW_hHK_2 = eW_hH \frac{(r - n)^2}{(r + 1)^2} = \text{Residual Kinetic Energy of hammer}$$

$$\tfrac{1}{2}R_d \frac{R_dL}{AE} = \tfrac{1}{2} R_dC_1 = \text{Energy lost in elastic compression of pile}$$

$$\tfrac{1}{2}R_dC_2 = \text{Energy lost in elastic compression of soil}$$

$$\tfrac{1}{2}R_dC_3 = \text{Energy lost in compression of pile cap}$$

$$R_ds = \text{Useful work done on pile}$$

Equating the kinetic energy of the pile to the useful work plus losses, we have

$$eW_hHK_1 = \tfrac{1}{2}R_dC + R_ds$$

$$R_d = \frac{eW_hH}{s + \frac{C}{2}} K_1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(A)}$$

$$K_1 = \frac{r\,(1 + n)^2}{(r + 1)^2}$$

Where the residual kinetic energy of the hammer is added to the kinetic energy of the pile,

$$eW_hHK_1 + eW_hHK_2 = \tfrac{1}{2}R_dC + R_ds,$$

$$R_d = \frac{eW_hH}{s + \frac{C}{2}} (K_1 + K_2) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(B)}$$

where

$$K_1 + K_2 = \frac{r + n^2}{r + 1}$$

These formulae were first developed by Hiley. Values of K_1 and K_2 are given in Table C. When $r = n$, in other words $W_h = W_pn$, the values of R_d from the two equations become equal, for in this case there is no residual hammer velocity. Where r is less than n, A must be used, for under this condition the residual hammer velocity is upward and so its energy cannot be transferred to the pile. Where r is greater than n, B may be used, although it may give results a little high if the residual hammer energy is not completely transferred to the pile.

In using these formulae, the values of e, n, and C must be evaluated. The following values of e are probably about right.

Table D

Type of Hammer	Values of e
Drop-hammer, free fall	1
Drop-hammer, line attached	0.75
Single-acting steam-hammer	0.9
Double-acting steam-hammer	1.0

For a free fall the energy losses in the hammer are small, but with a line attached to the hammer, the energy absorbed in pulling the line against the drive resistance is considerable. By applying A, we note that the values of e are inversely proportional to $s + \frac{C}{2}$. For these tests C/2 is small as compared with s; hence roughly e may be said to be inversely proportional to s, hence the values of e for restrained falls will be 0.5/0.7 = 0.71, 0.7/0.9 = 0.78, and 0.32/0.4 = 0.8 for piles 1, 2, 3 respectively.

The coefficient of restitution n, may theoretically vary from zero to one. The following values are widely used:

Table E

	n
Cast iron on steel	0.55-0.60
Cast iron on concrete	0.40
Cast iron on wood	0.20-0.25

The elastic compression of the pile is given by the formula, $C_1 = R_dL/AE$ which for a timber pile becomes $R_dL/(A \times 1,500,000) = 0.000,000,667LR_d/A$, where R_d/A is the unit compressive stress on the pile. This stress will usually vary between 500 and 2,000 lb./per sq. inch, the former representing easy driving and the latter very hard driving. If the mean cross section of the pile is 100 sq. in., these figures correspond to values of R_d of 50,000 and 200,000 lb., respectively. This expression for C_1 is strictly true only when the entire load is carried to the foot of the pile. Where the load is taken out entirely by friction uniformly distributed along the length of the pile, C_1 will be reduced to one-half.

The value of C_2, which represents the rebound of the top of the pile due to soil elasticity, is difficult to evaluate as it varies, and the following figures may be used: $0,00005R_d/A$ for firm gravel, $0.0001R_d/A$ for firm clay, and values as high as $0.00025R_d/A$ for soft ground.

The value of C_3, which represents the elastic compression of the pile cap, depends on the design and condition of the cap. If the packing is 6 inches thick and the bearing is on the sides of the fibers with an assumed modulus of elasticity of 100,000 lb. per sq. inch, then $C_3 = 0.00006R_d/A$.

Hiley gives the following average values for $C = C_1 + C_2 + C_3$ see Table F.

Various Dynamic Pile-Driving Formulae

Many pile-driving formulae are in use in addition to the two developed in the preceding article. Most of these have a somewhat

Table F

Length of pile, feet	R_d/A = 500 lb. per sq. in. Easy driving			R_d/A = 1,000 lb. per sq. in. Medium driving			R_d/A = 1,500 lb. per sq.in. Hard driving			R_d/A = 2,000 lb. per sq. in. Very hard driving		
	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
10	0.19	0.16	0.25	0.28	0.21	0.41	0.37	0.27	0.57	0.41	0.27	0.67
20	0.23	0.19	0.28	0.36	0.27	0.47	0.49	0.36	0.65	0.57	0.39	0.79
30	0.27	0.22	0.31	0.44	0.33	0.53	0.61	0.45	0.74	0.73	0.51	0.91
40	0.31	0.25	0.34	0.52	0.39	0.59	0.73	0.54	0.83	0.89	0.63	1.03
50	0.35	0.28	0.37	0.60	0.45	0.65	0.85	0.63	0.92	1.05	0.75	1.15
60	0.42	0.31	0.40	0.68	0.51	0.71	0.97	0.72	1.01	1.21	0.87	1.27

(1) For timber piles.

(2) For reinforced-concrete piles with 1-in. material on head.

(3) For reinforced-concrete piles fitted with effective driving cap.

rational basis, with coefficients developed from tests. Such formulas are generally satisfactory when applied within the limits of conditions obtaining in the tests. Few of them may be considered to be of general application, as shown by the wide variation of results when they are applied to a given set of conditions.

Four formulas are given below, the first two because of their sound rational basis and the second two because of their wide use in this country.

Let R_a = Allowable load on pile in pounds

W_h = Weight of moving part of hammer in pounds ~~per blow~~

W_p = Weight of pile and cap in pounds

r = W_h/W_p

H_e = Effective fall of hammer in feet (= eH)

W_hH_e = The actual delivered energy in foot-pounds per blow (including for double-acting steam hammer the work done by the steam pressure on downward stroke)

s = Average penetration per blow in inches under last few blows

A = Mean cross-sectional area of pile in square inches

L = Length of pile in inches

E = Modulus of elasticity of pile in pounds per square inch (1,500,000 for timber)

Taking Eq. A, which is the rational formula for ultimate resistance, and applying a factor of safety of three, we have, after multiplying the numerator by 12 (since H is expressed in feet with all other dimensions in inches) Hiley:

$$R_a = \frac{4eW_hH}{s + \frac{C}{2}} \cdot \frac{r + n^2}{r + 1}$$

Where e, C, and n are as given before.

The following pile-driving formula which appears in the Boston Building Code has the same form as the Hiley formula if n is assumed to be zero. For cast-iron on wood this coefficient of restitution is about 0.2 to 0.25, and, as it enters the rational formula as a square, the resulting error, in dropping it, is only 4 to 6 percent.

Boston Code:

$$R_a = \frac{mW_hH_e}{s + K} \cdot \frac{r}{r + 1}$$

Where $m = 3$ for drop-hammer

$m = 3.6$ for single-acting steam-hammer

$m = 4$ for double-acting steam-hammer

$K = \frac{1.5R_aL}{AE} + 0.05$ for a timber pile or wood driving cap

One of the oldest, simplest, and most widely used formulas the Engineering News formula developed by A. M. Wellington for use with timber piles placed with a drop-hammer. It was later Engineering News:

$$R_a = \frac{2W_hH_e}{s + c}$$

where $c = 1$ for drop-hammer

$c = 0.1$ to 0.3 for steam-hammer

In the development of this formula, Wellington assumed that all of the hammer energy, $12W_hH_e$, when expressed in inch-pounds, went to overcome the driving resistance energy, Rs. Equating these two and using a factor of safety of 6, he got $R_a = 2W_hH_e/s$. When applying this formula to piles having a small penetration under the last few blows, it was seen that the results were absurdly high. To correct for this, $c = 1$ was added to the denominator. With the advent of the steam-hammer, it was suggested that the coefficient be made 0.1 is too low a figure for small penetrations. In general, for penetration less than 0.15 inches, $c = 0.3$ should be used. It will be observed that the Engineering News formula is of the Hiley form when $n = 1$.

In the early years, when all pile driving was done by drop-hammers on timber piles, the weight of the hammer usually equaled, or was somewhat greater than, the weight of the pile; hence r was more or less a constant. The percentage of the hammer energy delivered to the pile varies widely for varying values of r; consequently, with the advent of heavy concrete and metal piles, it was found that the Engineering News formula gave bearing values far out of line with the results of static load tests. This formula was then modified to give

Modified Engineering News:

$$R_a = \frac{2W_hH_e}{s + \frac{c}{r}}$$

FAILURE OF PILE FOUNDATION

Structural Failure

Following are important causes of failure of pile foundation:

1. Use of a dynamic driving formula for bearing resistance in predominantly cohesive soils results in many settlement failures. Many such failures may be avoided by a check using static formula for friction and end bearing.

2. Misinterpretation of test-load data often occurs in consequence of assuming (a) that the load test on a single pile gives results applicable to a group or building; (b) that long-term settlements can be predicted from a short test loading; and (c) that the strata being tested are those which will finally have to carry the load.

Soft underlying strata below the pile tips are frequent causes of settlement.

3. Lack of adequate boring causes many failures. Boring is always necessary. In some cases it is sufficient merely to determine the

elevation of rock, whereas in others the character of the overburden may be sufficiently obtained from wash-water samples of wash borings. Sometimes dry samples from wash borings will provide all necessary information, but in other cases, the exact character of the soil becomes of vital interest, and undisturbed samples are necessary.

4. Collapse of thin shells of cased piles may be prevented by more careful driving or by use of a lighter hammer and jetting. In an instance where pressures developed by fine-grained water-bearing sand, estimated at not less than 4,000 psi, caused thin shells to collapse when withdrawing the mandrel, the use of heavier guage metal and welding circular beads around the corrugations in the lower 8 feet reinforced the boots so that they did not collapse.

5. Buckling of piles may occur as a result of inadequate lateral support, removal of side support, increased load, or overdriving.

6. Damage to an uncased pile in dense ground may occur, and if suspected, a pile may be excavated or casings which can be inspected after driving adjacent piles may be used either for all piles or for a few as a test.

7. Movement of earth into an open pile hole in soft ground may be prevented by the use of cased or precast piles.

8. Decay in wood piles may be prevented by keeping the cut off below the lowest possible ground water, by maintaining an artificial ground-water level, by preservative treatments, or by the use of a composite section.

9. Lateral forces, either static, intermittent, or vibrating, require adequate provision in the design.

10. Sliding of piles owing to sloughing banks may sometimes be prevented by stopping dredging, or by washing down silt deposits.

11. Disintegration of concrete piles may be greatly reduced by proper attention to the mix and location of reinforcement; also possibly by the use of armor or asphalt treatment.

Economic Failure

If piles selected are too strong and too expensive when one could select a better pile with less and adequate strength but lesser cost, we say they have an economic failure. This can not be seen physically but is felt in the cost of the project.

STATIC LOAD TEST ON PILES

There is no doubt that a static load is the only accurate method of determining the actual static resistance of an individual pile or group of piles; however, load tests give no indication of the long-time settlement of the pile or pile groups. Loading tests are most often quite expensive and hence much time and effort by engineers have been spent on pile-driving formulas.

In order to perform a static load test, many tons of dead weight must be placed on a platform above the pile or a group of piles, or a strong reaction must be available to jack against. Many times a heavy beam is used to jack against with the ends of the beam held in place by other anchor piles. However, the use of many tons of dead weight seems to be the most feasible procedure.

The usual procedure in test loading piles is illustrated in Figure 11. The loads and settlements of the piles are measured and recorded. These results are plotted in the form of load-settlement curve shown in Figure 12. In normal practice, the working load per pile is determined before the structure is built, and the usual procedure in pile test loading is to apply a load that is twice the working load. Tests made in this manner generally produce a settlement curve and a rebound curve such as illustrated by the solid line in Figure 13.

Unless the test load is increased to some product of P, at which time the pile would settle continuously without the application of more load, no information about the load at failure is obtained. All that is known, under the loading procedure described above, is that the factor of safety is at least two. The extension of the load settlement curve in Figure 12 is what might happen if the load were increased above 2P.

An important factor giving to misleading results from the test loading of a single pile is disregard of the time of testing. Common practice has been to load single piles to 150 percent or 200 percent of the design load, leaving the load on the pile 24 to 48 hours. If the settlement has not exceeded a specified maximum (often 0.01 inch per ton of applied load), the test has been considered satisfactory. Such results may vary widely from the final value of a pile, since changes often occur in the soil after pile-driving and before or after the load test has been applied.

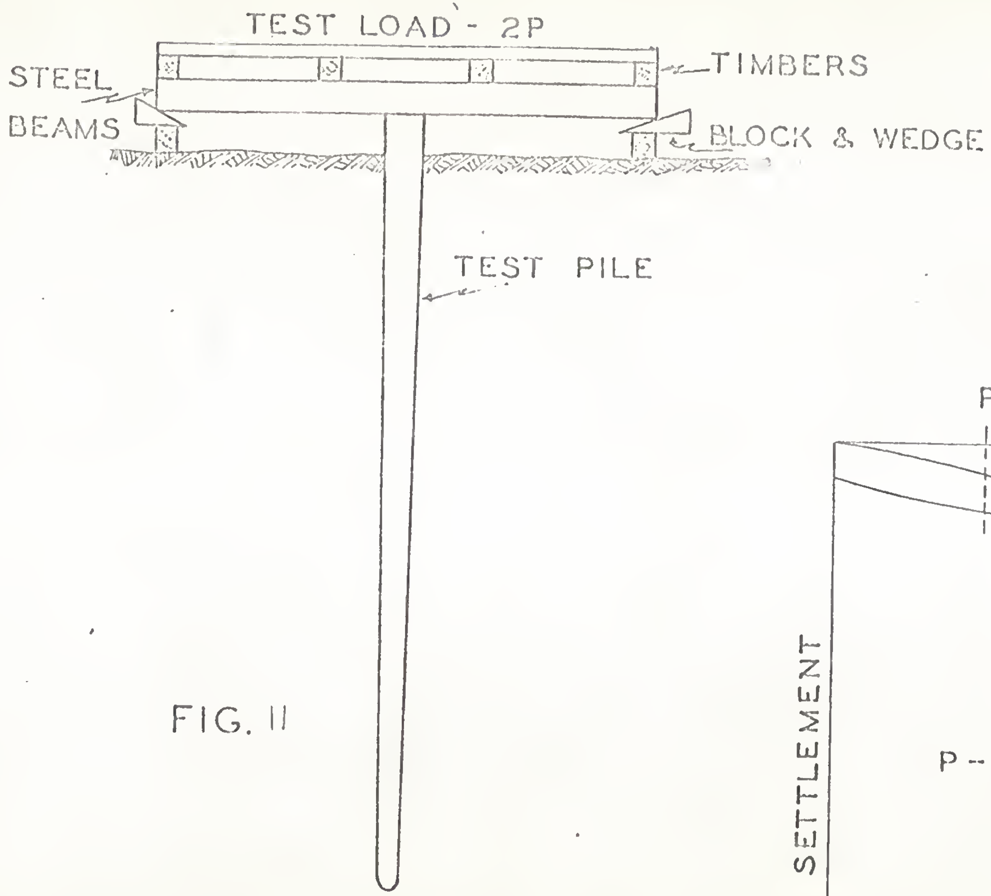

TEST LOAD - 2P
STEEL
BEAMS
TIMBERS
BLOCK & WEDGE
TEST PILE

FIG. 11

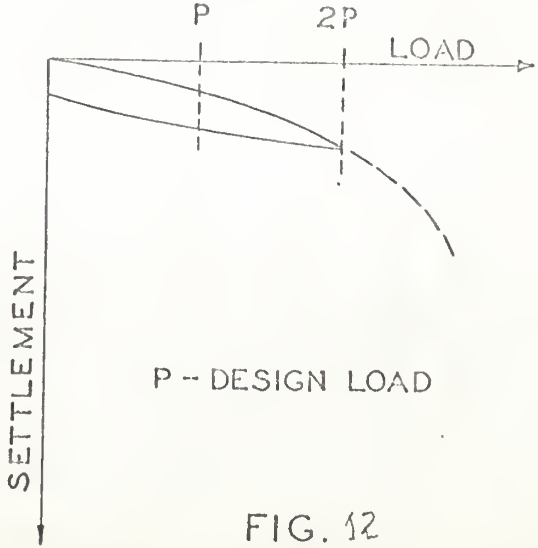

P
2P
LOAD
SETTLEMENT
P -- DESIGN LOAD

FIG. 12

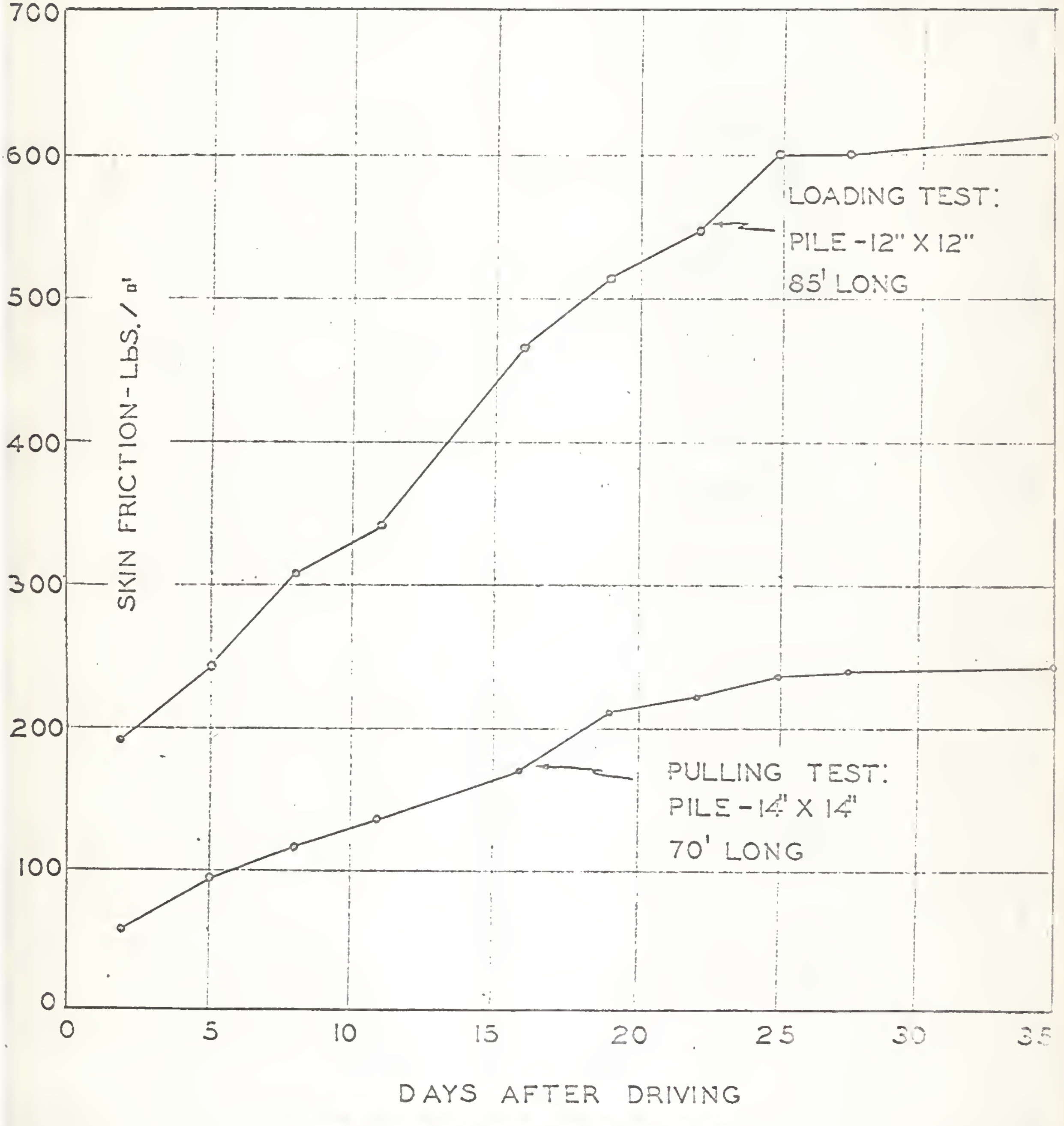


Figure 13. Loading Test Curves

If piles are driven in a coarse-grained, saturated, pervious soil where losses in resistance may reach over 40% during the 24 hours following driving, the load test should not be made until several days have elapsed.

If piles are driven in some submerged, uniform, fine-grained sand which are so loose that the jarring from the pile-driving makes the sand temporarily "quick" the piles will drive easily, but since the condition ceases after the blow, the stratum will be capable of supporting a much larger static load than indicated by the driving resistance. If sufficient time is allowed to elapse, a load will determine the bearing capacity.

If piles are driven into an impervious type of soil which heaves during driving, in which case the setup may amount to several hundred percent in the following weeks, it would perhaps be advisable to delay a load test until this condition exists to obtain a more true bearing capacity.

Figure 13 illustrates the increase with time in the bearing capacity of two friction piles. The foundation on friction piles near the coast of Scotland were driven into a soft brown clay temporarily and locally passed into a viscous liquid state. This was demonstrated by the following observation: when a pile was being driven, it rose after each blow, including the last one, through a distance between 4 inches and 6 inches, although the permanent penetration produced by each blow was frequently smaller than a 1/2 inch. One of the piles followed the hammer after the last blow and rose 15 feet. It was necessary to eliminate this nuisance by providing the driving rig with an attachment that prevented the piles from rising after each blow. All the piles had to be driven at least twice, because while the last piles in a cluster were being driven the first ones rose from 1 to 3 feet, and several of the piles rose 10 to 15 feet. In one case, the first pile rose 20 feet when the last pile in the cluster was being driven, although the two piles were 40 feet apart.

To determine the safe load capacity of these piles, five loading tests and six pulling tests were performed. The very first test demonstrated that the skin friction was practically equal to zero immediately after driving and that it increased with some unknown law with respect to time. These tests showed that the skin friction which resisted an upward movement was much smaller than the resistance to penetration. The ratio between these two values, for adjacent piles, was practically independent of time. For different locations, it ranged between the limits of 2.1 and 2.2 for short piles and 2.4 to 2.6 for long piles.

This variation between loading resistance and pulling resistance is explained by the fact that during a loading test, skin friction plus end-bearing acts on the pile; whereas, in a pulling test only negative skin friction is acting on the pile.

COST ANALYSIS FOR PILES

A brief statement of the unit costs of various types of piles is given here for pile selection in making cost estimates.

Pile Driver	Unit.	Mat.	Inst.	Total
Steam hammer type, all equipment including, transport, set up, remove	total charge			3,000
Pile Concrete				
12" Pre-Cast assume 200 Pile 60 ft. long	L.F.	4.00	2.00	6.00
16" " " " " " " "	"	4.75	2.25	7.00
20" " " " " " " "	"	5.50	2.50	8.00
16" Cast-in-place, Casing removed	"			4.50
Step tapered steel conc. filled butt dia. 12".	"			4.75
Cylindrical - do -	"			4.75
Steel pipe conc. filled 10" dia.	"	5.00	1.00	6.00
assume 200 12" "	"	6.90	1.10	8.00
piles 60' long				
14" "	"	8.00	1.35	9.35
16" "	"	9.00	1.70	10.70
Splices	ea.			10.00
Points				13.00
Steel "H" sections 8 x 8 36 lb.	L.F.	3.00	1.30	4.30
assume 200 piles 60' long 10 x 10 42 lb.	"	3.30	1.40	4.70
57 lb.		4.40		5.80
12 x 12 53 lb.	"	4.10	1.50	5.60
74 lb.		9.60		7.10
14 x 14 73 lb.	"	5.50	1.50	7.00
89 lb.		6.70		8.20
14 x 14 102 lb.	"	7.60	1.60	9.20
117 lb.		8.80		10.40
Splices for "H" piles 10"	ea.			25.00
14"				40.00
Caps " " "	"			20.00
Wood Untreated 30 to 40' long 12" butts 6" point	L.F.	0.80	1.05	1.85
For piles with 8" 40 to 50' long 12" butts 6" point	"	1.00	1.00	2.00
Points add 15¢ per L.F. 50 to 60' long 12" butts 6" point	"	1.10	1.00	2.10

		Unit.	Mat.	Inst.	Total
	60 to 80' long 14" butts 6" point	"	1.35	1.00	2.35
Creosoting	30 to 40' long 12" butts 6" point	L.F.	1.30	1.05	2.35
	40 to 50' long 12" butts 6" point	"	1.40	1.00	2.40
	50 to 60' long 12" butts 6" point	"	1.55	1.00	2.55
	60 to 80' long 14" butts 6" point	"	1.70	1.00	2.70
Sheet Piling Wood 8' excav. 1 use		S.F. wall			1.00
Incl. bracing, pull and salvage	10'	"			1.11
	12'	"			1.21
	14'	"			1.42
	16'	"			1.57
	18'	"			1.65
	20'	"			1.75
For creosoting add cost of treatment.					
Sheet Piling Steel Left in Place		ton	153	47	200
- do -	with pull and salvage 20 uses	"	11	70	81

CONCLUSION

It must be concluded from the various types of piles and methods of driving, that the choice of the right one, which must be neither too strong nor inadequate in strength, is a difficult problem. This choice is difficult without practical experience, as pile driving formulae and load tests give the picture of capacity only at the time of driving and do not account for prolonged settlement with time.

Since the rise of modern soil mechanics during the past twenty-five or thirty years, engineering literature has contained considerable material on pile foundations. And it would be well to utilize research in the fields of soil mechanics and combine their findings with load tests to come to a particular decision rather than to go by formulae which are entirely theoretical. Soil is never homogeneous. This fact makes it difficult to arrive at any hard and fast rule for the interaction of soil and pile. So even today the engineer has to depend much on empirical formulae and experience. It is nevertheless advisable to take all precautions, as described in this report, while designing, making, and driving the piles. Also, the existence of highly compressible soil strata should be detected by borings. Where such a stratum is found, piles should be driven through it and not stopped with their points just above it.

From the point of view of economy, the choice of pile will depend upon availability of materials for the pile, which differ in different countries. We cannot say that a particular type of pile is best. This is determined by economy and by the conditions to which it will be subjected.

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AN INVESTIGATION OF PILE FOUNDATION, THEIR USES AND COSTS

by

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AN ABSTRACT OF A MASTER'S REPORT

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ABSTRACT

Very often the soils at or near the surface of a proposed building site are not suitable foundation materials. In such cases there are three alternatives: (1) remove and replace the poor material, (2) abandon the site, (3) carry the foundation loads down below the poor soil. The first alternative is, in most cases, uneconomical. The second alternative is still resorted to in some cases, but modern industrial expansion is necessitating greater use of what used to be considered marginal lands. The third alternative may be accomplished by extending the piers, adding a basement or sub-basement if necessary, or by placing the foundation on piles. Economic studies establish the best route to follow. However, when unsuitable soils exist at substantial depths below the soil surface, piles are almost always the only practical solution.

Piles may be defined as structural members whose main purpose is to distribute foundation loads in such a manner as to provide a reasonable factor of safety against bearing failure and or excessive settlement.

Piles may be classified as friction piles or end-bearing piles, according to the manner in which they transfer their loads into the underlying soil. Piles are designated by the material of which they are composed, as timber piles, concrete piles, metal piles (steel piles), and large variety of each are available. In cast-in-place concrete piles alone, there are many commercial types. Pre-stressed piles are the latest addition to the family of piles. These with their many advantages over other piles are likely to be the most popular piles in the future. The procedure of design of a pile foundation include the selection of the type of piles, the determination of bearing capacity, the pile length, and the pile spacing.

The design of piles rests upon three equally important basic considerations: first, a consideration of the geology of the site and the results of the subsurface exploration: second, the study of pile types and equipment by means of a dynamic pile-driving formula; and third, the study of pile carrying capacities by the static formula. Test-pile and test-load results should be combined with these studies in many cases. The complete procedures for design and analysis of pile foundations are presented in this report.