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P I L E S A N D P I L E D R I V I N G

BY

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THESIS FOR THE DEGREE OF CIVIL ENGINEER

NEWARK COLLEGE OF ENGINEERING

June 1932

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PREFACE

This thesis on the subject of "Piles and Pile Driving" has been written to fulfil one of the requirements for the granting of the degree of Civil Engineer by the Newark College of Engineering. The material contained in this thesis has been gleaned from many books, catalogs, magazines and from the author's own experience. Much still needs to be accomplished in the field of research but this can be done only through the cooperation of the companies who are engaged in this work and have the equipment necessary for making many tests under actual field conditions.

The author wishes to acknowledge his indebtedness to the following companies for the information which they have supplied and also for the illustrations, some of which are reproduced in this thesis: - Russell Company, Charles R. Gow Company, Mac Arthur Concrete Pile Corporation, The Raymond Concrete Pile Company, and The Southern Wood Preserving Company. The author is also indebted to Professor William S. La Londe of the Newark College of Engineering for reading the manuscript and making valuable suggestions.

R. W. Van Houten

Newark College of Engineering

January, 1932

CONTENTS

	Page
PREFACE	ii
CHAPTER I	
History of the Use of Piles	
Origin of piles and pile driving	1
Foundations of ancient bridges	1
Famous bridges	3
CHAPTER II	
Development of Pile Driving and Pile Driving Equipment	
Wooden mauls	7
Primitive forms of derrick pile- drivers	8
Present day pile-drivers	12
The hoisting engine	13
Steam pile-hammer	14
CHAPTER III	
The Theory of Pile Driving	
Problems to be solved	18
Test borings	19
Types of soil	22
Piles acting as columns	23
Pile supported by skin friction	24
Spacing of piles	29
Lateral forces acting on a pile	31
Pile driving formulae	34
Test piles	39

CONTENTS

	Page
CHAPTER IV	
Timber Piles	
Wood used	42
Requirements for good timber piles	45
Preparation of piles for driving	47
Overdriving	51
Use of the water-jet	55
Protection against alternate wetting and drying	57
Marine borers	62
Protection against marine borers	66
Cutting off and pulling piles	74
CHAPTER V	
Concrete Piles	
Advantages of concrete piles over timber piles	79
Pre-molded piles	81
Corrugated pre-molded pile	84
Cummings pre-molded pile	85
Chenoweth pre-molded pile	86
Hennebique pre-molded pile	87
Cast-in-place piles	88
The Raymond Pile	88
Simplex Piles	98
Pedestal or Mac Arthur Pile	101
The Gow or Palmer Pile	103
Precautions in driving cast-in- place piles	104

CONTENTS

	Page
CHAPTER VI	
Metal and Sheet Piles	
Tubular piles	107
Screw and disk piles	109
Sheet piling	112
Bibliography	119

PILES AND PILE DRIVING

CHAPTER I

History of Use of Piles

The origin of piles and pile driving is not known. No definite date can be set as the time when the first pile was driven but it is certain that timber piles were known as long ago as the early lake dwellers of Europe. Whether this was the origin of piles and pile driving; whether they were first used in the jungles to keep the huts off the ground and away from wild beasts; whether they were forked branches of trees driven into the muddy bottom of a stream to support the stringers of a crude bridge, we cannot say. All we do know is that piles have been used for many centuries and that in type and method of driving there have been few radical changes over the period from their inception until the present time.

More is known, however, of the use of piles in the building of ancient bridges and a brief resumé of the construction of bridge foundations will serve to show the part that piles played in their development. It has been determined from the study of the ruins of ancient bridge foundations that the first piers were begun by dumping loose stones in the water until the surface

of the river was reached. Then the masonry or wooden bridge was constructed on that. In the arid countries the bed often dried up for many months of the year and the foundation could then be built without having to contend with the stream. Another method of constructing bridges and their foundations was to build them on dry land adjacent to the river. After the bridge and foundations were completed, the river was diverted under the bridge and the old river bed filled in.

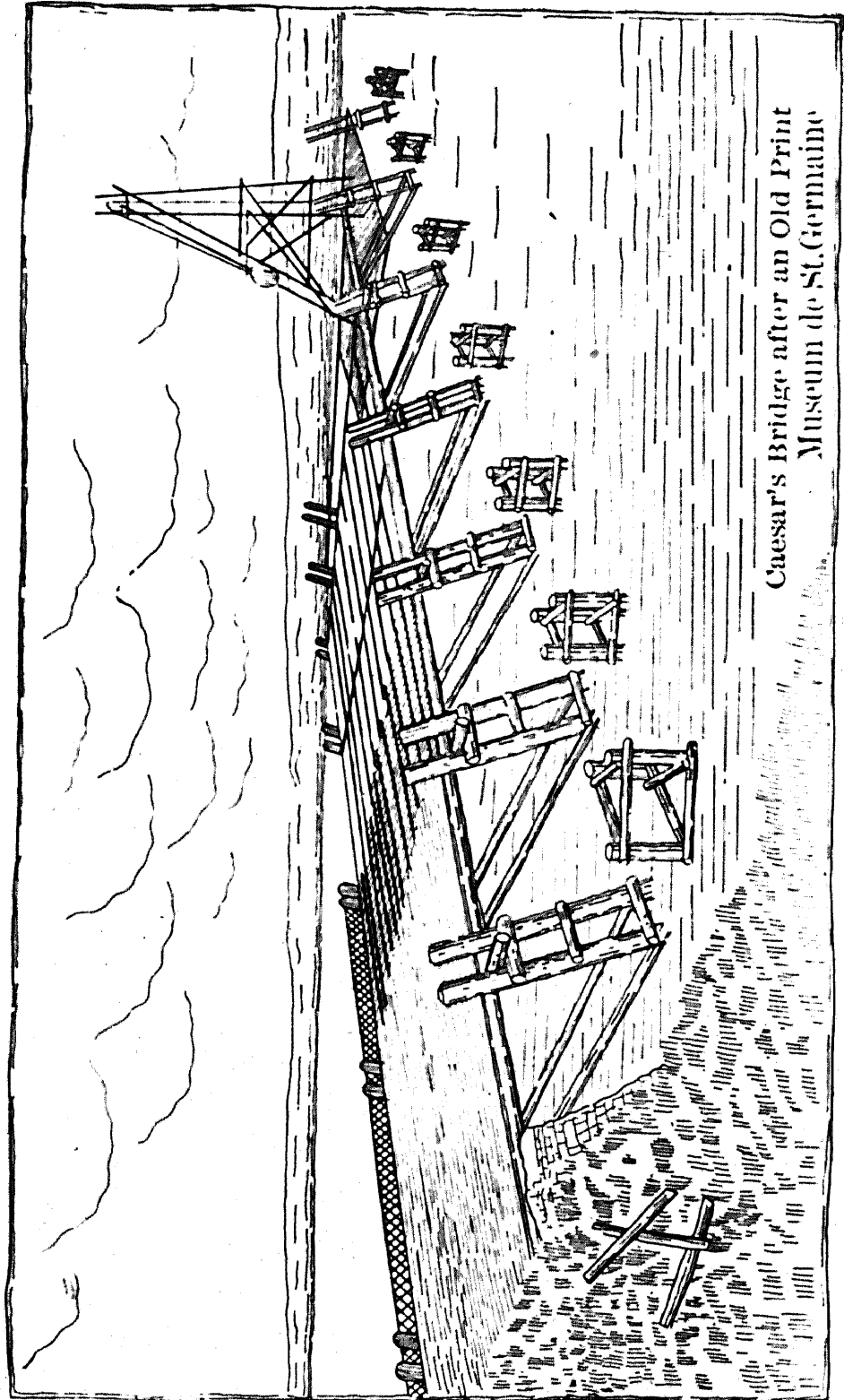
Following these types of bridges came the single arch bridge which was originated by the Romans. With the spread of civilization and the construction of more roads the need for better bridges became apparent. The single arch bridges of the Romans were satisfactory for many narrow streams but some method had to be devised for traversing the wider rivers. Several methods for constructing piers in water came into use. Only two of these are of special interest in a study of piles and pile driving. First, was the method of driving piles over the area of the foundation until the heads were below low-water level. They were spaced at distances apart as required by the nature of the bottom. These piles were not driven so that the heads were at the same level but were encased in a form of coarse concrete such as the Romans used. This was leveled up

and on it was laid the stone for the footing course of the pier. The second method was that of encasement. This consisted in inclosing the space for the pier with sheet piling, after which as much loose material as possible was removed from within the encasement. Stones were then dumped inside until nearly up to low water after which the pier itself was constructed.

Of all the ancients who used piles the Romans by far were the most proficient. The Pons Sublicuis, which means "pile bridge," was built over the Tiber at Rome more than six centuries before Christ. It was attentively cared for by the high priests and endured for at least three hundred years.

Julius Caesar during the invasion of Germany bridged the Rhine with a pile bridge. He gave a good description of it in his writings. The bridge was 1800 feet long and was built in ten days. When it is taken into consideration that the builders were harassed by enemy force all during the construction of the bridge, it indicates that the Romans were very familiar with that type of construction.

A more recent but equally famous example of a bridge built on piles driven in cofferdams is the Pont de la Concorde bridging the Seine in Paris, built by Jean Rodolph Perronet from 1787 to 1791.



Caesar's Bridge after an Old Print
Museum de St. Germaine

This bridge still stands and is in use. The London Bridge built by Sir John Renne in 1831 was said to be "well founded" on elm piles.

Another illustration of a bridge which was built on piles but which offered special problems was the bridge constructed across the Danube at Buda Pesth. This was constructed through the efforts of Count Szechenyi who went to England in 1832 as a member of a committee to investigate types of bridges. A suspension bridge was finally decided upon. In order to protect the two towers from the heavy ice in the Danube, which during the winter became from six to ten feet thick, it was necessary to build heavy and extraordinary cofferdams. Four of these were constructed and a total of 5224 piles were driven of which about sixteen percent had to be drawn and redriven. The piles and timber were obtained from the forests of Bavaria and Upper Austria. The first pile was set on dam number three on April 8, 1842, but owing to difficulties encountered it was not finished until April 4, 1845, three years later. No statement is made in the account of the building of the cofferdams as to whether the difficulties encountered were financial or physical. After this the work progressed more rapidly but often five to seven days were required to drive a pile to a depth of five or six feet into the clay. The average

was from twelve to fourteen days to drive one pile.
Many broke off and had to be drawn.

This gives a few of the highlights in the development of the use of piles from the earliest information available up to the century. Now I wish to touch upon the development of pile driving. This, too, is not greatly changed in the general appearance of the pile driver nor especially in the method which is similar to that used centuries ago.

CHAPTER II

Development of Pile Driving and Pile Driving Equipment

"In no department of engineering have ancient methods been more rigidly adhered to than in that of pile driving." This is a statement made by Fowler in his book "Ordinary Foundations." A study of the development of pile driving substantiates his remark without a reasonable doubt. The form of the pile-driver derrick has changed so little that a person who is but slightly familiar with pile driving would experience little difficulty in recognizing the pile driver in the illustration of Caesar's bridge.

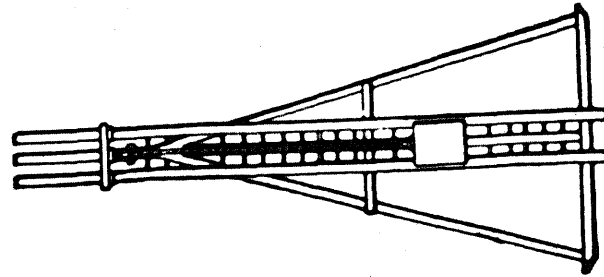
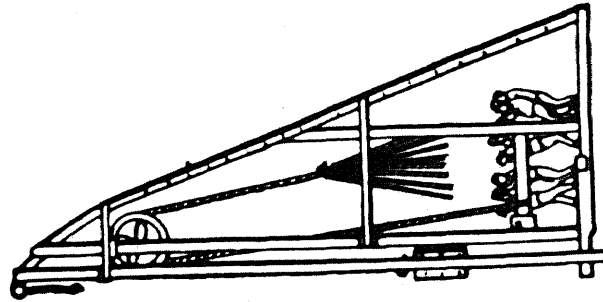
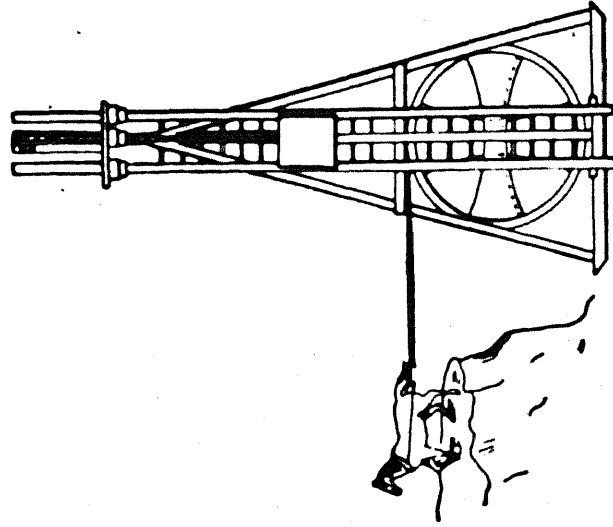
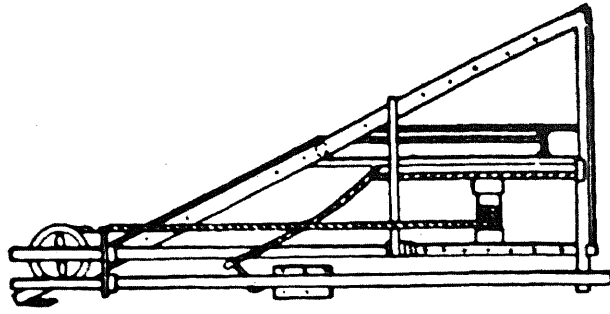
Before derricks came into use a large wooden maul which Cresy called "a three-handed beetle" was used. It was formed from a block of hard wood bound with iron and had three handles radiating from the center. Two of these were to be used by two men to drive the pile. The third handle was shorter than the other two and was used by a third man to assist in lifting the maul.

Wooden mauls are still used in the driving of sheet piling into a soft bottom and heavy iron mauls or sledges are also used. If the bottom is too soft it is better that it be dredged and some more elaborate equipment be used to drive the piles to a harder stratum. A pneumatic

hand tool for driving sheet piling has been constructed by the Ingersoll Rand Company. It was used by the Illinois Power and Light Company in East St. Louis to drive piling 2" x 8" x 16'0" ten feet into sticky clay. It was found that it drove the piles faster and at a lower cost than the hand method.

The most primitive form of the derrick pile-driver is one which is similar to that used by Perronet at the Bridge of Orleans in 1751. It consisted of the typical type of derricks and leads with the hammer being attached to a rope while the other end of the rope was splayed. This permitted a number of men to pull down at one time. The drop of the hammer was limited by the length of the men's arms. A windlass was also included in the equipment for the purpose of raising the pile into position between the leads.

This type of derrick was later improved upon by Perronet who added a large bull-wheel to the windlass. On this was wound a rope to be pulled by a horse. As the animal moved out from the pile-driver the lead line was wound on the windlass. The illustration, which is taken from an old print, shows the horse on an embankment beside the derrick. There is no reason to assume that this was always the case. By the addition of another pulley the horse could have been on the same



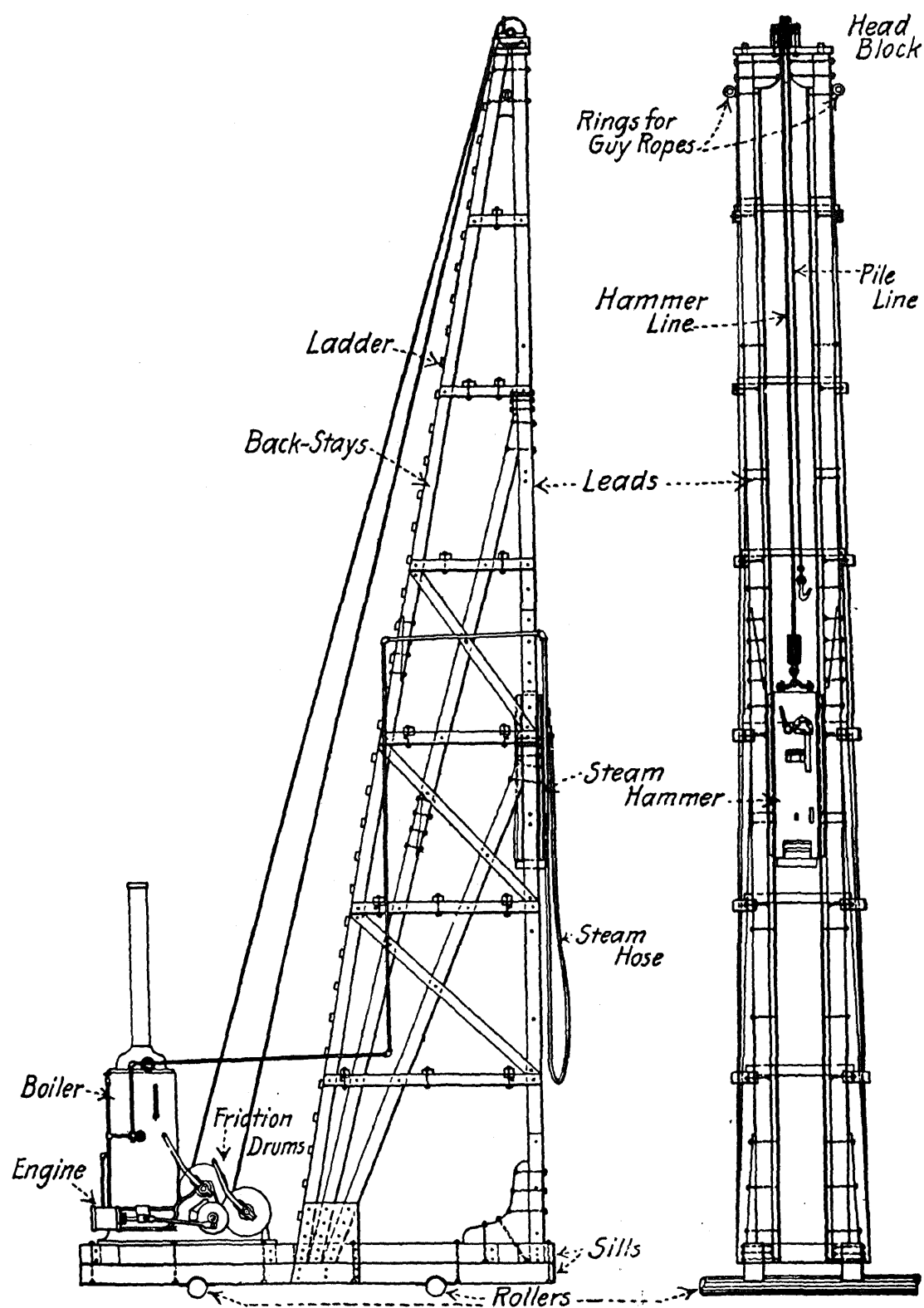
Perronet's Bull-Wheel Pile-Driver

Perronet's Pile-Driver

level as the bottom of the pile-driver. With one or two changes this same type of apparatus has been used down to the present time. The windlass, now installed, is at right angles to the one shown in the sketch and steam power has replaced man or horsepower.

Another example of the old types of pile-driver was that used by De Cessart about 1756 at the Bridge of Summur. He used a driver with a bull-wheel in the periphery of which were set pins to form handles for men to pull upon and rotate the wheel. Eight men, by making three turns of the wheel, were able to raise the ram, weighing 1500 pounds a distance of six feet. Then it was unhooked and allowed to drop.

Of the more recent of the pre-steam types is one described by Julian A. Hall in the Engineering News of March 16, 1893. He described a simple form of pile-driver in which the hammer was hewed out of a section of hardwood log. Additional pieces of the log were bolted on the sides of the hammer to hold it in the leads. These were placed so as to give ample clearance and avoid binding. The derrick was constructed of very light timber, the verticals being four inch lumber and the bottom pieces 6" x 6" timbers. The rope was passed over the top sheave and down over steps on the back of the driver. Men stood on these steps to pull the line



Typical Pile-Driving Rig

and operate the hammer. This was found to be a very inexpensive piece of equipment and to work well.

The foregoing gives a brief account of a few of the types of pile-drivers before the advent of the use of steam. The illustration on the previous page shows a typical pile-driver of the present day. It is apparent that the form of the modern derrick differs little from those shown in the preceding illustrations. The main differences are the boiler and engine, the drums at right angles to the old bull-wheel, the steam hammer and the rollers. The rollers permit the moving of the driver forward, backward, or sidewise. An experienced foreman can maneuver a driver around with remarkable ease and rapidity considering the bulkiness of the equipment. Some of the more efficient and modern drivers are mounted on turntables and are known as swiveling pile-drivers. These combine the ability to swing to the right or left together with the motions already listed. Other drivers are mounted on scows while a few are built for railroad service and are built to travel over rails.

The derrick of the pile-driver is now built of wood or steel with the trend being toward steel. Drivers which are to be used in excavations or on scows sometimes have rigid detachable leads which extend to the desired depth. A better method is the use of telescopic leads

which slide inside of the stationary leads and are controlled by an extra line to a third hoisting drum. By using some type of extension lead, piles may be driven in deep trenches or in the bottom of cofferdams containing a large amount of internal bracing. A few drivers have the tower part of the derrick pivoted at its base so that piles may be driven on a batter. This type is especially suited for use on railroad trestles. Still one other type has been built to combine the functions of a pile-driver and a steam-derrick for use in the erection and maintenance of small bridges and culverts.

The ram, or hammer, has undergone more changes than perhaps any other part of the pile-driving equipment. The hammer used in olden times was of oak, bound with iron. For the work at Orleans, a 1200 pound hammer was used on piles nine to twelve inches in diameter. These were driven three to four feet on centers and about six feet into the bed of the river. The hammer for the sheet piles weighed only about one half as much.

With the advent of the hoisting engine the work was reduced. The rope was left attached to the hammer so that it was unnecessary to run the tongs down after every drop of the hammer. This saved considerable time and in addition a good engine man could catch the hammer

on the rebound and greatly decrease the time between blows and, therefore, the cost of driving.

For the smaller sized hammers, from 1000 to 1500 pounds, a ten horsepower engine is generally used as it is better to have surplus power in case of need. A 3000 pound hammer would probably use a twenty horsepower engine as being the best and most economical. Not infrequently a twenty five horsepower one is used. The cost of an outfit varies greatly. Too many variable factors enter into the cost to give any prices for certain sizes of engines. One thing to keep in mind in purchasing an outfit is that with a double drum engine the second line may be used to hoist the piles into place without detaching the first line from the hammer.

Another factor which has also speeded up the driving of piles is the steam pile-hammer invented by James Nasmyth. The principle used is that of the steam forging-hammer which Nasmyth applied to pile-driving. He developed this invention in 1845 and the hammers of this class are now called Nasmyth hammers. He believed that the drop hammer was constructed more for destruction than for useful effect. He termed it "the artillery or cannon-ball principle." In the Nasmyth hammer, the elastic force of steam is used in raising the ram or

driving piston. When the piston reaches its highest point the driving-block is disengaged and its entire weight of three tons descends on the head of the pile. This process is repeated eighty times per minute and the pile is driven at a remarkably more rapid rate of speed than it is by the drop-hammer.

When Nasmyth made his first experiment with his new type of hammer, he drove a fourteen inch pile fifteen feet into hard ground at the rate of sixty-five blows per minute. The saving in time was astounding. A pile could be driven in four minutes that had previously taken a day which meant a ratio of saving in actual driving time of about one to eighteen hundred. Of course the time spent in hoisting the pile and placing it was not reduced so that the total percentage of time saved was not quite so large. It was, however, a very much faster method than was the old drop-hammer system.

One of the original ideas introduced by Nasmyth was that of using the pile as the support for the piston casing and striking block. The casing was held in the leads but the entire weight of both it and the block rested on the pile while it was being driven. This method used the dead weight of the hammer as well as the live blows struck by the steam piston. Steam was

used as a buffer in the upper part of the cylinder and had the effect of a recoil spring. This greatly enhanced the effect of the downward blow.

This hammer has been manufactured in many modified forms. One which is used to a great extent today is the Warrington-Nasmyth hammer made by the Vulcan Iron works. This is manufactured in three sizes, 550 pounds for sheet piling, 3000 pounds for general pile driving and 4800 pounds for heavy work. This hammer is provided with a positive valve-gear, a short steam passage to avoid waste of steam, a wide exhaust opening to prevent back pressure as the piston drops and a piston-head forged on the rod and channel bars on the side to allow the pile to be driven lower than the leads of the derrick. The hammer of this type is made fast to the hoist rope which is left slack when the hammer is resting on the head of the pile. The bottom of the casting is in the shape of a bonnet which encases the top of the pile and prevents brooming or splitting. When driving is to begin, the steam is turned on and the hammer delivers blows at the rate of sixty to seventy per minute. These hammers should have plenty of play in the leads and the steam pipe should extend half way up the derrick in order to save lengths of hose. Some drivers of

this type have driven as high as seventy-five to one hundred piles per day. One account gives a record of three thousand lineal feet of piling per day.

Another form of the Nasmyth hammer is the cram. This is quite simple in construction and consists of a hollow driving-head. The steam enters the hollow piston rod and causes the head or cylinder to rise on the rod. This is made in four sizes, 430 pounds, 2000 pounds, 3000 pounds, and 5500 pounds. All hammers have the same number of blows per minute. One of these hammers was used on the Passaic River and a record was established of 121 piles driven seventeen feet into a bed of sand and oyster shells in one day.

The problems encountered in driving the different types of piles will be considered when each type of pile is discussed.

CHAPTER III

The Theory of Pile Driving

Piles are used in materials that are notable to bear the weight of structures, after spreading the bases of the structure by the use of concrete or timber, either singly or combined, or where the cost of preparing the foundation in such a manner would be excessive. They are also used when the material, while being firm enough to bear the weight, is in danger of being scoured out by water. Again, piles are many times driven purely on account of convenience, expedience and economy.

From the foregoing paragraph it may be seen that the problem resolves itself into four general questions. Briefly they are these: first, the weight of the structure which must be carried by the foundation; second, the type of soil to be found and its supporting capacity; third, the number of piles to be required and how they will be grouped; fourth, the determination as to when each pile has been driven to the proper depth to develop the required supporting capacity. It is not within the scope of this thesis to discuss the determination of the loads to be imposed on the foundation by the weight of the structure. The

other three questions will be discussed, however, and an attempt will be made to answer them in the light of present day practice.

Test Borings

The type of soil into which the pile is to be driven can be determined by making what are known as test borings. Of course, until these borings are made, the question as to whether piles are to be used or not is not determined. The borings, however, do have a decided effect upon the length of pile and the number required, once the necessity for piles has been established. It is essential that a sufficient number of test borings be made to determine accurately the character of the ground in question. The author has in mind one pile-driving job where sufficient tests were not made and great difficulties developed. Rocks were struck, piles had to be redriven many times and considerable time was lost. This all occurred where the ground was supposed to be sandy. Thus, failure to obtain accurate information may result in the loss of thousands of dollars.

There are several methods of making soundings or borings. Some are good and others worse than useless. The first method to be described is one in which an

iron pipe or rod about one to one and one-half inches in diameter is driven into the ground. The rod is driven by constant hammering and turning and may be made to penetrate to a depth of over thirty feet. The information obtained by this type of test is meagre and unsatisfactory. The character, thickness or layers of different strata penetrated cannot be determined. Boulders, large or small, will stop the driving of the rod as will also logs, drifts, or wrecks. While this method is still used, it is strongly condemned as it leads to erroneous conclusions. For the construction of one bridge in Ohio, plans were drawn and estimates and contracts closed on the supposition that rock would be reached shortly below the ground surface. It was later discovered that no firm material existed under from sixty to seventy feet below low water. Expensive changes in the plans were thus made necessary. The test borings had been made by the method just described.

A better and more satisfactory method of obtaining test borings is to sink a terra cotta or iron pipe from three to eight inches in diameter by the following procedure: The pipe is first pressed into the surface as far as practicable. Then a long narrow bucket with a cutting edge and a flap valve a little distance above

the cutting edge and opening outwards is dropped into the pipe and alternately raised and dropped. This is repeated and the pipe gradually sinks. Other sections of the pipe are added from time to time. Sometimes it is necessary to pour water into the pipe to aid in cutting, and also to facilitate the flow of material into the bucket. Great depths can be reached by this method with fair rapidity and at no great cost. The thickness and nature of the strata and whether they are composed of sand, gravel and clay, is thus determined. The main fault with this method is that no indication is given as to the state in which the material exists. Clay, for instance, will be brought up as mud. For this reason a third and better method has been developed.

The method of making test borings now to be described, makes use of two sizes of pipe, one about one and one-half inch in diameter, and the other about three-quarters of an inch in diameter. The smaller one is equipped with a chisel bottom and is lowered inside of the larger pipe. Both are forced down, meanwhile being turned. The smaller pipe can be withdrawn at any time, and the material which has been collected may be pushed out. Thus a cylindrical specimen may be obtained which indicates the exact

condition of the material as it exists at the depth at which the smaller pipe was withdrawn. This method, while working better in clay, silt or mixed soils, may be used to drill thru logs and rocks. An experienced man can tell, when rock is encountered, whether it is a boulder or solid rock. This may be determined by letting the chisel drop and observing the rebound and the sound. This outfit is cheap because any plumber or mechanic can make it. At the same time the results obtained are very satisfactory.

Types of Soil

After the soil has been investigated the next problem is to determine how the piles will probably act and how much load each one can take. Three general possibilities exist. The soil may be such that it is fluid or soft and the piles may be driven thru it until a stratum of firm or practically unyielding material is reached. In this case the pile receives little, if any, lateral support and therefore acts as a column.

The second type of soil is that in which, while no firm stratum may be reached, the earth will compact under the pile and will also produce friction on the surface of the pile. The strength of this condition

of piling depends upon the bearing capacity of the soil under the point of the pile, and the adhesion of the ground to the surface of the pile, or upon the compressive resistance of the material in the upper part of the pile.

The third soil condition is very similar to the second. It involves the case in which skin friction between the surface of the pile and the earth is developed, but in which the earth does not compact under the point of the pile. The piling under this condition depends solely upon the skin friction or the compressive resistance of the material in the pile.

Piles Acting as Columns

The total load coming on any one area due to the weight of the structure depends, of course, on the design of the structure under consideration. Having determined the load for any given area, the question that naturally follows is, "How many piles will be required?" If the condition is that of the first case described, the problem becomes one of determining the bearing capacity of the firm stratum and the ability of the pile to act as a column. The bearing capacity may be determined from information obtained

from test borings, and from a knowledge of the allowable strength of the material for that particular locality. The ability of the pile to act as a column may be determined by knowing the probable length of the pile, its diameter, slenderness ratio and allowable stresses. If any eccentricity is to be caused by the loading, that also should be taken into consideration, tho such a loading should be avoided if at all possible.

Piles Supported by Skin Friction

In the case of skin friction a different problem is confronted. The method of determining the allowable stress for each pile, which is now to be discussed, applies to cases two and three of the soil conditions previously considered. When the earth compacts under the point of the pile, some of the load may be carried by the compacted ground. The amount to be carried depends upon experience and a knowledge of how certain material will compact under various driving conditions. It probably varies between fifteen and twenty percent of the total static bearing capacity. What it is proposed to discuss now is how skin friction develops, and how its resistance to settling may be determined.

When a pile is being driven under conditions in which skin friction is presumed to develop, water is

usually squeezed out of the soil. This forms a slimy mud which lubricates the sides of the pile and thus reduces friction to a small value. The resistance of the pile is therefore largely due to that of the point where the pressure is high. The point causes the soil to displace and push up along the sides of the pile. Measurements have indicated that the amount of soil displacement at the surface is equal to the volume of the pile in the ground.

After a pile driven under these conditions has set for a time, the excess water is reabsorbed by the soil, by the pile, or both, causing the soil to grip the pile. When the pile is loaded there is, therefore, full friction along the sides and small comparative point resistance.

It is sometimes advocated, therefore, that the allowable load be the resistance determined by a pile-driving formula after the pile has set for some time. The pile-driving formulas are based upon the assumption that the earth is not allowed to set up around the pile during driving. What these formulas are and how they are assumed to operate will be discussed a little later in this chapter.

Frank J. Mullen relates that in driving piles for the John Hancock Mutual Life Insurance Company in Boston,

Massachusetts, it was impossible to obtain the proper penetration on the last blow during the initial driving. The piles were allowed to set until the next day and upon re-driving the desired resistance to driving was readily obtained. Later load tests substantiated the data obtained on re-driving the piles.

At the time of re-driving, if the pile has been allowed to set for at least over night, full friction along the surface of the pile will probably develop. Then when re-driving is attempted, it will be found that the soil under the point of the pile cannot readily displace upward, as it is held in place by the friction along the pile. The resistance to re-driving is, therefore, equal to the full frictional resistance plus high point resistance.

Pile driving formulae, of course, give results which are on the safe side. However, to use them indiscriminately seems, to the author, to be rather poor engineering practice. When it is known that skin friction is to be developed, the supporting capacity of the friction should be considered.

Several tests have been made upon piles under various conditions to determine the skin friction in pounds per square foot. Some of these were made by the Whangpoo Conservancy Board in Shanghai, some

by French engineers in Tunis, and still others by Ackerman in England, who made tests on model piles. All of these tests showed that in clays and silts the frictional resistance per unit of pile surface in contact is practically the same regardless of the depth in the soil. The Shanghai tests actually indicated somewhat smaller values for the greater depths.

If it is possible to obtain the ultimate frictional resistance per unit area, the bearing value of a single pile may be easily calculated by multiplying the resistance by the area in contact, neglecting the point resistance, which is small. This is the method which was adopted at Shanghai. To obtain these friction values, it is necessary to test the pulling resistance and the bearing capacity. Little of such information is available but on the following page is a table of the friction values for soils in several localities.

It may be seen that while there are a variety of opinions on the subject of the supporting capacity of a pile under certain conditions, it is possible to determine, with a reasonable degree of accuracy, just how many piles are required in certain areas under a structure. A careful study must be made of the soil

-FRICTIONAL RESISTANCE OF PILES IN SILTS, CLAYS, ETC.

Location	Soil	Penetration (Feet)	Contact Surface (Sq. Ft.)	Ultimate Load (Pounds)	Friction per sq. ft. (Pounds)	Source of Information
Aquia Creek, Va.	Fluid mud	45-50	117	13,333	95*	Eng. News, Feb. 23, 1893
New York, foot of 17th Street, North River	Mud	50	219	33,600	130*	Proceedings Int. Eng. Cont., St. Louis 1904
Rhine Valley	Soft muck	0-35	---	-----	130	Terzaghi
Rhine Valley	Soft clay	25-35	---	-----	295	Terzaghi
Proctorsville, La.	Mud, sand, clay	35	144	62,500	370*	Eng. News, Feb. 23, 1893
Portland, Me.	Soft blue clay	14	58.5	50,000	740*	Fay, Spofford & Thorndike
Hull, England	Stiff blue clay	18	---	-----	1,850	Terzaghi
Shanghai	Silty microscopic sand	4-50	---	-----	130 to 900	Terzaghi
Tunis	Soft muddy clay	100	---	200,000	370*	Le Genie Civil Dec. 2, 1929

* Friction calculated after deducting 15% for point resistance

encountered and the allowable loads for the locality determined before deciding on the number of piles required.

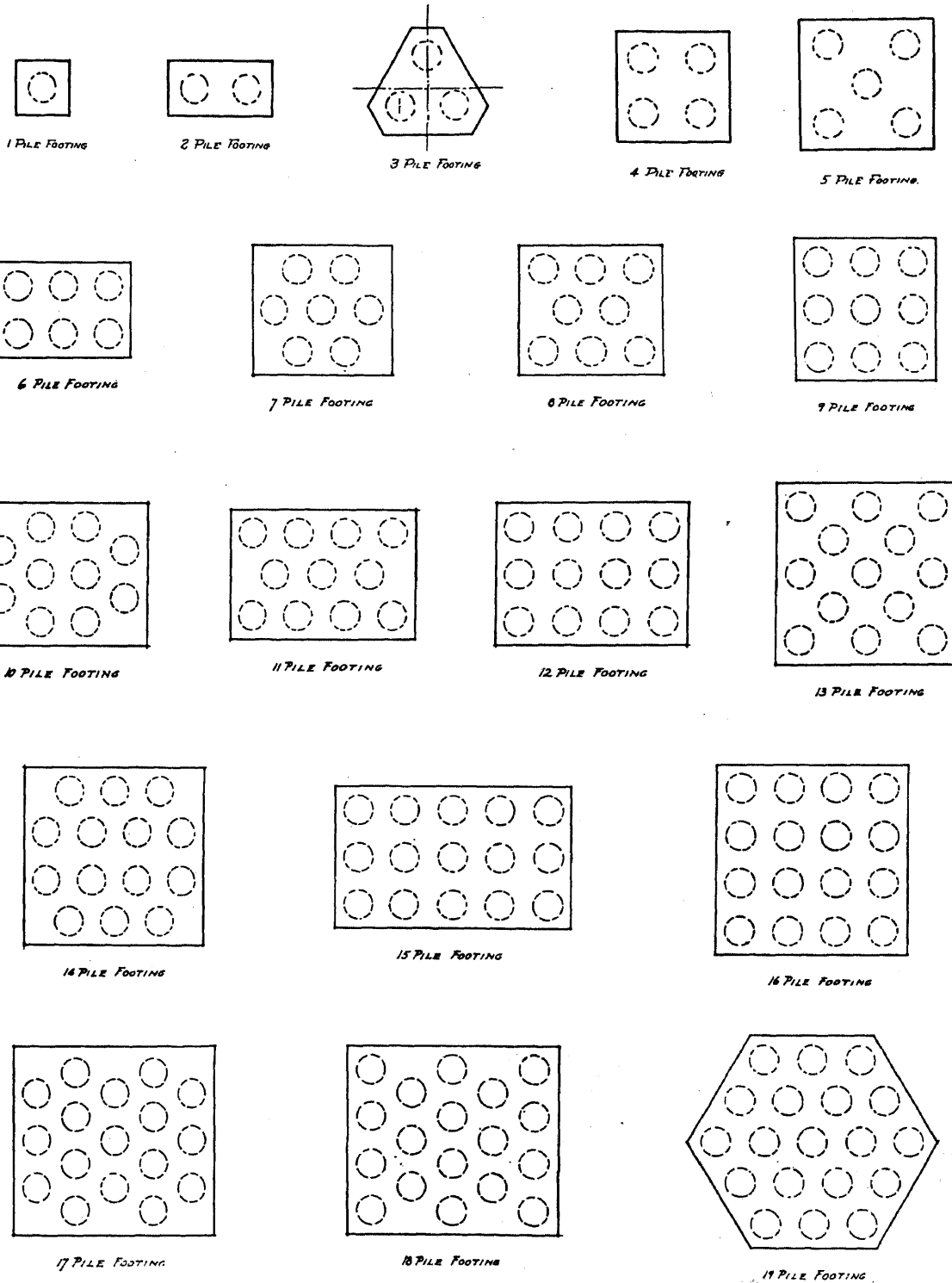
Spacing of Piles

When more than one pile is required at any one point, they are arranged in what are known as clusters. In all ordinary foundations piles are usually spaced about three feet on centers. They may be spaced more closely, but that is the usual practice. It is also desirable in so far as possible to spread the load by means of the footing so that each pile will receive practically the same load. On the following page is an illustration of typical pile footings.

Occasionally it becomes necessary to provide pile foundations under a retaining wall or dam, where an unequal load distribution exists. Mr. E. P. Arneson in the Engineering News-Record for October 9, 1919, suggests a simple method for determining the proper spacing of piles under such conditions. It is imperative that an excessive load is not caused to exist on any one pile. Mr. Arneson's plan is to divide the trapezoid of pressure under the cross-section of the retaining wall or dam by vertical lines, into several sections of equal area. The area

Typical Pile Footings

This chart gives a general idea of customary arrangement of piles in typical concrete footings.



of each section is to represent the allowable load on any one pile. The piles are then spaced at the center of gravity of each one of these sections, thus causing each pile to bear practically the same load. The method is quite simple and eliminates the danger of overloading any one pile.

Lateral Forces Acting on a Pile

Before leaving the subject of the strength of a pile, it is necessary to touch upon the subject of the lateral forces which may act on a pile. Bearing piles located in streams often have to resist lateral forces due to the impact of drift, ice, etc. As far as possible, such forces should be provided for by sway or lateral bracing. In the case of a retaining wall or dam, lateral forces also may need to be considered.

In discussing the lateral forces acting on the piles, it will be assumed that the cross-sectional area of the piles is large enough to offer sufficient resistance so that, when pressure is applied against the wall, the piles will not shear off just below the footing course. It is also important to know the point of zero rotation of the pile. By this is meant the point about which the pile will tend to rotate as

a horizontal force is applied to it. Mr. Dimitri P. Krynine in the Engineering News-Record for November 26, 1931, reported on some observations which he had made. His results showed the point of zero rotation, by actual tests, to be located at a depth of 0.52 h to 0.69 h and averaging close to two thirds "h", where "h" is the length of pile in the ground. He neglected, however, to specify the points of application of the horizontal forces. Mr. Wilcoxon of Detroit, Michigan, replied to Mr. Krynine in the December 17, 1931, issue of the Engineering News-Record giving the results of his stress analysis of the problem.

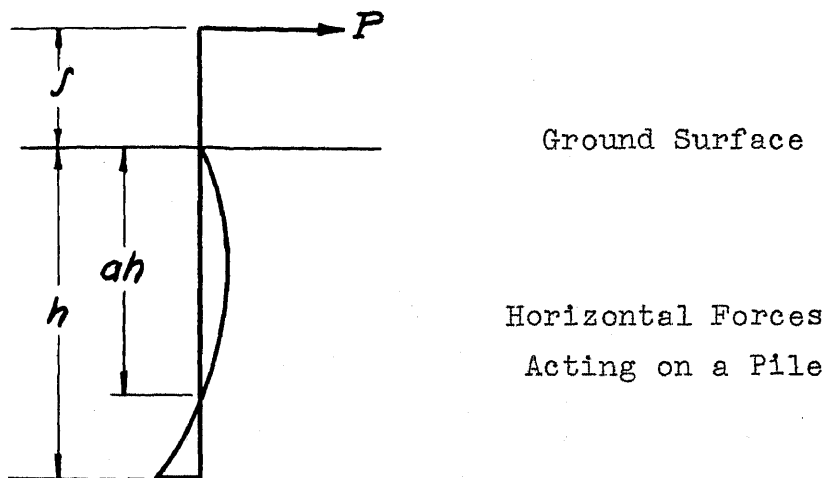
Mr. Wilcoxon's report may be briefly explained as follows: It is shown that the vertical bearing power of a soil is proportional to its depth by forcing a rod vertically into a soil of uniform material. The horizontal power of a soil is then accordingly assumed to be proportional to its depth below the ground surface. Then by assuming a point of rotation at some distance "ab" below the level of the ground, Mr. Wilcoxon derives the following formula

$$A = \frac{2}{3} \frac{1 + 1.5 h}{1 + 2 h}$$

h = length of pile in the ground

a = a coefficient to be multiplied by " h " to obtain the position of the point of zero rotation below the ground surface.

l = distance from the ground surface to the horizontal force acting on the pile. It is assumed that " l " is positive where the force acts above the ground and negative when it acts below.



Some of the critical values are these. When $l = -2/3 h$, $a = \infty$. This means that for this condition there is no tendency for the pile to rotate. When $l = -0.50 h$, $a = 1.00$. For this condition the point of rotation is at the bottom of the pile. When $l = 0$, $a = 0.75$, and as l increases further " a " approaches two thirds as a limit.

It will thus be seen that, when the horizontal force acting on the pile is above the ground, the

range of "a" is between 0.75 and 0.67, which compares favorably with the values of 0.69 and 0.52 of Mr. Krynine. Once the point of zero rotation is established, it becomes a comparatively simple matter to calculate the horizontal resistance to rotation which the pile must offer. This can be determined by equating the turning moment of the forces acting on the pile and the resisting moment of the ground forces also acting on the pile.

File-Driving Formulae

Previously in this chapter the subject of pile driving formulae was discussed. These are necessary in order to determine when a pile has been driven to the proper depth to develop adequate bearing capacity. Of course, as previously discussed, when skin friction is to be the determining factor it is possible before driving, to calculate how much of the pile must be in the ground to obtain suitable surface area. Even so, the results obtained from a pile-driving formula, when re-driving of a pile subject to skin friction is attempted, gives a fairly accurate conception of how much load each pile will carry.

From the test borings it is usually possible to estimate at what depth, if at any, a firm strata will

be reached. The depth of this strata probably varies either slightly or considerably over the area in which the piles are to be driven. Because of this and also because of the conditions in which piles depend upon the compacting of material under their point, pile-driving formulae help greatly in knowing when to stop driving.

The term "pile-driving formulae" refers to formulae based on the energy of the blow of the hammer and the penetration of the pile. Such are dynamic formulae. An exact formula of this type can only give the resistance of the pile to rapid penetration while what is desired is its static bearing capacity. The driving formula is of value, therefore, only in such cases as the dynamic resistance is some measure of the static bearing capacity. These formulae give fairly accurate results in the usual sands, gravels and other relative permeable, cohesionless soils where the resistance to rapid and slow penetration is about the same. The use of such formulae, when skin friction develops, has already been discussed.

There have been many pile-driving formulae developed. Some are very complicated and many assumptions are required in their solution. Some are interesting only from a mathematical point of view. The author intends

to discuss only one of these many formulae, but that one is the most universally used. It is known as the Engineering News Formula.

The Engineering News Formula was developed by A. M. Wellington in 1888 from an almost purely practical standpoint. The work done by the hammer of weight " W " in falling thru a distance " h " is equal to " $W h$ ". The useful work done upon the pile is the product of its resistance multiplied by its penetration under the last blow. The ratio of these two products measures the efficiency of the hammer blow and the proportion of the work wasted.

The energy stored in the hammer may be absorbed in four ways: first, in brooming and washing the fibers either at the head or the foot of the pile or at some other part of its length; second, in bouncing and thus striking two or more light blows instead of one heavy one; third, in compressing elastically the material of the pile and pile hammer; and four, in causing the pile to penetrate against the resistance of the surrounding earth.

Brooming, which will be considered in the next chapter, constitutes a serious loss of energy. If brooming occurs at the head of the pile it should be cared for by cutting the broomed section off just

before penetration is obtained. This causes a fresh surface of unbroken fibers to receive the final blows.

Bouncing of the hammer means waste of energy, either because the pile has struck a solid obstacle like a boulder, or because the hammer is too light, or the velocity too great, or both. The presence of a boulder can readily be detected by an experienced man. When too light a hammer or too great a velocity is obtained, it is impossible to get the pile in motion before it reacts elastically with more force than the hammer is exerting to push it down. A slight rebound, however, is always present in good pile-driving, due to the elasticity of the pile.

In the formula developed by Wellington, the elastic compression of the pile and hammer is cared for in the factor of safety which is six. Wellington's formula for pile-driving with a drop hammer is: -

$$\text{Safe load} = \frac{2 W H}{S + 1}$$

W = weight of the drop hammer in pounds.

H = fall of hammer in feet.

S = average penetration in inches under the last few blows.

The pile-driving formulae when a steam hammer is used is similar to the one just given. The greater

efficiency of the steam hammer is due primarily to the rapidity of its blows. The Engineering News or Wellington formula for pile-driving with a steam hammer is: -

$$\text{Safe load} = \frac{2 W H}{S + 0.1}$$

Charts have been constructed for use with both of these formulae so that the safe load for any given penetration, weight of hammer and fall, can be readily obtained.

This last mentioned formula has been further modified so that for double-acting hammers it is as follows: -

$$\text{Safe load} = \frac{2 W H}{S + 0.3}$$

Later the question arose as to what influence the steam exerted in the driving of the piles. The following rule was suggested: "Ascertain as nearly as possible the foot-pounds represented by the blow delivered by the hammer. This can be done by adding to the foot-pounds represented by the free fall of the hammer, the foot-pounds obtained by multiplying the mean effective pressure by the area of the piston and the length of the stroke in feet. The result is the numerator of the formula.

In the absence of any specific data on the mean effective pressure it may be assumed as twenty five pounds per square inch.

Thus for a double acting hammer the new formula becomes: -

$$\text{Safe load} = \frac{(W + A (\text{m.e.p.}) h)}{S + 0.3}$$

The safe load and W should be taken in pounds if the m.e.p. is in pounds.

Other formulae pertaining to special types of piles will be discussed when these special piles are considered in Chapters V and VI.

Test Piles

One other phase of the theory of pile driving remains to be discussed, and that is the subject of test piles. Test piles are piles which are driven under standard conditions and then loaded and the settlement observed under various loadings and over a period of time.

This method gives the most accurate results as to the actual bearing capacity of a pile. It would be ideal, of course, if these piles could be driven in various parts of the ground where a building is to be constructed before the pile foundation was designed.

This, however, is impractical both because of the time involved, the cost, and also the fact that quite accurate information can be obtained by the methods already mentioned.

It should be required, however, that a certain percentage of all of the piles driven on a job be tested by loading and the settlement noted. This has always been feasible in the case of timber and steel pile, but only in the last few years has it become practical with concrete piles, especially those which are moulded in place.

The change has been brought about by the invention of alumina or quick-setting cement. It is much more expensive than ordinary portland cement so is not feasible for use in all of the piles. It should be used, however, in those which are to be tested. The alumina cement develops its full strength in twenty four hours as against twenty eight days for ordinary portland cement. Harlan D. Miller, bridge engineer of the California Highway Commission, writes in the Engineering News-Record for February 11, 1926, that samples of alumina cement were tested forty eight hours after pouring. It was impossible to break the sample in the state testing machine which had a maximum capacity of 200,000 pounds. This indicated

a strength of greater than 5600 pounds per square inch. Thus, by using this cement in the test piles, loads may be applied as soon as twenty four hours after the concrete has been poured.

CHAPTER IV

Timber Piles

Wood Used

The kind of wood used in timber piles depends, to a great extent, upon the type of construction, the location of the piling, whether subject to alternate wetting and drying, and the permanence desired. For standard construction purposes the following woods are suggested: white, burr and post oak; longleaf pine, Douglas fir, tamarack; eastern white and red cedar; chestnut; western cedar; redwood, spruce and cypress. For less permanent construction the following types of wood are suggested: red and all other oaks, not already listed; sycamore; sweet, black and tupelo gum; maple; elm; hickory; Norway pine or, in fact, any sound timber that will stand driving. Other species which have been used to a limited extent under special conditions are beechwood, ash, and basswood; and even palmetto piles are not unknown. Each of the kinds of wood mentioned has its advantages and disadvantages. Oak is exceedingly tough and hard and will stand more hammering than any of the other species.

It has several disadvantages, the chief among them being that oak piles cannot be obtained that are as large, as straight or as long as those of either pine or cypress. In certain localities oak piles are quite expensive because of the charges for transportation. Due to the heaviness of oak piles, any great number of them made into a raft and carrying others are likely to sink. In some localities where oak is abundant, piles of this kind are used extensively.

There are two main types of pine, white pine, found in the northern central states, and longleaf yellow pine, found in the south. The former is soft, white, easily worked, and possesses great strength and durability. Since the beginning of the twentieth century white pine has been in such demand for other uses in building construction that it seldom has been used as material for piles in the present day. The longleaf yellow pine is found in abundance and is considered to be harder and stronger than white pine.

There exists two apparently distinct species of the longleaf yellow pine both of which present practically the same outward appearances. One, however, has a large proportion of sap-wood and a small proportion of heartwood. This type should never be used in structures unless immersed under water

at all times. The other has very little sap-wood and long, large, straight pieces of almost clear heartwood can be obtained. Such timber is unsurpassed for use in structures above ground exposed to alternate wetness and dryness. Straight trees of this kind of pine can be obtained in any length up to ninety or one hundred feet, and in diameters at the butt end of from twelve to eighteen inches or more, and from ten to twelve inches at the small end. Pine logs can be floated in large rafts at comparatively cheap rates. What has been stated regarding the strength, durability, etc., of pine piles may also be said of cypress. The main objection to cypress is that it does not stand the hammer as well as pine but has a tendency to split and splinter.

Of the other kinds of wood mentioned a word or two about several of them will suffice. Douglas fir piles may be obtained in longer single sticks than may any other woods. Elm is also considered good material for piles but does not seem to be used to any great extent. Spruce obtained from certain localities has unusual toughness, giving the piles increased resistance to the tendency to split.

Requirements for Good Timber Piles

The requirements for good timber piles vary in some degree but the specifications of the American Railway Engineering Association cover all of the main points: "Piles shall be cut from sound trees; shall be close-grained and solid, free from defects, such as injurious ring shakes, large and unsound or loose knots, decay, or other defects, which may materially impair their strength or durability. Piles must be cut above the ground swell and have a uniform taper from butt to tip. Short bends will not be allowed. A line drawn from the center of the butt to the center of the tip shall lie within the body of the pile. Unless otherwise allowed, piles must be cut when the sap is down. Piles must be peeled soon after cutting. All knots shall be trimmed close to the body of the pile. Square piles shall show at least 80 percent heart at each side at any cross-section of the stick, and all round piles shall show at least a $10\frac{1}{2}$ inch diameter of heart at the butt. Piles of the railroad false-work grade, however, need not be peeled, and no limits are specified as to diameter or proportion of heart."

Most engineers and authorities concur in the greater portion of these specifications. The main

point of disagreement is the amount of permissible lateral curvature. Some engineers specify that the center of any cross section shall not depart more than one-eighth of its diameter from the straight line joining the centers of the butt and the tip. Others permit a maximum divergence of one percent of the length of the pile. When a pile bends in two directions, it is regarded as sufficient cause for rejection on first-class work.

There is one phase in the development of good piles that has not received the proper attention of engineers. That is the time of year in which timber is cut for piles. I shall quote from Foundations of Bridges and Buildings by Jacoby and Davis - "Tests made in Germany of four spruce trees, growing close together in the same soil, showed that if the strength, when cut in December, is taken as 100 percent, those cut in January, February and March had strengths of 88, 80 and 62 percent respectively. Beech timber cut in December and January gave an average mechanical life of six years, where as the same kind of timber cut in the same location in February and March gave a service of only two years."

There have been cases in this country which substantiate these reports from Germany. Some piles

of the best species of wood were cut in summer. Decay due to fungi and worms became manifest when the sapwood began to decay. Some of the piles were completely eaten thru in two years.

Preparation of the Piles for Driving

After the selection of the logs for the piles, the next step is the preparing of the logs by cutting or sawing the large end square. The small end is then brought to a blunt point with an axe, the bevel being from $1\frac{1}{2}$ to 2 feet long. Finally the pile is stripped of its bark. In soft and silty material there is no need for pointing a pile at all, and in fact the piles are better when left blunt. Pointed piles on striking an obstruction will glance off and no available power can prevent it. A blunt pile will cut or break the obstruction. There are many illustrations to justify this point of view. The large end of the pile is chamfered for a few inches from the end so that a wrought-iron band from 10 to 14 inches internal diameter will just fit and will clasp the pile uniformly and tightly with one or two light blows of the hammer. Sometimes a ring from 1 to $1\frac{1}{2}$ inches less in diameter than the pile, is simply placed on the top of the pile and driven into it by

light blows. This, however, is apt to split long layers from the pile. It is imperative to put the band on the pile before starting driving operations. Once the pile begins to show signs of splitting then the ring is too late to be of any advantage.

The use of the ring is not without its advantages. Of course it would be too expensive to use a new ring for each pile, so after the driving is completed the ring must be removed. With ordinary tools such as hammers and bars the work is quite difficult. A method has been described in Water Works and Sewerage for January 1930 which greatly simplifies the problem of removing the ring. A hook and lever arrangement has been devised. The hook is caught under the edge of the ring, and the lever extends across the top of the pile. The hammer is allowed to drop about 6 inches with the result that the ring is usually loosened sufficiently to permit the removal of the ring with a sledge. If the ring still remains wedged, the hook may be caught under the opposite side of the ring. A second blow of the hammer on the lever will usually free the ring. This saves labor and prevents damaging of the pile head.

If a ring were not used on the head of a pile, what is known as brooming would take place, That is,

the repeated blows of the hammer would compress the fibers until the ultimate resistance in compression was reached. At this point failure would take place and the fibers would yield by bending, buckling or crushing. The adhesion to the adjacent fibers would be destroyed and every blow of the hammer would tend to injure the fibers further down. Wooden fibers are more compressible when a load is applied on their sides than on their ends and hence the broomed head of the pile becomes more elastic. This causes it to act like a spring or cushion and much of the useful work of the hammer is wasted in overcoming the cushioning effect of the broomed head of the pile. Many times the brooming of the head is followed by the splitting of the pile. To prevent these failures rings should be and are generally used.

Another way in which timber piles may need protection is at the foot. As was mentioned before, it is not necessary to sharpen or point the pile when the driving is easy. In driving a pile with a blunt end, a cone of compressed soil forms under it and this acts as tho the pile were pointed. Some authorities contend that even when driving thru hard material the cone of earth is better than a point would be. This is hardly true if the pointing is done

properly. When the cone of earth strikes gravel or rock it is going to be destroyed. Then what is needed is not a blunt end on the pile, but rather something which will act like a wedge. To obtain a wedge-like point the foot of the pile is cut to the shape of a truncated pyramid, the end being from four to six inches square. In compact material the bearing power of the pile is practically the same, with or without a point.

At times the driving becomes so hard that, even tho a pile is pointed, it will be damaged in driving. To overcome this as much as possible metal shoes are sometimes used to replace or protect the point of the pile. The shoes should fit tightly and preferably be attached to the pile by straps, or some other method, so that the shoe acts as an integral part of the pile. Some engineers condemn the use of shoes. In most cases it has been because of their unsatisfactory experience with them. This was probably caused by improperly designed shoes or by driving in ground so hard that piles were not really necessary.

Occasionally it is necessary to use longer piles than can be obtained in single sticks. Then it is necessary to splice two piles together and the best

method is the fish plate splice. Four or six fish plates may be used. It may also be necessary to splice piles because of limited clearance under a bridge. Each job presents its own problems, and the solutions may vary in detail but the general remedies remain fairly constant.

Overdriving

Piles must also be protected against what is known as overdriving. This consists in driving the pile beyond the point where the desired bearing power has been obtained. This may be caused by the pile apparently penetrating the ground while it actually is splitting or crushing. It also may be caused by permitting too long an interval to occur between blows of the hammer thus permitting the earth to set up under the pile and making the driving much harder.

In Jersey City some piles were driven into the surface of a street to temporarily support a large water pipe. Later the street was excavated for the construction of a railroad. At the time of the driving it had been thought that the piles were in good condition and well driven. Upon excavation, however, it was discovered that about



Damage of Timber Piles Caused by Overdriving

half of them were ruined in driving. Some were broken off square across and the upper piece driven beside the lower piece. One of the piles struck a flat rock about 16 feet below the surface. The fibers at the tip of this pile were turned aside for a distance of about 15 feet.

The conclusion was expressed, by one contracting engineer of great experience, that "more piles are dangerously injured by improper driving than are rendered unsafe through insufficient driving." This engineer believes that much of the value of the pile is lost by overdriving and that this is due largely to the "use of drop hammers with excessive weights and undue heights of fall." He cites the case where 10 successive piles in an important foundation were driven in hard material by a 3000 pound drop hammer and a fall of 30 feet. After they had apparently reached "refusal" the heads suddenly moved several inches. The inspector assumed that the pile had penetrated a hard stratum material and ordered the driving continued until penetration took place. Later these piles were removed and it was found that every one of them had been broken off near mid-length. It is also the contention of this engineer that over driving not only injures the pile in the manner already

described but that it also "results in a degeneration of the fiber which reduces the strength of the piles acting as columns and materially hastens decay."

The Topeka and Santa Fe Railroad recently constructed a temporary underpass on piles where each pile required from 24 to 30 hours of constant driving with a large steam hammer. Later, when these piles were excavated, it was found that some of them had been compressed to one quarter their original length. In some cases where the driving had been on gravel, a coal-like substance had formed under the pile. Whether this was caused by compression or heat it was impossible to say. Probably a combination of the two caused the unusual conditions.

The Southern Pacific Railroad also had an incident occur which, while out of the ordinary, indicates some of the problems which confront an engineer in driving piles. Wood piles were driven and at a depth of forty feet, water-bearing sand was hit and the driving came to an abrupt stop. With continued driving some of the piles on an adjacent track had penetrated this stratum so the driving was resumed. One pile was driven from 10 A. M. to 12 noon when it was observed that it was brooming at the top. It was decided that the ideal thing to do

was to pull the pile and replace it by a new one before continuing the driving. It was thought that this would prove to be a difficult operation but at the first strain it "popped" out. It was found to be in good condition with the exception of the tip which was steaming hot. A new pile was replaced and the driving continued. Just before 5:00 P. M. as the hammer reached the top of the leads, the pile was suddenly blown out of the hole and was followed by clouds of steam and sand. Eleven feet of the pile tip was left in the hole. Examination showed the fibers were crushed and steaming hot, giving off the odor of charred wood. Continued driving had generated heat due to the friction which formed steam sufficient quantities to blow the pile out of the hole. Incidents such as these just described could be almost wholly eliminated if a better study were made of the kind of ground to be encountered when driving.

Use of the Water Jet

Piles which offer great resistance to driving may be more easily or more quickly placed by the use of what is known as a water jet. This consists of a long pipe, usually about 2 inches in diameter which

discharges water under pressure at or near the foot of the pile. It is especially useful in sandy soils but gives good results in nearly all other types as well with the exceptions of hardpan and rock.

The method of driving with a jet differs from that of driving with a hammer. In the former case one or more jets are used. The water is discharged under pressure near the foot of the pile while the jet is moved up and down. As the water comes up around the sides of the pile, it carries with it some of the material. Thus it not only serves to excavate or loosen the soil in advance of the pile but also tends to reduce the frictional resistance of the earth. In some cases all that is necessary is for the hammer to rest on the top of the pile and it will settle due to the combined weight of the pile and hammer. Other cases require the use of blows with a restricted fall. In either instance, however, the jet or jets are withdrawn just before the pile reaches the desired penetration. The final driving is completed by a few blows of the hammer. The water has a puddling action and, after the jets are withdrawn, the earth tends to pack around the pile, thus furnishing excellent skin friction.

One jet may be used if the driving is being carried on in soft ground, but in most cases two jets used on opposite sides of the pile give better results. The pile tends to "walk" toward the side where the jet is. The use of two jets tends to eliminate this difficulty and the piles generally may be more accurately placed. Sometimes three jets are used, but whether one, two, or three are employed, it has been shown by experience that piles may, with the two exceptions noted, be driven by using the jetting method at a great saving in time and energy.

Protection against Alternate Wetting and Drying

Another problem is the protection of wood piles when they are subject to contact with either fresh or salt water. This has taxed the inventive genius of hundreds of people. Wooden piles used to support permanent structures, or in places where they cannot readily be renewed, must be under water at all times in order to prevent decay. This condition may be neglected in temporary structures or where piles can be readily replaced.

Often when wood piling is used under the footings of a wall or piers of a building, it

becomes very expensive to excavate to a depth which is below the permanent surface of the ground water. In cities and towns the surface of the ground water is often lowered several feet as new pipe-trenches and sewers are introduced. Some foundation piles which are well under water today may have their tops out of water a few years from now. Because of this, it is advisable to drive the piles so that the cut off may be below the existing water-line but even this does not always adequately take care of the situation. Another problem is the protection of the piles against marine borers, which are more prevalent in some places than others.

History informs us that piles driven in the first century for the bridge of Emperor Trojan across the Danube were examined in the eighteenth century. They were found to be in excellent condition and petrified to a depth of $\frac{3}{4}$ of an inch. Beyond this the timber was in its original state. This is an unusual case, as may be seen by contrasting it with the case in San Francisco where many of the piles were destroyed in from 22 months to 10 years by the work of marine borers.

First, the methods which are used at present to counteract the ravages of decay will be discussed.

Some of the methods used to prevent decay are also used to resist the attacks of marine borers and vice versa.

The first and most common method used is that of forcing creosote under pressure into the wood. The general procedure for accomplishing this is as follows: The material to be treated is loaded on trams and pushed into a cylinder about 8 feet in diameter and 130 feet long. The cylinder is equipped with doors at each end and it is so designed and constructed as to permit a working pressure of 225 pounds per square inch to be used inside the cylinder. After the trams are in the cylinder the doors are closed and bolted. The cylinder is then air tight. Live steam is then turned into the cylinder under a pressure of from 20 to 30 pounds. The length of the steaming depends upon the class of material being treated, and the quantity of oil to be injected. Green material to receive 12 pounds of oil per cubic foot would be steamed in the neighborhood of eight hours. Material to be treated with 24 pounds of oil per cubic foot would be steamed from 14 to 16 hours.

The material is steamed to open up the pores of the timber and heated so that the moisture can be drawn out. After the steaming process has been

completed a vacuum is created by means of vacuum pumps designed so that the vacuum created is practically perfect. This vacuum is maintained for from three to four hours. This draws the sap and moisture from the timber to be treated. In order to know when the sap is out of the cylinder, there is a drum with a gauge glass which shows the amount of sap at any time contained in the drum. After the vacuum process the cylinder is filled with coal tar creosote, and pressure is applied to force the oil into the wood. The pressure applied is sometimes as high as 175 pounds per square inch. When the correct amount of oil has been injected into the timber, the oil remaining in the cylinder is drawn back to the working tanks from which it was originally taken. The length of time required to get the proper and desired penetration varies in practically every case. To procure the proper penetration, skilled engineers are required who make a specialty of this work. The doors of the cylinder are then unbolted and the tram cars pulled to the yard or dock for unloading or loading for shipment.

It is impossible to assign any definite life to creosoted piles but there is no question that treated piles outlast untreated ones. There are too

many variables affecting the life of a pile to estimate the life excepting for innumerable specific conditions.

Another and more recent method used to prevent decay has been the development of what is known as the ZMA method. This means the zinc meta-arsenite method. This was developed thru the desire of engineers in telegraph companies to find a substitute for creosote. While creosote does prevent decay it has several objectionable features. It has a strong odor, an unpleasant color, will not take paint well, and has a high fire risk. Zinc meta-arsenite was finally hit upon and was obtained by the reaction zinc acetate and meta-arsenous acid to form zinc meta-arsenite and acetic acid. It was found that this new compound did not contain the objectionable features of creosote and also that it was not soluble in water but was soluble in the acid body juices of the fungi which causes decay. This, too, may be used to resist the attacks of marine borers, as well as to prevent decay. This development is so new that it is impossible to obtain any data as yet on the life of piles treated by the ZMA process. It is believed however, that the life of the pile will be long, due to the ability of zinc meta-arsenite to kill any wood-

destroying fungus.

Marine Borers

Before discussing the protections against marine borers, it is better to explain briefly what the more common types are and how they act.

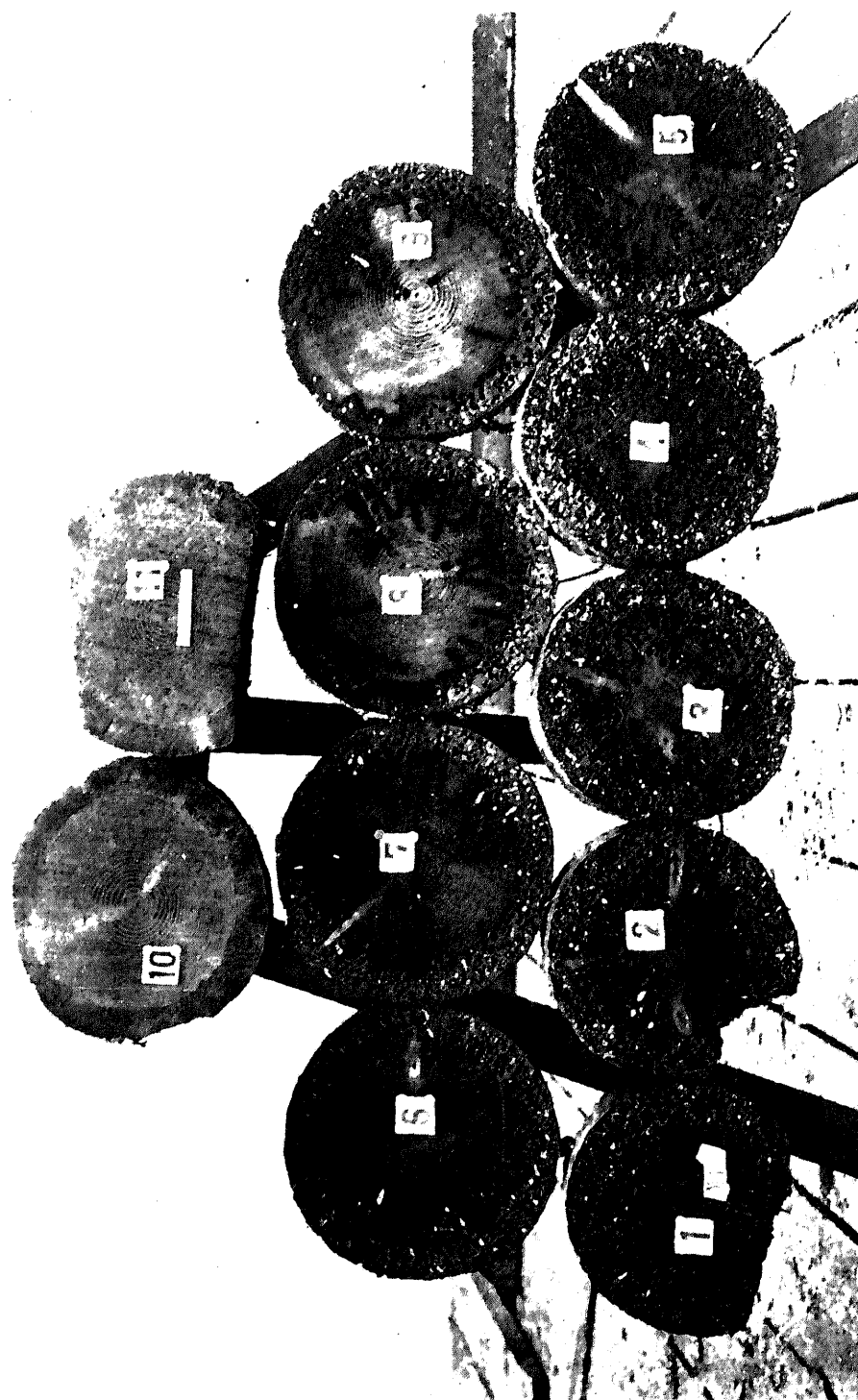
Marine borers belong to two families, the Crustacea and the Mollusca. The Crustacea are composed of three genera which are destructive to timber. These are the *Limnoria*, *Chelura* and *Sphaeroma*. *Limnoria* resemble the ordinary wood louse and are from 1/8 to 1/4 inch long. They destroy piling by gnawing their interlacing branching burrows into the surface of the wood. As many as 200 to 240 burrows per square inch have been found in heavily attacked timber. They quickly destroy the outer layer of wood, which washes away, exposing the next layer to attack.

Limnoria work at all levels in harbor waters from near the mud line to the uppermost tidal level with great facility. They are, however, most active between tide levels, cutting off piling below mean tide level or reducing them to an hour-glass shape.

This borer is found on both the Atlantic and Pacific shores of the United States, north to Bering Island and has been reported on European coasts from the



Untreated Douglas fir piling in Oakland Estuary, destroyed by *Limnoria*. Good piles shown are re-placements.



Fender pile, Shell Oil Company dock, Martinez, California. Sections three feet apart, mud-line to high water. November, 1920. Note deeper penetration on down stream (right side) and offshore (lower) exposure.

Adriatic to Norway. It seems to thrive in sewage-laden waters but the salinity of the water also seems to have an effect. It has not been found where the salinity falls below 15 parts per thousand for any considerable length of time.

Chelura works with Limmoria in marine structures, and excavates burrows in much the same fashion. For this reason it easily may be overlooked and the necessary precautions not taken against its destructive work.

Chelura is known as a wood destroyer in European waters from Norway to the Black Sea, and on the Atlantic Coast of North America. As yet it has not appeared on the Pacific Coast, but the Panama Canal and the increase in round-the-world and interoceanic shipping will probably cause it to appear there.

Sphaeroma are larger, stouter borers than Limmoria. They are about $\frac{1}{2}$ inch long and $\frac{1}{4}$ inch wide in diameter when disturbed. They are very often found in crevices or other sheltering works outside of their burrows and are evidently foragers. They do not appear to depend upon the wood eroded from their burrows for food but seem to feed upon the minute vegetable and other growths which cover the surface of the piling.

The excavations made by the Sphaeroma are very characteristic in size, distribution and location.

They make circular openings up to nearly $\frac{1}{2}$ inch in diameter, enter the wood horizontally or turn more or less abruptly and run with the grain in the softer layers of the wood.

Sphaeroma are prevalent on the Pacific Coast from Alaska southward. They have also been known to attack piles in fresh water in St. John's River, Florida, where in eight years they reduced piles from 16 to $7\frac{1}{2}$ inches in diameter.

The other family of marine borers are the Mollusca which are bivalves and are distantly related to the clam family. The most important groups of this family are the Teredo, Baukia, and Martesia. The latter resembles a clam being wholly enclosed within a shell. The other two are like worms but have heads of shell material.

When very small the Mollusca enter timber and spend their entire life there, burrowing and enlarging their holes as they grow. Piles have been known which have only a few small holes exposed but which have been completely honeycombed on the inside. The Teredo are generally only a few inches long, while some species of the Baukia are known which have reached a length of 3 or 4 feet and a diameter of one inch. The Martesia make borings not over one inch in diameter and $2\frac{1}{2}$ inches

long.

Protection Against Marine Borers

When timber piles are not chemically treated or mechanically protected and the waters are infested by marine borers, the piles have a short life. The average life of a timber pile on the coasts of the South Atlantic, Gulf and Pacific states ranges from about 8 months to 2 years. The development and activity of the borers are stimulated by high temperatures, and therefore in some of the more northern coasts the average life may extend to three or more years. On the other hand there are cases in very salty water and during a hot season where piles 18 inches in diameter have been entirely honeycombed in three years.

Many suggestions have been offered for the protection of timber piles. Some have proved better than others while many are utterly useless and ridiculous. All of the useful methods in protection of timber piles may be grouped into the following general classifications: - bark, chemical means, and mechanical protection.

It is known that the bark of fir and hemlock and of many other species are not as rapidly attacked

as the wood itself and this has naturally resulted in many attempts to use piling with the bark on. Bark adheres to the wood more firmly in the winter than in spring. For this reason it is common to require that such piles be winter cut. The objection to this method of protection is that the bark is easily knocked off in spots. This permits the marine borer to attack the wood in these spots, bore their way in and destroy the pile beneath the bark.

Of all the chemical methods of protection perhaps the most satisfactory is that of creosoted impregnation. The durability of creosoted piles depends on several factors. The timber must be of good quality, free from decay, and should have sufficient sapwood to take the requisite amount of creosote oil. The method of impregnating the pile with creosote already has been described. Extended experience has shown that creosoted piles may be depended upon to protect timber piles from ten to fifteen years.

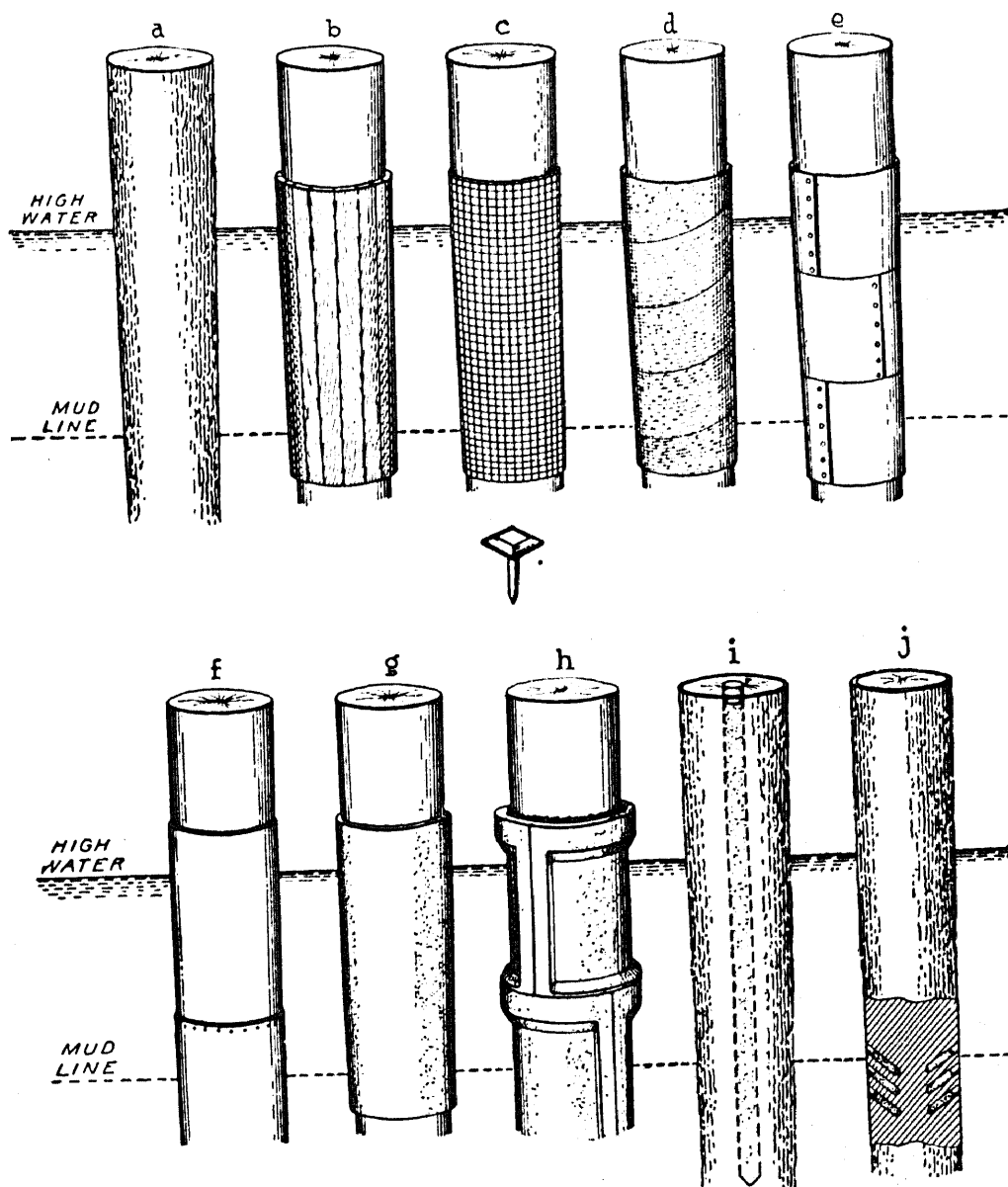
Zinc-meta-arsenite is also used as protection against marine borers. This process also has been described. The life of timber piles treated with zinc-meta-arsenite has not been determined as yet. The process is too new for any extended studies to have been made.

Some compounds of copper sulfate and lead acetate have been tried. While they are extremely poisonous to animals life, they tend to become leached out by the action of sea-water and hence lose their toxicity.

Countless other methods of protection have been developed and are being developed all the time. It is impossible to cover all of these in this thesis. What is suggested today may be proved a failure tomorrow. The author, therefore, refers the reader to the Reports of the Committee on Wood Preservation of the American Railway Engineering Association, to the Proceedings of the American Wood Preserver's Association, and to the Engineering Index. In these publications the discussions of the subject are kept up to date, and the results of good practice are recorded.

When mechanical protection is used it is the best practice to protect the pile from a short distance above high-water level to an elevation below the mud-line. For this reason mechanical protection offers the possibility of a cheaper solution of the problem than chemical treatment which must of necessity cover the entire length of the pile. Various methods have again been suggested but the author will discuss only a few of the more feasible possibilities.

The illustration on the following page is reproduced



Types of Mechanical Protection

from Circular 128 of the United States Forest Service, entitled Preservation of Piling against Marine Borers by C. Shotwell Smith. The ten methods shown will be briefly discussed.

Fig. "a" illustrates a pile with the bark left on. This method of protection has already been discussed and its advantages and disadvantages related.

Fig. "b" shows a pile sheathed with planks. This was based on the theory that the shipworm would not cross a crack. The Limmoria however has none of the apparent scruples of the shipworm and bored its way on thru the sheathing and the pile. Later tar paper, felt or other similar material was used under the sheathing and this proved to be fairly effective.

The Sante Fe Railway developed a method of protection by driving three penny and four penny nails spaced one half inch on centers. It is not necessary that the heads of the nails touch as protection comes not only from the nail head but also from the rust formed by the corrosion of the metal. The application of strips of sheet iron with open spaces between the strips has been tried. This has not proved so effective as the use of nails, as the rust does not seem to penetrate the wood so deeply.

In Fig. "d" is illustrated a type of protection

where burlap soaked in different chemicals is used to cover the pile. Sometimes the surface of the piles is painted previous to the placing of the burlap. Quite a few of these methods are patented. One process makes use of a solution of asphalt, slaked lime, rock salt, sulfur, marble dust and sand.

The use of metallic sheathing is illustrated in Figs. "e" and "f". The covering usually consists of thin sheets of iron, zinc, yellow metal or copper. Iron is susceptible to rapid corrosion. Zinc sheets of nine to fourteen gauge, prolong the life of the pile but records do not show that its use is very economical. Yellow metal, which is an alloy of copper and zinc, has been used with quite a good deal of success. Copper sheathing is expensive and its high junk value makes it likely to be stolen. Copper is an effective protective but like all metallic sheathing it is subject to wear and may be easily torn by floating debris.

Fig. "g" shows a casing of cement mortar or concrete in contact with a timber pile. The design of the forms and the method of placing the concrete are the determining factors in the cost and the results obtained from this type of protection. The types of forms used vary according to the concern manufacturing them. One simple type of form consists of sheets of

steel in sections eighteen inches long and split longitudinally. Vertical angles are riveted to the joints so that they may be tightly clamped together with rubber gaskets serving to make the joints tight. The slightly reduced lower end of each section fits into the slightly enlarged upper end of the next lower section. Each section is filled with mortar by a diver before the next section is fitted into place. The lowest section is placed in an excavation below the mud line and the sections extend up to the mean-tide level. Above this the remainder of the pile is painted with a wash of neat cement.

In the harbor at Seattle, Washington, and again in the construction of bulkheads at Miami, Florida, the following method was used with considerable success: The untreated timber piles were wrapped with galvanized three by three inch electro-welded mesh and the pile then gunited to a thickness of one and one half inches. The proportions were one to three. The cement gun was operated between tides and the gunite set up so quickly that no trouble was experienced from the tide. The piles used at Miami have been in service for almost four years and still are in excellent condition. There is no record available as to how those at Seattle are withstanding attack.

Another type of protection is illustrated in Figure "b". This consists in fitting sections of vitrified clay-pipe or reinforced-concrete pipe around the pile and filling the space between the pile and the inside of the pipe with sand. This type of protection may be easily repaired as the pipe is constructed with longitudinal joints for each section. Thus a half section may be readily and easily replaced and sand poured in at the top to replace any sand which leaks out. Reinforced-concrete pipe is superior to vitrified pipe as it resists much better the accidental blows of floating debris. The blows of such debris forms the weak point in the mechanical resistance of the other types of protection previously mentioned. Once the sheathing is punctured the marine borers may get in their work.

Figures "i" and "j" illustrate the protection of piles by boring holes into them and filling the holes with a poisonous substance. This treatment is no longer used.

In concluding this discussion of the methods of protecting timber pile from the attack of marine borers, the author does not intend to infer that these are the only methods of protection, but rather

these are the more commonly used methods of resisting the destructive work of the marine borers.

Cutting Off and Pulling Piles

Before concluding this chapter on timber piles the subject of cutting off and removing piles will be briefly discussed. Several problems are present. First, the cutting off of piles when the heads are to be incased by a concrete footing; second, the cutting off of piles when timber grillage or caps are to be used; third, the removal of temporary or old piles either by pulling or cutting them off.

When the heads of the piles are to be incased in concrete it is not essential that they be cut off to exactly the same level. As long as the heads extend into the footing some distance which shall not be less than the minimum specified, great precision need not be used in setting the point of cut-off. The concrete footing can be brought to the proper elevation.

When timber grillage or caps are used, however, to transport the load from the superstructure to the piles, it is essential that the piles be cut off at the exact elevation level. Concave, convex, or inclined heads are not acceptable. The best method for making

the cut in open air is to use an ordinary cross-cut saw set upon two straight-edge guides attached to the piles. The method which is second best to this is to use a circular saw mounted upon a vertical shaft which is rigidly held in position by a movable frame.

When the elevation of cut-off is below the surface of the water special means must be resorted to. In general the methods used by different contractors are the same, so only one type will be discussed here.

At Portland, Oregon, over two hundred piles for the pivot pier of the Morrison Street bridge were cut off close to the bed of the river. A solid falsework was constructed upon which tracks were laid so that a carriage might move back and forth on the tracks. A second carriage was placed on the first one so that it would work perpendicular to the tracks. A four-post steel frame built of angles was suspended from the second carriage. This frame extended down to the required depth and upon one corner of it was attached the shaft which drove a five-foot circular saw operated by an electric motor. By taking proper precautions the piles were cut off to a practically true level.

Sometimes it is impossible or impractical to construct the falsework and carriage arrangement and it becomes necessary to work from a scow. Then the

shaft of the saw is held in a truly vertical position for the cut off. Remarkably accurate results have been obtained by this method. The main requirement being that the position of the saw be accurately checked.

Many times piles are used for temporary construction and have to be removed after they have served their purpose. Several methods are used depending upon the penetration of the pile and the skin-friction developed. If the penetration is not too large a pile may be pulled by the pile line of the pile-driver or by block and tackle. To reduce the initial resistance the pile should be tapped by the pile-hammer before pulling it. If water-jet equipment is available it may be used around the pile to loosen the earth and speed up the work or removal. In tide-water piles are sometimes fastened by a chain to a scow at low tide and the rising tide used to pull the pile. Care must be used to watch the action of the pile for if the resistance of the pile to being pulled is greater than the lifting power of the tide the scow may be sunk. Sometimes the pile-driver is used to pull the piles. This is accomplished by forming a sling under the hammer, running a rope up over the sheave wheel at the top of the rig and then down to

the pile where it is attached. As the hammer is carefully driven against the sling, the pile is pulled from the ground. The use of the water-jet materially helps here. If hard ground surrounds the pile it may be started by securely attaching a block of wood on each side of the pile and lifting by the aid of two screw-jacks.

Sometimes it is not necessary to remove a pile completely but only the part protruding above the ground. Two methods may then be used. Either the pile may be cut off as previously described or dynamite may be used. Innumerable methods of using dynamite have been developed each depending upon the difficulties encountered and the ingenuity of the man in charge.

One of the most commonly used methods has been to form a ring of telegraph wire, large enough to slip over the pile. Three sticks of dynamite are attached to this and each stick connected to a fuse long enough to reach a battery. The ring is then lowered to the proper elevation and the charge set off. The cut off is clean and the method is cheap and quick.

An improvement upon this method has been suggested by S. Standish of the Standish Engineering Corporation of Chicago, Illinois. His plan is to make a bundle

consisting of three to five sticks of dynamite and an equal number of iron bars of approximately the same length as the dynamite. These are bound together and the bundle lowered to the proper point and within three feet of the pile. The explosion will cut the pile off clean, the bars acting much like shrapnel.

This concludes the chapter on timber piling. It is impossible to quote costs which would prove of any value as too many factors enter into the cost of the placing of piles. Only a careful study of the conditions encountered on each particular job will indicate the probable cost.

CHAPTER V

Concrete Piles

Advantages of Concrete Piles Over Timber Piles

The difficulties encountered in the driving of timber piles, the very short life they have when subjected to alternate wetting and drying, and the necessity for protecting them from marine borers, prompted engineers to look for a substitute. These difficulties coupled with the increasing cost of timber and the decreasing cost of concrete led to experiments with the latter which eventually brought forth the concrete piles of today.

Hennelbique, in 1897, introduced reinforced-concrete piles in Europe, and in America, in 1904. Before the use of these piles in America, however, A. A. Raymond, after many experiments, developed what is known as the Raymond pile. He first used these piles in 1901 in a building foundation in Chicago. During the decade up to 1910 many other forms were developed. Some of these were patented while others were designed by engineers without the use of any patented method.

The types of piles developed were of two general

classes. One group were molded to a regular form, allowed to set and cure, and then handled and driven like timber piles. These are known as pre-molded piles. They were first developed in Europe and are practically the only type used there. The second group were what are known as cast-in-place piles. These are formed in place either with or without the use of casings. The Raymond pile was one of this type and because of its use in America before the introduction of pre-molded piles, it has gained a lead which the latter type of pile, with all its advantageous features, has never been able to overcome.

It has already been noted in the previous chapter that timber piles when used in ordinary foundations must be cut off below the ground-water level. This often causes extra excavation, heavier footings, and increased cost of material and labor. Even with these precautions, the ground-water level may be lowered due to changing conditions and the pile may become rotted. This may cause expensive changes in the foundation of a structure.

It must be admitted that concrete piles cost more per pile than timber piles but it must also be remembered that the life of concrete piles is

independent of the ground-water level. This eliminates the expensive excavations and heavy footings that are necessary with the use of timber piles. Furthermore, concrete piles have a greater bearing capacity and hence fewer are needed. Roughly, a timber may carry from ten to twenty tons while a concrete pile will sustain from twenty to fifty tons. Generally, concrete piles afford a saving if the tops can be placed more than three feet above the cut-off for the timber piles. Concrete piles also have the advantage that they may be bonded into the concrete grillage or cap by means of their own reinforcing steel and the pile and cap will act together as a monolithic structure.

Pre-molded Piles

Pre-molded piles may be divided into two classes depending on whether they are patented or not. All of them have certain general features. They are always reinforced with steel bars or rods in combination with lateral reinforcement in the form of wire hoops or spiral wrapping. The piles may be square, hexagonal, octagonal or round in cross-section. It is usually customary to chamfer the corners of square piles. With the exception of circular piles, they are

all usually tapered from butt to tip.

It is also necessary that certain factors be considered in the design of pre-molded piles. The steel reinforcement must be ample and so placed as to resist the stresses due to handling and driving the pile as well as to aid in resisting the stresses when the pile is in its final position. The longitudinal bars receive their greatest stresses when the pile is lifted from a horizontal position. Due to the position of the cable in handling the piles before driving, the latter must be able to resist flexure due to its own weight as well as the shock or impact due to its meeting obstacles. Some designers add as much as one hundred percent to the weight of a pile to provide for shock due to handling. If proper care is used in handling, experience has shown that fifty percent is a safe and more reasonable allowance.

The lateral reinforcing bars are of two types. One type consists of a continuous spiral wrapping which varies in pitch at the head and foot of the piles. The other is composed of separate wire hoops or binders either square or circular in shape and spaced at intervals which vary along the length of the pile. The lateral reinforcement is primarily used to

increase the resistance of the concrete to compression longitudinally. It also may aid in resisting diagonal tension. The total percentage of steel in the section area of a pile varies, depending upon the design, from 0.6 to 2.8 percent. Better practice dictates that the reinforcement be not less than 1 percent.

The area of the head must be sufficient to resist in direct compression the load which the pile is to support. The unit stresses to be used should be dependent upon the quality of the concrete, the percentage of reinforcement and its arrangement, and the character of the loading. If the pile is tapered the critical section for direct compression is not at the butt but rather at some distance below the ground surface. Further, when a pile is to act as a column it must be designed to resist column action. To allow for hard driving of a concrete pile, additional section area must be provided or extra cement must be added to the batch of concrete which comprises the head of the pile.

These comprise the points of similarity of all pre-molded piles. To attempt to describe the innumerable types of unpatented piles would require an accounting of all the many varieties developed to meet special conditions. Suffice to say that they all

meet the requirements just stated and that they are in the main very successful. One noteworthy example of unpatented piles were some driven at the Port of Manilla. They were twenty four inches square and one hundred and ten feet long. They were of necessity driven by a special pile driver. When a test load of one hundred tons was applied a settlement of twenty seven sixty-fourths of an inch was observed. The application of an additional one hundred tons caused an additional settlement of twenty seven sixty-fourth of an inch. Twenty one sixty-fourths of an inch of this settlement was recovered when the loads were removed.

Corrugated Pre-molded Pile

There are several well-known types of patented piles. The first of these to be described is the corrugated pile which is hexagonal or octagonal in cross-section. It is constructed with approximately semi-cylindrical grooves on each face and with a round hole along the axis. Both the hole and the pile is tapered from butt to tip and the pile is reinforced with electrically welded wire fabric. The hole in the pile is used to permit a water-jet to pass through it, and is tapered so as not to decrease the area of the concrete at the tip as

well as to permit the plug used to cast the hole to be readily withdrawn. The corrugations are added to increase the surface of the pile so as to produce greater skin friction. They also furnish outlets for the escaping water from the jet, thus reducing friction during driving. The corrugations, however, are not extended along the head or the tip so as to avoid reducing the cross-sectional area at those points.

Cummings Pre-molded Pile

The second type of pile to be discussed is the Cummings concrete pile. It is an octagonal pile about fourteen inches in diameter at the head and about nine inches at the tip. The reinforcing consists of longitudinal rods held in position at approximately five foot intervals by flat rings of one quarter inch metal and a helical wrapping or wire which performs the function of hooping and also resists diagonal tension. The foot of the pile is protected by a conical sheet metal point protector. At the head there is a series of horizontal bands closely spaced to give special lateral support to the concrete when being driven. Each of these steel bands in the head contains a horizontal spiral within

it to further reinforce the head. It has been claimed that this reinforcing is so resistant that the head of a Cummings pile has never been broken.

Chenoweth Pre-molded Pile

The Chenoweth concrete pile is a third type of patented pre-molded pile. It is known as a rolled pile. The machinery used consists of a moving platform, a number of rolls and a mechanism for turning the tubular mandrel about which the pile is formed. The reinforcement consists of longitudinal bars wired to strips of wire mesh. This mat arrangement is laid on the platform and then ends of the wire mesh are attached by wire clips to the mandrel. The concrete is then spread over the mesh and by simultaneously moving the platform and turning the mandrel, the pile is coiled and rolled into a cylindrical form which is compacted by means of special rollers. At the same time, the pile is wound every six inches during the process of rolling. After the rolling the central tube is withdrawn and the pile is moved to a drying table. Here a concrete point, shaped like the frustum of a cone and the head of the pile, is added. It is necessary

to use a very dry mix in making these piles, otherwise the cement will be squeezed out with the water when the rolling takes place.

Hennebique Pre-molded Pile

The fourth and last type of pre-molded patented pile to be described is the Hennebique pile. This is usually constructed as a square pile without taper. The four edges are slightly bevelled and the longitudinal reinforcing rods are placed near them. These rods are bound together by wire collars or binders at short intervals. The standard type of Hennebique pile has a cast-steel shoe forming an integral part of the pile.

Before leaving the subject of pre-molded piles, a few words must be written regarding the curing of these piles. The practice varies, but in general the forms are removed in from twelve to eighteen hours after which they are directly exposed to live steam for three or more days or until sufficiently set to be handled by a derrick. They are finally placed in the storage yard and left there for at least thirty days before being driven.

Cast-in-place Piles

While no record is available, it is highly probable that cast-in-place piles were first suggested by what are known as sand piles. If loamy soils are confined from moving laterally by the surrounding earth, they can be made efficient by the use of sand piles. These are formed by excavating to the proper depth and then driving wooden piles. The wooden piles are then pulled leaving holes which are filled with clear sand thoroughly tamped.

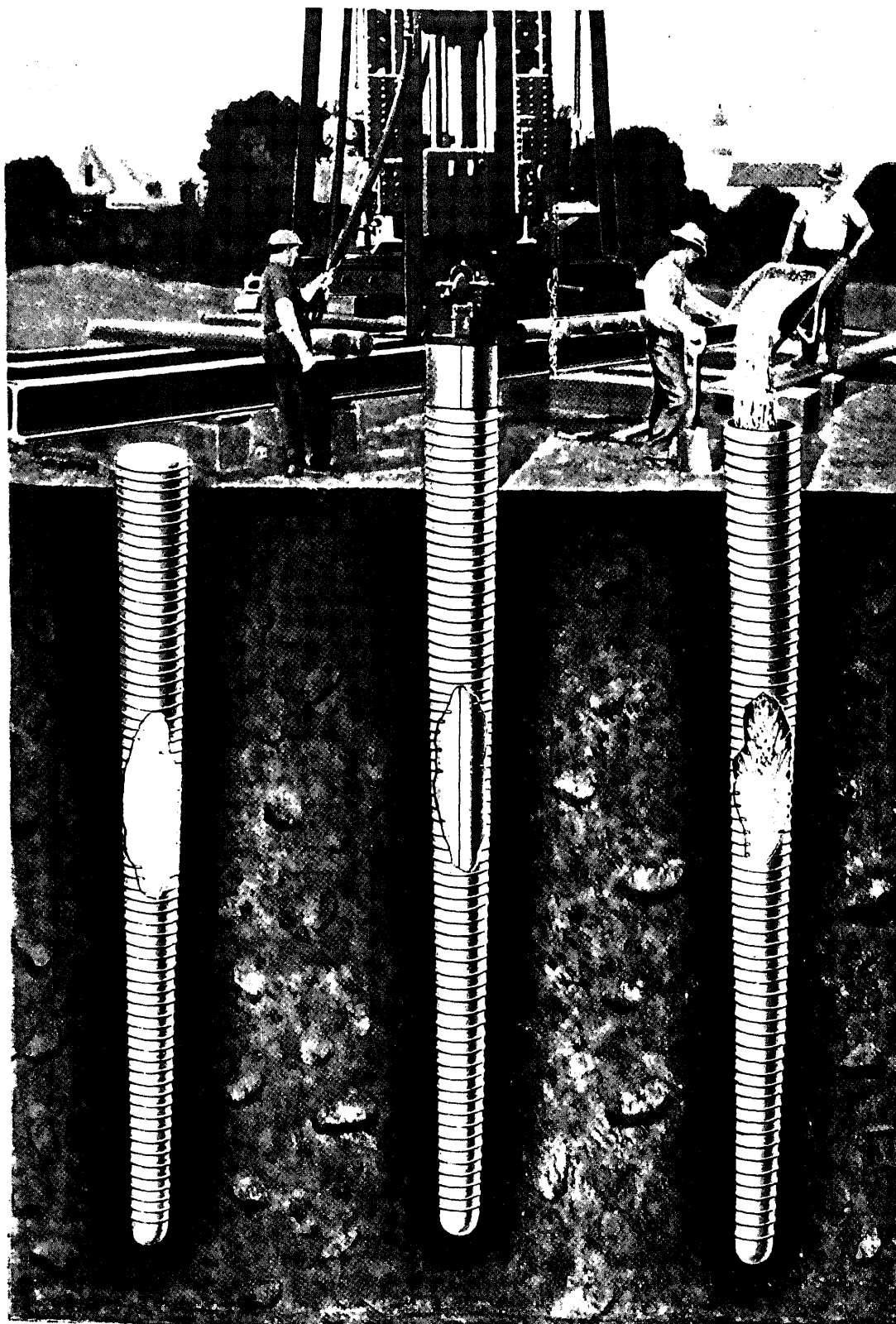
The driving of the wooden pile compresses the soil and the sand holds it in place. After the sand has been placed a test load should be applied to determine the bearing capacity of the foundation. Sometimes a conical iron weight may be used in place of the wooden pile. Holes three feet in diameter and fifty feet deep have been formed in this manner. The use of concrete instead of sand opened greater fields for the concrete pile until today it is a very essential part of foundation work.

The Raymond Pile

The pile invented by A. A. Raymond was formed

by driving a tapering sheet steel shell to refusal by means of a collapsible steel core, by withdrawing the core, and then, by filling the shell with concrete. The shell is spirally reinforced with one quarter inch wire and of sufficient thickness to retain its shape after the core is withdrawn. The shell not only holds the earth in position and forms a mold for the concrete but also prevents earth and water from mixing with the concrete. The shell is made in varying diameters, is of conical sections about eight feet long, to enable of easy shipment, and overlaps tightly in telescopic fashion. The shells are easily slipped over the core and the bottom is closed by a section called a boot. The boot is made of pressed steel to withstand the cutting effect of stone and other obstacles encountered in driving the core.

After the driving of the shell and the withdrawing of the core, it is a comparatively simple operation to inspect the inside of the shell. This may be done by reflecting, with a mirror, sunlight or a bright artificial light into the shell, or by lowering a lantern on a cord into it. The purpose of the inspection is to locate any breaks which are admitting water. If leaks exist because of the cutting of the shell, another shell may be easily driven inside of the first one.



Raymond Standard Pile

This may be inspected also and it will usually be found that the leak has been closed. It is only occasionally that the driving of two shells is necessary. The Raymond people claim the ability to inspect the form before the placing of the concrete as one of the outstanding features of their piles.

After the shell has been approved as watertight, the concrete is deposited in it. Either a 1-2-4 mixture using three quarter inch stones or a 1-3-5 mixture using one and one-quarter inch stones is used. The mix is rather wet and as longitudinal reinforcement is seldom used, the concrete may be readily placed in the shells without voids. Bars about three to four feet long are sometimes placed in the concrete at the top of the pile to assist in bonding the pile to the footing. The shell is usually filled with concrete to a point about four inches above the approximate cut-off. Then, after the concrete has been allowed to set for a week, the precise cut-off levels are established and the excessive concrete removed with a cold chisel.

The manufacturers of the Raymond pile also claim two other advantages for their pile: The first is the ability of the steel core to be driven through very hard material which cannot be penetrated by any other

kind of pile at a reasonable cost, the bearing capacity of every pile being determined by the average penetration of the steel core under the final blows of the hammer. The second advantage claimed is that the taper employed on Raymond piles greatly increases the bearing capacity over the straight-sided or nearly straight type of pile. This point has been much debated by engineers. The Raymond Concrete Pile Company made a test of straight piles and of their tapered piles. This test was supervised by a prominent engineer who was an ardent advocate of the straight-sided pile. Following is a report of the tests as published in the Raymond catalog: "Two piles each twenty feet long were driven within a few feet of each other. One core, "Core A", was six inches in diameter at the point and twenty inches in diameter at the top, while the other core, "Core C", was thirteen inches in diameter at the point and eighteen inches in diameter at the top. "Core C", with the large point, drove fairly hard from the start, and required nine hundred and forty-four blows of the steam hammer to secure a penetration of twenty feet. "Core A", with the smaller point, started easily and required only eight hundred and seventy-five blows to secure twenty feet of penetration. At the

expiration of about a month, both piles were loaded and carefully tested. The test showed that the pile with the greater taper carried a proportionately greater load, showing no appreciable settlement up to sixty-five tons, whereas the straight pile showed the same settlement with a load slightly more than twenty tons. This result is particularly interesting, in view of the fact that the engineer who made the tests did so for the specific purpose of demonstrating that a straight pile had a greater carrying capacity than a tapered pile. The results of these tests have been repeatedly confirmed in the course of our experience."

It is not to be assumed that the Raymond Company advocate tapered piles for all conditions. They do claim, however, that they are more efficient in soils where surface friction is to be developed. They do advocate the straight pile when it is necessary to penetrate to rock or hard pan through very soft or semi-fluid material. Such piles are considered solely as columns and as such require a very slight taper and a large point bearing area.

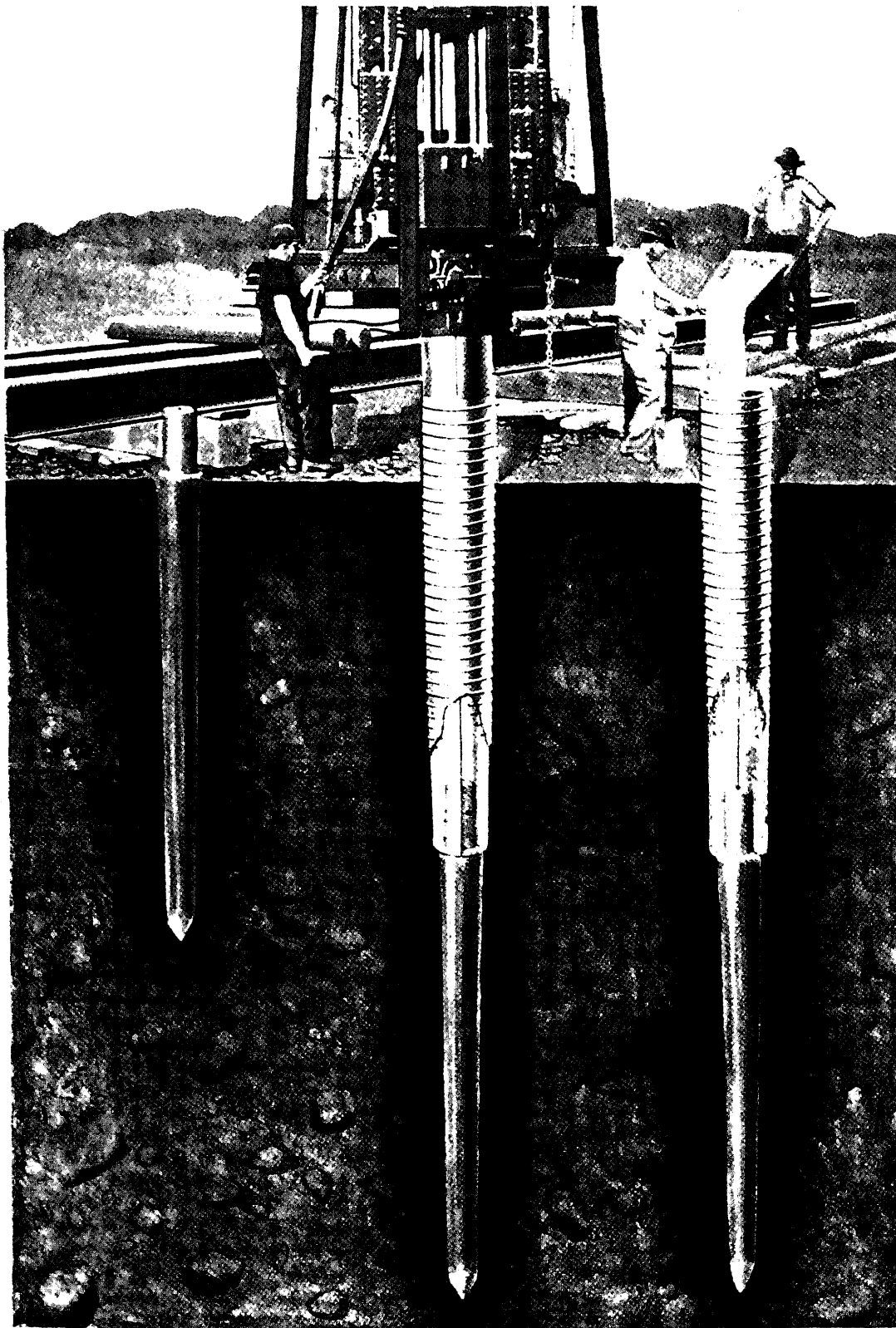
Recently the author had the privilege of observing tests made by the Raymond Company of a new type of shell. This shell was constructed of smooth sheet steel not

spirally reinforced. The sections were only about three feet in length and each was lined with about one inch of neat cement. The sections were so arranged that the lower one overlapped the one above it. This new type of shell was intended to be used when it was necessary to drive through ground containing many boulders. The driving of the ordinary steel shell in such ground usually results in its being torn and necessitates the re-driving of one or more additional shells inside the first. Upon making tests, however, it was found that it was faster to drive the second or third shell than to handle the neat-cement-lined shells. The latter were much heavier even for the shorter section and required great care in handling so as not to break the lining. Thus, it took much longer to place them on the core. In addition each section had to be held in place on the core while the one below it was pulled into position. This is not necessary with the ordinary steel shell as it can be pulled up tight and is held in place by friction. In addition it was found upon driving and withdrawing the core that certain sections of the lining had been jarred loose due to the vibrations in driving. This type of shell may be developed at a future date but at present it is quite impractical.

The Raymond Concrete Pile Company also drive what are known as composite piles. These are used where a long pile is necessary and the permanent water level is within a reasonable distance below the surface of the ground. In such cases wood is substituted for concrete in that portion of the pile which is permanently submerged. The main difficulty has been the development of joint of sufficient strength and rigidity, together with a method that will insure uniform and satisfactory results. This has required considerable thought and ingenuity and a long series of experiments.

The Raymond catalog lists the steps in the placing of a composite pile as follows:

- "1. Driving the wood pile to ground level.
2. Fitting on to the top of the wood pile the collapsible mandrel or follower encased in a spirally reinforced steel shell.
3. Driving the combined unit to its final penetration.
4. Withdrawing the mandrel, leaving the steel shell in the ground to protect and serve as a mold for the concrete at the joint.



Raymond Composite Pile

5. Filling this shell with concrete."

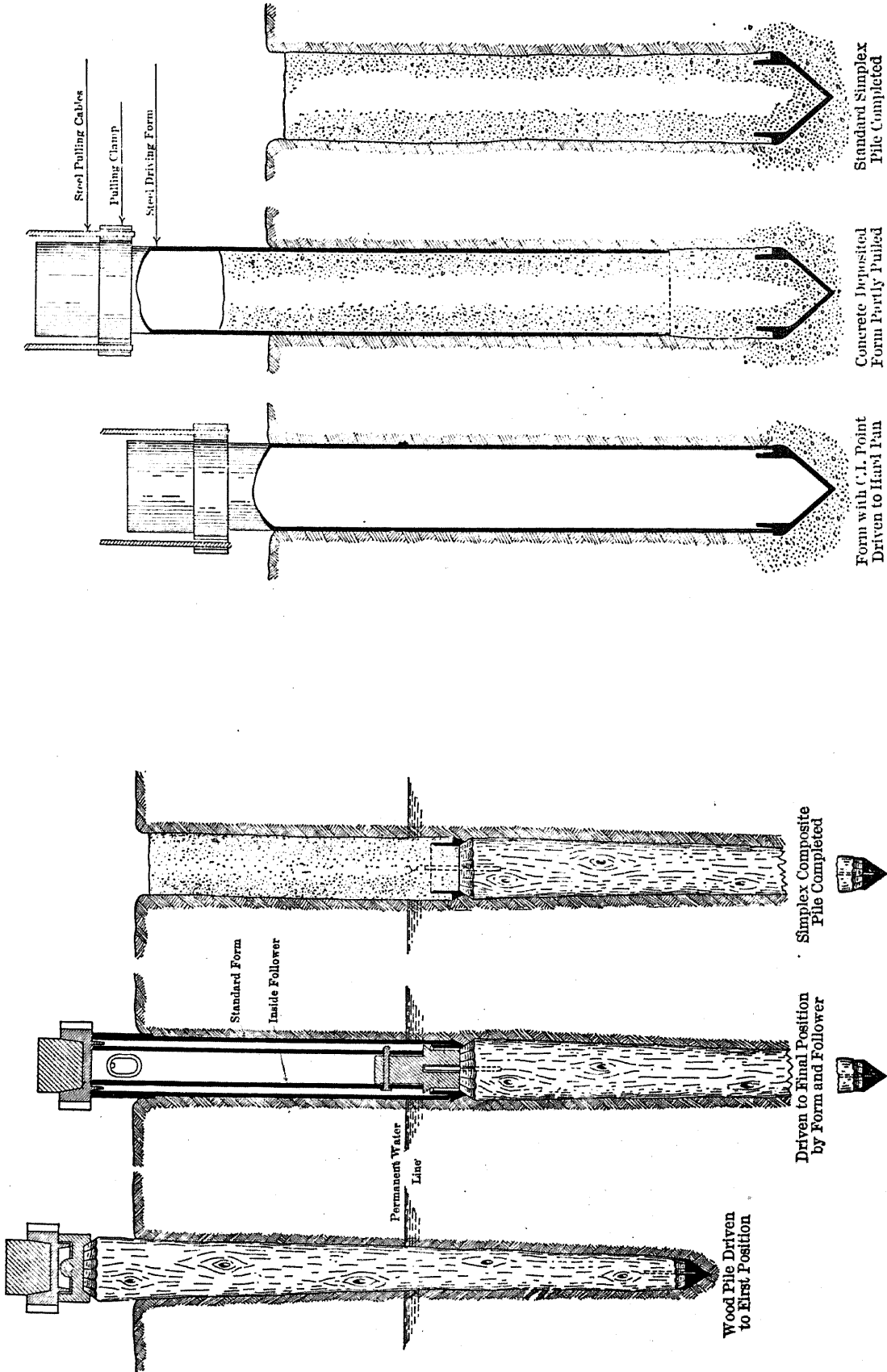
"Before driving the wood pile, it is provided with a tenon approximately nine and one-half inches in diameter and eighteen inches long. By means of a special machine, the tenon is accurately shaped and cut square on the end. This provides perfect contact between the follower and the pile thereby avoiding any brooming or damage to the tenon during the driving. This tenon fits closely the cylindrical opening at the end of the Raymond core. A hollow boot closely encases the bottom of the steel shell on the core, and at the same time, fits tightly over the tenon of the wood pile."

Before placing the wood pile in the leads, "a hollow steel socket is embedded in the center of the tenon and secured by a seven-eighths inch steel pin extending transversely through the tenon and socket." The socket is provided with a heavy internal thread into which the threaded end of a deformed bar is screwed after the driving has been completed and the core removed. This bar provides reinforcement in the concrete and also acts as a lock between the wood and the concrete.

Simplex Piles

The second type of cast-in-place pile which is to be discussed is the Simplex pile. This was first introduced in 1903. The Simplex piles may be divided into four classes: the standard, the molded, the shell, and the composite.

The standard Simplex pile is formed in the following manner: A conical cast-iron point which is fitted loosely to the lower end of a sixteen inch diameter, three-quarter inch thick steel tube or form, is driven to suitable bearing. This is assumed to compress the soil. When the proper depth is reached soft concrete is deposited inside the tube by means of a drop bucket until the surface of the concrete reaches the desired elevation. Then the steel shell is withdrawn and the soft concrete flows laterally by its own weight thereby filling the hole. The concrete is made of a fairly wet 1-2-4 mixture using three quarter inch stone or gravel. It is possible to use reinforcement when desired. The main objections to this method are that the pipe must be extra heavy and the pile-driver must have extra strength equipment to pull out the pile. Furthermore, a new cast-iron point is required for



Simplex Standard Pile

Simplex Composite Pile

each pile as they are all left in the ground.

The Simplex molded pile is used in very soft soils. The shell and point are driven as described in the standard pile. Then a small amount of concrete is placed in the bottom of the tube and a molded concrete pile is lowered into the freshly deposited grout. The tube is next withdrawn and a thin grout is poured between the pile and the tube during withdrawal. The molded piles are thirteen inches in diameter and the metal point which is left in place is seventeen inches in diameter.

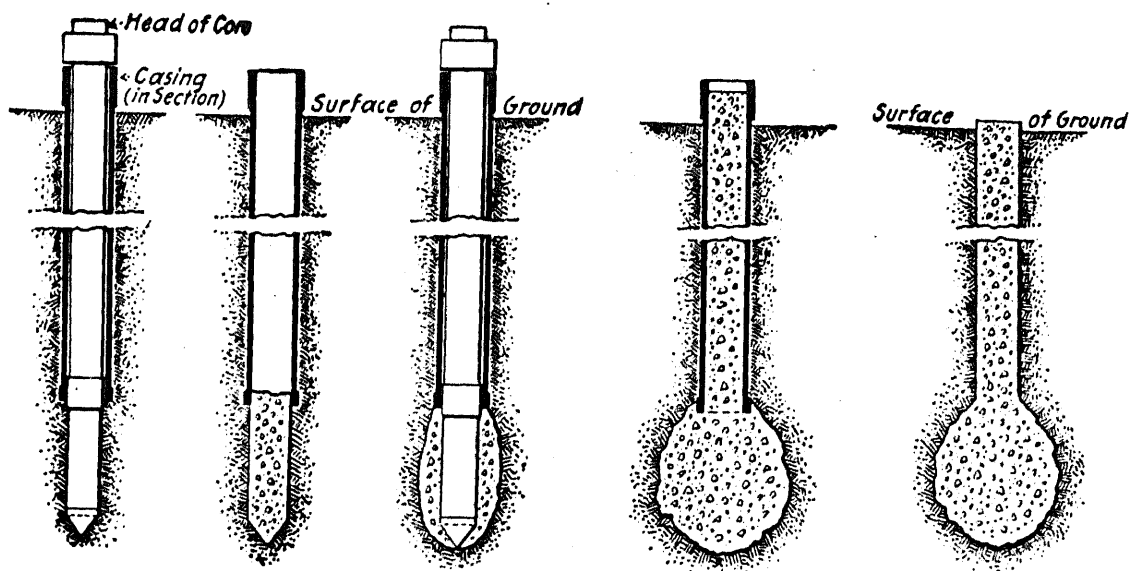
The third class of Simplex pile mentioned was the shell pile. For this construction the cast-iron point is driven as before. After the driving has been completed, a thin steel shell, slightly smaller in diameter than the inside diameter of the tube, is lowered until it rests on the cast-iron point. This shell is then filled with concrete and the driving tube withdrawn.

The reasons for driving a Simplex composite pile are the same as for driving a Raymond composite pile and the procedure is, in general, the same. The wooden pile of the proper length is driven in the usual manner. When it is down to a convenient level, the top is prepared for a heavy cast-iron ring and

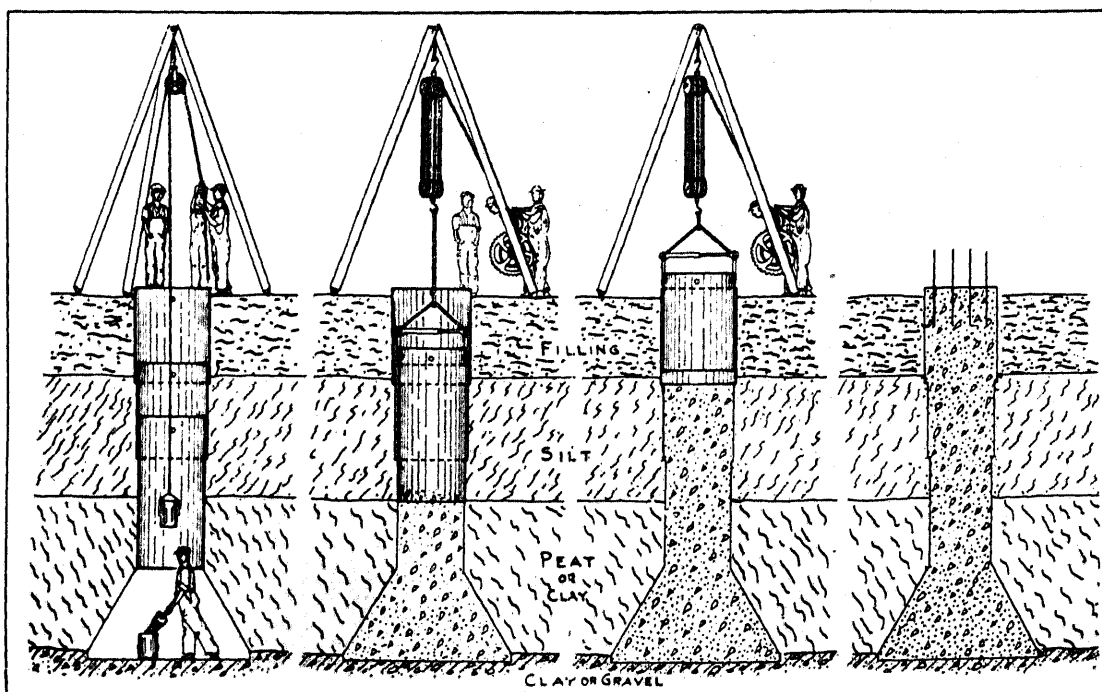
dowel pin. The follower is then placed on top of the pile and the steel tube is placed on the ring. The combination is then driven until the top of the wooden pile is well below the permanent surface of the ground water. The follower is then removed and the steel form filled with concrete and withdrawn. In stiff, non-water-bearing, or clay soils, where the ground has no tendency to flow, the Simplex standard pile is claimed to be the cheapest method of installing concrete piles.

Pedestal or Mac Arthur Pile

The pedestal or Mac Arthur pile was invented by Hunley Abbott and may be considered as a modified Simplex pile. The Mac Arthur pile is formed by first driving the steel casing and core to the proper depth. The casing is a steel pipe sixteen inches in diameter and three eights of an inch thick with outside reinforcing bands at top and bottom. The core is a smaller and longer pipe with a cast-steel point and an enlarged cast-steel head. The core fits inside the casing, engaging the top of the casing with the enlarged head and the point of the core projects some four or five feet below the bottom of the casing. After the core and casing have been driven to the



The Mac Arthur or Pedestal Pile



The Gow Pile

desired depth, the core is withdrawn and a batch of concrete dropped to the bottom of the hole. The core is then driven into this concrete forcing it laterally into the soil. This process is repeated until a footing of sufficient size is secured. Finally the core is removed and the casing filled with concrete to the top when the casing is slowly withdrawn. The concrete thus flows laterally and completely fills the hole. The original top surface of the concrete will sink from three to six feet as the casing tube is withdrawn.

The bulge at the bottom of the pile is assumed to greatly increase its supporting capacity. This of course depends upon the nature of the ground and its homogeneity. If the earth for any reason should resist unequally on opposite sides of the hole, the resulting form of the base would make its action eccentric.

The Gow or Palmer Pile

The Gow or Palmer pile is to be the fourth and last type of cast-in-place concrete pile to be considered. This pile is formed by sinking a steel casing or pipe into the earth by means of a water jet.

The casing consists of a series of short steel cylinders varying slightly in diameter so as to telescope through one another, the largest size being used as a starter. The others are inserted in turn through those already in place. The material is excavated by laborers and raised to the surface in buckets. When the casing has reached the required depth it is withdrawn a few feet and a lozenge-shaped cutter lowered to the bottom of the tube. By turning this tool and opening it gradually the bottom of the pile assumes the form of a truncated cone with its large base at the bottom. The casing and chamber are then cleaned out, filled with concrete and tamped, the casing being gradually withdrawn as the concrete fills the hole. Thus a pile having a large circular flat bottom is formed.

Precautions in Driving Cast-in-place Piles

In concluding this chapter a few words should be included regarding the precautions to be taken in placing cast-in-place concrete piles and some of the objections which have not been mentioned as yet. Care must be taken in the placing of the concrete in the shells or casings. Wet concrete thoroughly stirred with a rod moving up and down will obviate a great deal of the porous structure of the concrete.

Where casings are left in the ground, and several casings adjacent to each other are driven before any concreting is done, each casing should be inspected to see that it has not been injured by the compressing of the soil due to the driving of casings near by.

Authorities on piles and pile-driving generally agree that when casings are to be withdrawn, several should be driven before any are filled with concrete. They contend that otherwise green concrete in a pile may have its section materially weakened by the earth being forced into it by the adjacent casing. This recommendation, if followed, would mean that with certain types of piles it would be necessary to have more than one shell or casing so that several might be in the ground at any one time.

Occasionally concrete piles which have been formed by casings which are withdrawn have failed to set because of certain chemical constituents in the ground water. In still other cases, piles have had their section areas reduced anywhere from twenty to one hundred percent. Even if a shell is used and left in the ground, it must be remembered that it is highly probable that the

green concrete will be injured by the driving of adjacent piles. For this reason the practice of driving adjacent shells before filling any with concrete is recommended.

It must be understood that all of these objections do not necessarily apply to any one type of pile but that for given conditions some types are more satisfactory and cheaper than others. It again depends upon the old question of the type of ground to be encountered.

CHAPTER VI

Metal and Sheet Piles

Tubular Piles

The first metal piles were introduced in 1901 and consisted of a heavy steel pile filled with either plain or reinforced concrete. This type of pile was suggested by the use of steel pipe for underpinning the foundations of buildings. The piles are, in general, about twelve inches in diameter and three eighths of an inch thick but may be procured in any diameter of which pipe and well casing are manufactured. The ends are machined so as to be perpendicular to the axis of the pile. This insures a true alignment of the pile and a uniform bearing of the metal.

The pile of this type is made in sections, each section being provided with an inside sleeve. The foot of the pile may or may not be protected in driving by a hollow conical shoe of cast iron or steel. This depends upon the soil through which the pile must be driven. The shoes are usually provided with a hole so that a water-jet may be used if desired. The pipe is driven like

an ordinary pile, the top being protected by a cap.

After the driving has been completed, the pipe is filled with concrete. When reinforcing is included, the usual practice is to use four two-inch square rods placed vertically in the pile. If the pile is driven without any shoe, it is, of course, necessary to remove the material inside of the pipe before filling the pipe with concrete. The earth may be removed by an air or water-jet or by using a small orange-peel bucket.

The trade name for a casing of this type is the Simmons sectional concrete pile casing. Through experience it has been determined that if the earth surrounding the piles is undisturbed, they will last for many years. The casings, however, are subject to rapid rusting when exposed to the action of air or water. It is also possible that the action of electrolysis may damage the casing. All of these conditions must be determined before hand, if possible, and the necessary precautions taken to protect the casing.

Piles of this type have been driven to a depth of eighty five feet. It must be remembered, though, that these piles act as columns and must

be designed for such conditions.

Recently attempts have been made to use heavy H sections as piles. The process is too new and the results too inadequate for any detailed report to be given at this time. It is possible that at a later date they may be developed to the stage where they will displace some of the types used at present.

Screw and Disk Piles

Screw piles were first used in 1838. They consist of a broad-bladed screw attached to the foot of the pile. The blade is usually constructed of cast-iron or wrought metal while the stem is constructed of wood, cast-iron or steel. The diameter of the screw is from two to eight times that of the stem and has a pitch of from one sixth to one third the diameter of the screw. The pitch is always dependent upon the type of soil in which the piles are to be placed. In general there are also four types of points available for screw piles. The gimlet point is mainly used for gravel; the blunt one for sand; the hollow, conical point for use with a water-jet in gravel or sand; and the serrated point for soft rock or coral.

Screw piles are put in place by simply

screwing them into the ground by means of hand or power levers. This of course subjects the stem and blade of the pile to torsional stresses and these as well as the connections must be carefully designed so as not to fail while the pile is being placed. There are cases on record where the frictional resistance has been so great as to cause the piles to twist off. It has been also discovered, however, that by discharging water against the upper surface of the screw blade, the friction can be reduced so that the sinking of the piles may be accomplished without difficulty. It further has been determined that, by using a water-jet, only about one tenth as much power was needed to screw the piles into the ground.

The load which a screw pile will support depends primarily on the bearing capacity of the soil at the depth of the screw. The following formula has been developed for the determination of the bearing capacity of screw piles.

$$p_o = h w \left(\frac{1 + \sin \phi}{1 - \sin \phi} \right)^2$$

h = depth of the screw below the surface of the soil, measured in feet.

w = weight of the soil in pounds per cubic foot.

p_0 = the bearing capacity of the soil in pounds per square foot at the depth of "h".

ϕ = angle of response of the soil.

Thus by determining the bearing capacity of the soil at the depth of the screw, and calculating the area of the screw, the supporting capacity of each pile may be determined.

Disk piles were developed after the screw piles and were not used until 1856. These consist, as the name implies, of a large disk attached to the foot of the pile. They have been used, principally in ocean piers and wharves, where the total penetration is not large and is subject to more or less variation.

The disk is a casting which is composed of a horizontal circular plate stiffened by a number of radial ribs. The disk is connected to a pipe-like casing, either by bolting to a flange on the pipe or by fitting inside the pipe and being bolted in that position. A hole is provided at the bottom of the disk so as to permit the use of a water-jet through it. The disk piles are placed mainly by use of the jet but when some soil is encountered which it is not easy to displace, the pile may be

rotated to cause the ribs to act as cutters.

The sizes of the disks and stem vary, depending upon the bearing surface desired. The diameter of the disks range from one and three-quarters to four feet, the diameter of the cast-iron pipe from eight to fourteen inches and that of steel pipe from six to ten inches.

Both the screw and disk pile are unsuitable for deep foundations where the overlying material is soft or liable to scour, since it is impossible to provide bracing of the piles below the surface. For this reason they do not play a very important part in building foundations.

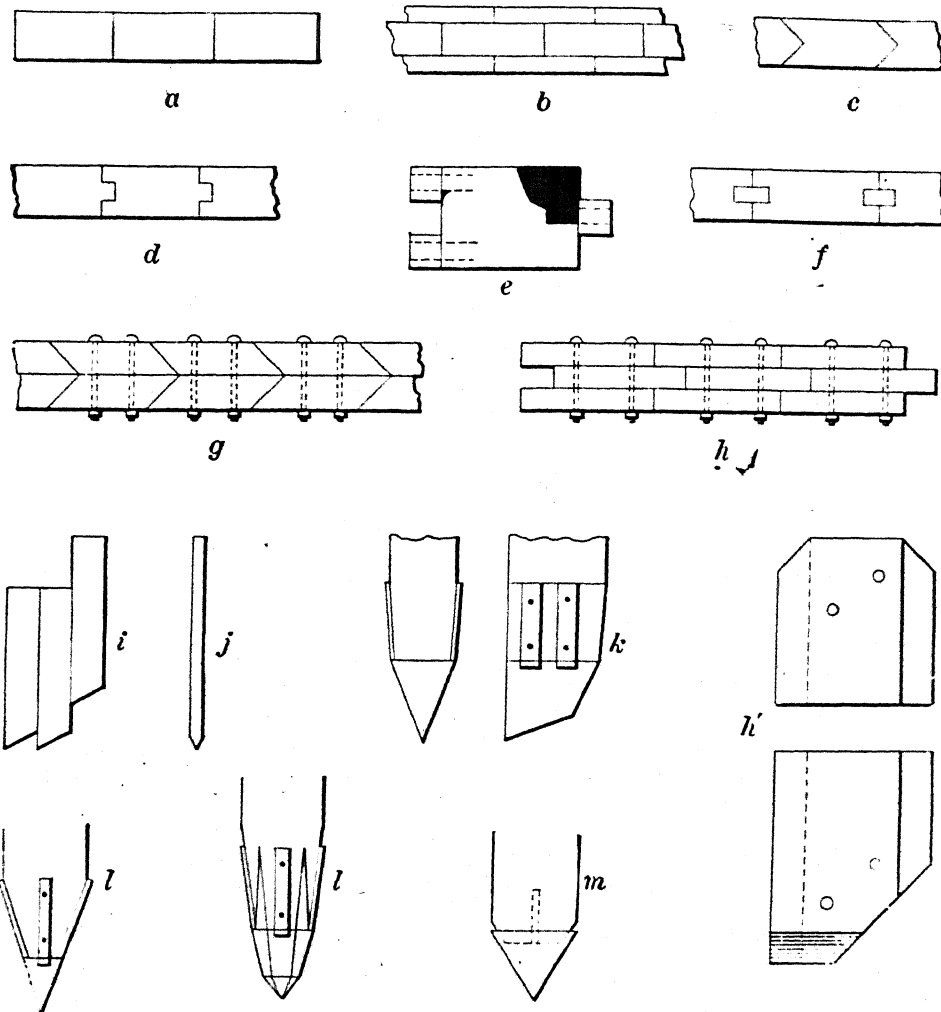
Sheet Piling

Sheet piling is used to retain the sides of excavations, to prevent the lateral flow of soft earth, and in the construction of cofferdams. It is made of wood, steel, concrete or reinforced concrete, according to the purpose for which it is to be used.

In retaining the sides of excavations the sheet piling may or may not need to be driven up tightly, depending upon the type of soil to be supported. Some soil only needs supports every ten

or fifteen feet while with soft earth, which will flow laterally, the piling needs to be driven up tightly to prevent the soil from seeping through the joints. In the construction of cofferdams the problem is even more difficult. They must be water-tight so that when the water is pumped out of the enclosure, none will leak through the joints of the piling. Sometimes it is necessary to drive a second row of sheet piling, about three feet from the first, and to fill the space between the rows with a mixture of gravel and clay in order to make the cofferdam water-tight. If the leaks are not bad they possibly may be stopped by throwing bran, manure, or other fine material into the stream so it will be drawn into the leaks in the dam.

There are many forms of timber sheet piling, the more general types of which are shown on the following page. Fig. "a" shows the type constructed of planks of considerable thickness. The planks are usually from three to four inches thick and from ten to twelve inches wide. In general the points of timber sheet piling are the same. Fig. "i" shows the points sharpened so that the piling will drive together tightly while Fig. "j" shows the pointing so that the piling drive straight and easy. The



Forms of Timber Sheet Piling

same principle is embodied in the patented metal point, shown in Fig. "k", which is used when driving through coarse gravel. Flat planks are also used as shown in Fig. "b". In this case a second and third row is driven and these are used to close the cracks in the main row. The extra rows may be made of thinner plank so long as it may be driven. Fig. "c" shows the V-shaped tongue and groove piling. The ordinary tongue and groove piling is shown in Fig. "d" but a type which is more frequently used is that in Fig. "e". In this type two pieces of wood forming the groove and one piece forming the tongue are spiked to the main piece of timber with six inch spikes which are driven so as to slope upward. The piling shown in Fig. "f" is seldom used. It is formed by cutting grooves in each edge of the piling and then driving a key into these grooves after the piles are in place. The difficulty lies in getting the grooves to exactly match.

Sheet piling formed of two or more planks bolted together is being extensively used. One type is formed, as shown in Fig. "g", by sawing bevelled edges on two planks and then bolting them together, thus constructing sheet piling similar to

that shown in Fig. "c". This forms a pile which is easy to drive because of its size and which requires supports in the shape of waling-pieces. Fig. "h" shows the Wakefield patented sheet-piling and Fig. "h" shows the way in which it is pointed. It is constructed of three layers of plank from one to four inches thick depending upon the pressure to be sustained. The center plank must be sized so as to keep the tongue and groove uniform. The planks are bolted together with six bolts for each length of from sixteen to twenty feet and two extra bolts are added near each end. For long piles, spikes should be driven between the bolts. The bolts vary in diameter from three eighths of an inch for one inch planks to three quarters of an inch for four inch planks. Figures "l" and "m" show the types of metal points used on the ordinary round or square piles. Fig. "l" shows a patented type of shoe.

Wooden sheet piling may be pulled and used a second time but the expense of repairing them is usually large and the total loss considerable. This, coupled with the cost of pulling them, often prompts contractors to leave the piling in the ground where practical.

Steel sheet-piling is constructed in many

patented forms, too numerous to describe here.

The steel sheet-piling is constructed so that water tight joints are formed and at the same time is strong enough to withstand the earth or water pressure against it. Steel sheet-piling possesses the advantage over timber piling that, in most cases, it can be withdrawn and used many times.

Concrete and reinforced concrete sheet piling are usually rectangular and are molded and allowed to harden before being driven. They are cast with tongues and grooves or are provided with some form of metal interlocking joints. This type of piling is used to retain earth and is left in place. It has been found especially suitable for the construction of sea walls. Precast concrete sheet piles with tongue and groove joints were used to protect "made" ground in Lincoln Park, Chicago, from the attacks of Lake Michigan and were found to be most satisfactory.

All forms of sheet piling are driven much the same as are ordinary piles. The only suggestion being that rapid blows driven by a hammer having a short drop are more effective and cause the least damage to the piling. This applies especially to piles of considerable length. Wooden and steel sheet piling, four to five feet in length, can be driven with mauls,

while slightly longer piling may be driven by means of the pneumatic type of hammer already mentioned in Chapter II. The water-jet has also been used with success and is very efficient in sandy soils.

No attempt has been made in this chapter to describe the types of cofferdams and the methods of bracing them. That is a study in itself involving a consideration of the type of soil and the construction problems to be met.

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