DESIGN, INSTALLATION AND TESTING OF NEARSHORE PILES

[1]Frank Rausche, Ph.D., P.E.

ABSTRACT

Driven piles are a very common foundation solution in nearshore environments. In fact, historically speaking, pile driving was the only means of making use of nearshore areas. Nearshore areas are often flooded or permanently covered with water. Construction therefore requires special considerations. For example, material selection, corrosion potential and prevention, material handling, construction control, preconstruction and construction control testing, pollution prevention, safety concerns and subsoil conditions, among other items, differ from those on land sites. This paper addresses a few areas of concern and gives examples of design details and construction aspects of several interesting projects which the author has visited over the years.

INTRODUCTION

The Definition of Nearshore

It may be theorized that the oldest piled foundations were built in areas where either flooding from nearby oceans or lakes occurred frequently or where it was desirable to live above water because of many hygiene and safety related concerns. The author of this paper grew up in an area near Lake Constance which forms the border between Switzerland and Germany. Archeological digs uncovered well preserved piles which were dated between 4000 to 2000 BC. Today, the *Pfahlbaumuseum*, or piled building museum in southern Germany, has rebuilt and displayed near the shore of Lake Constance a replica of a complete historic village on piles (Figure 1).

To most people, the term nearshore probably means an area which is at least partially covered by shallow saltwater. It is probably also acceptable to include freshwater locations such as the Great Lakes in this definition. This means that nearshore construction sites include any type of harbor work such as piers, wharfs, bulkheads, flood gates, seawalls and artificial islands. Bridges are also often built over bays or connecting islands to land, thereby requiring foundations in brackish water or saltwater. Waterfront buildings, both residential and industrial, may be built on stilts over the water and one might even call floating bridges or buildings "nearshore structures". With this definition, it is probable that more than 50% of pile driving projects are constructed near shore.

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[1]Goble Rausche Likins and Associates, Inc., Cleveland, Ohio

Water depths may be zero at low tide and may be 30 m or more where the shore falls off steeply. Distinguishing nearshore from offshore construction is not always easy.

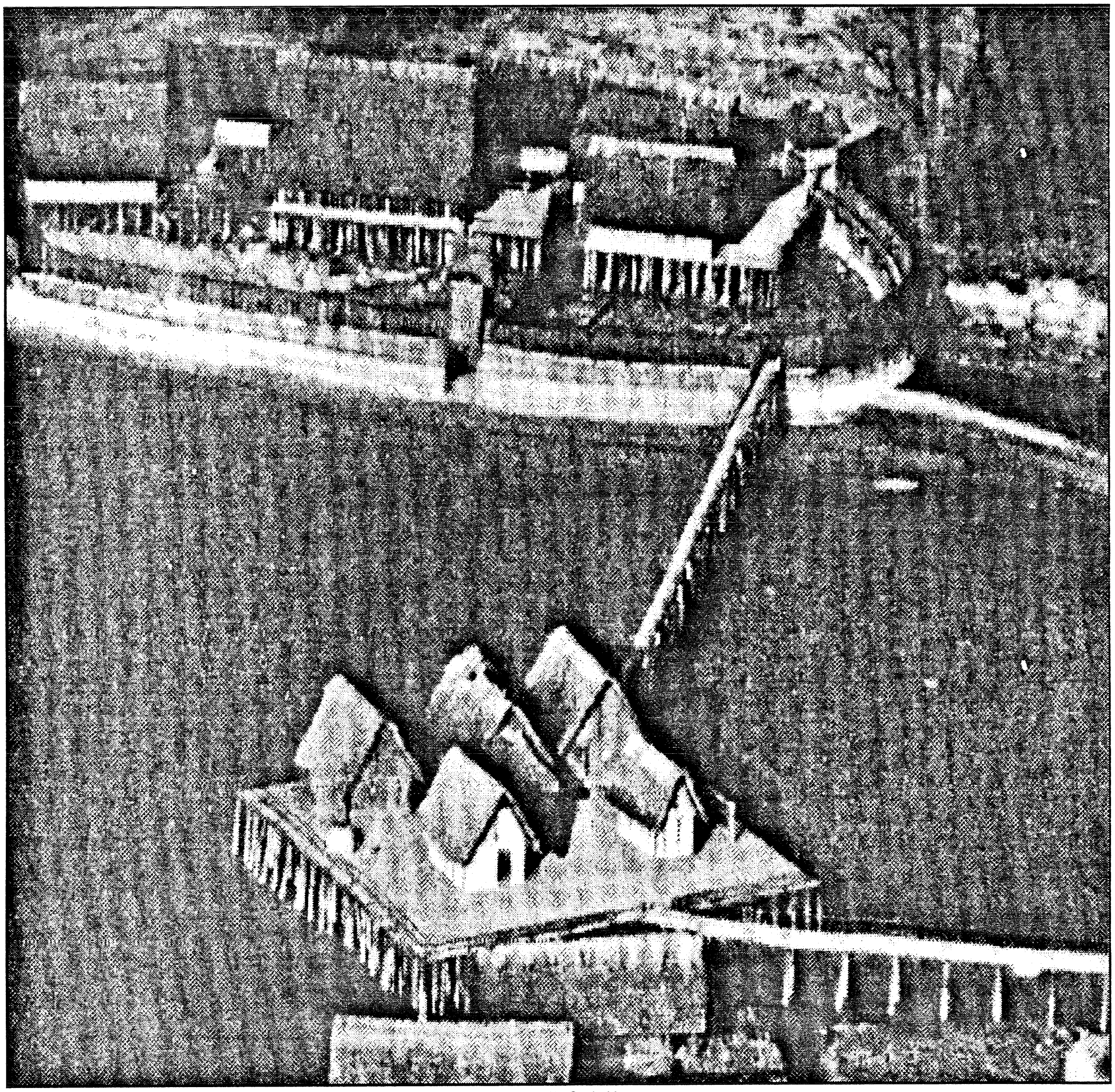

Figure 1. The Pfahlbaumuseum

This paper is a summary of experiences which the author has made on a variety of construction sites. Visits to these sites were not selectively done but rather "happened" relatively randomly. Therefore, the situations described here do not necessarily cover the whole range of possible designs, installation or testing procedures for nearshore piles. In other words, a complete treatment of the nearshore piling technology is not given in this paper.

Special Considerations of Nearshore Construction

Nearshore construction offers both challenges and opportunities for piling professionals. The challenge is probably the corrosive environment, the lack of a firm construction platform, the difficulty of accessing the construction sites, the problems in establishing accurate surveying references, the lack of stable loading frames for load testing, *etc.* Another, more manageable, problem is the structural requirement for bracing of the unembedded piling portion against buckling. In recent years, pollution problems and even the protection of fish against sound pressure waves in water have made nearshore construction more complicated.

For the engineer, opportunities exist in nearshore construction due to the possibility of easy transportation and handling of loads, and therefore the possibility of installing large piles with heavy hammers. Noise pollution problems for residential areas are usually of no concern.

Nearshore construction often involves seawalls, and one of the most important construction elements is the sheet pile wall. It comes in a variety of configurations and materials including timber and steel (Figure 2) and even concrete. Sometimes the sheet pile wall has to withstand not only lateral but also significant vertical loads. It then may include pile elements which are part of this discussion.

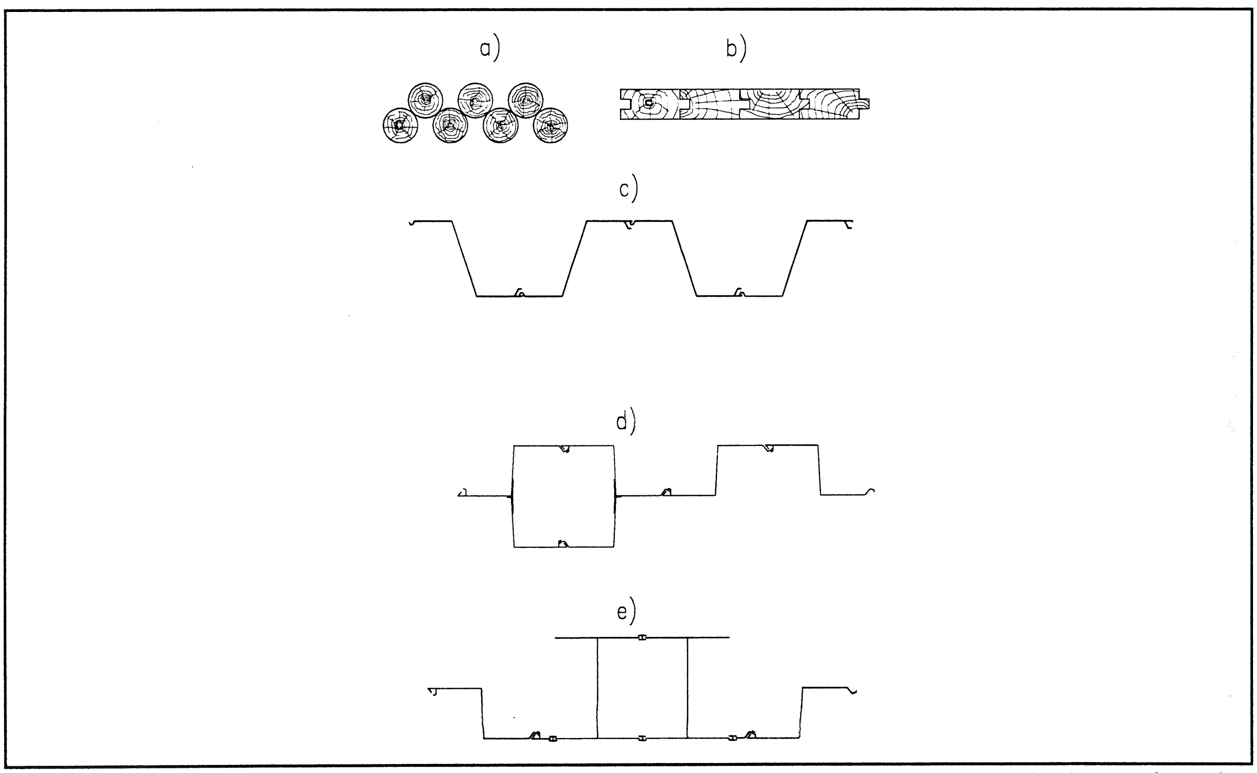

Figure 2. Sheet pile types (a), (b) timber, (c) traditional steel sheet, (d) sheet pile with box pipe and (e) sheet pile with two H-piles.

PILE TYPES

There are three basic types of piling material: timber, steel and concrete. All three types of material are frequently used in nearshore installations. All three materials have advantages and disadvantages.

Timber

The timber pile is **the** historic pile type both on land and in water. The conical shape of the timber pile might be beneficial for bearing capacity development. Timber is easily adapted to varying soil conditions although it is desirable to order the pile length sufficiently long to avoid splicing. Timber piles are also architecturally pleasing where they form a part of an exposed structure. They are used for smaller buildings or bridges. Very commonly, timber piles are used for docks and piers and in groups as dolphins, navigational devices or where they enhance the architecture of a structure. Timber sheet piling also may be used where earth pressures are moderate.

Questions are always asked as to the life expectancy of timber piles. Today timber piles are protected by creosote or copper arsenate based preservation materials whether they are used on land or in water (Johnson, 1987). Timber is attacked by marine organisms such as bacteria, fungi, mollusks and crustaceans. There are even creosote-tolerant borers, called *Limnoria tripunctata*, which are present in the state of Florida. Fortunately, in the Vancouver area one only has to deal with *Limnoria quadripunctata, teredinid*s and *Limnoria lignorum*. In any event, it is important to realize that not all preservation materials work equally well in all areas. It is well known to most piling experts that timber performs very well under water or below the water table. Most damage probably occurs in the tidal zones or where the piles are embedded in soil above the water table. In general, a 50 year life can be expected from a treated nearshore timber pile. The timber life may be shorter in warmer climates than in colder ones.

Steel

Steel piles come in a variety of shapes and are conveniently used for a variety of purposes. For example, sheet piles often form a seawall, single large diameter pipes serve as a dolphin, and H-piles are used as a tension pile in piers - usually under a 45° inclination. Several sheet piles may also be joined to form a pipe-like pile. The moment resisting capability of the seawall may be greatly increased when such box like pipe piles are included in the wall at regular intervals.

As a foundation element for nearshore buildings, the most common steel pile type is probably the open ended pipe pile which may or may not be filled with concrete. Pipe pile diameters range from 300 to 1200 mm and wall thicknesses vary between 6 and 25 mm. For dolphin construction, diameters may be several meters. Special, particularly European applications include sheet pile formed pipe like box profiles which lock into neighboring sheet piles and provide bending strength to the wall (Figure 2).

Prestressed and Post-tensioned Concrete

Prestressed concrete piles are very conveniently used in any nearshore application. Their weight does not pose difficult handling problems and transportation even with lengths of 50 m do not present unsolvable problems. The relatively good resistance against animal and chemical attack makes concrete usually the preferred pile material choice.

Concrete piles come in a variety of makes and forms. Most common, at least in the United States, is the square solid prestressed concrete pile with widths between 250 and 750 mm. The larger piles may also be produced with internal, circular voids. The octagonal prestressed concrete pile is manufactured with nominal sizes between 400 and 600 mm, again the larger one with internal voids.

Cylinder piles are manufactured in short sections by spinning them after pouring the concrete in a cylindrical form. Typical diameters and wall thicknesses are approximately 900x130, 1400x130 and 1700x150 mm (36x5, 54x5 and 66x6 inches). They are made into one pile by post-tensioning several sections together. Concrete quality is usually high and therefore the undamaged concrete is much more resistant to corrosion than concrete of lesser density. However, unless great care is exercised, internal pressures in the cylinders can cause bursting pressures resulting in vertical cracking.

Often, the reinforcement of nearshore concrete structures is coated with epoxy to protect the steel from corrosion. According to some critics, the coating has not been as successful in protecting the steel as hoped and galvanizing is now also being tried as another means of protection. Studies of reinforcement steel protection in chlorotic environments are still being made. Prestressed piles, however, usually do not require coatings. In fact, they may be detrimental to the steel-concrete bond. The prestress tends to close hairline cracks should they occur during driving. In fact, such cracks might even "heal" by the never completed cement hydration.

The most dangerous situation for concrete piles driven through water is the water jet cracking. In the presence of high tensile stresses, cracks open and close during the hammer blow, thereby pumping water into the crack and then expelling it at high speed. The water jet pressures breaks off concrete near the crack, a process that is helped by the high, sudden compressive impact at the crack surfaces. The prestressing in the pile reduces this danger, allowing tension stresses of 7 MPa or more during driving without any danger of cracking. Also, cracking of the concrete pile due to high handling (bending) stresses are usually not a problem unless a very careless crew moves the piles.

Another source of damage exists in very cold weather when piles are driven through ice and water. The air temperature and therefore the initial temperature of the concrete may be very low, while water and soil have higher temperatures. This may cause strong temperature gradients and therefore the possibility of cracking. Again, prestressing might alleviate the problem.

Non-prestressed Piles

In many countries non-prestressed, regularly reinforced piles are preferred to prestressed piling even in nearshore construction. Arguments for regularly reinforced piles are their lower net compressive stresses in the pile both during driving and under service loads, reduced danger of pile top cracking and simplified splice details. The latter allows for short pile sections which are easily transported and which allows for simple pile length adjustments to variable soil conditions. It is important to drive the splices below mudline and to use relatively large ram masses and low strokes to avoid tensile cracking. However, this pile type is usually made of high strength concrete which can accommodate tensile stresses of 4 MPa without cracking.

The damage situations discussed for prestressed piles are even more of a problem for regularly reinforced piles. Again, short sections reduce the danger of cracking both during driving and handling.

Composite Piles

A variety of concrete-steel and concrete-timber piles have been designed and installed in nearshore applications. The most common composite pile is the square concrete pile with a "steel stinger". The steel stinger typically consists of a steel H-pile section which either extends into the concrete section or which is welded to a steel end plate. This pile type allows for pile toe penetration into hard materials when uplift is necessary. Another example of a composite pile is a 24x24 inch concrete pile on top of a 16 inch pipe. This solution was developed for a causeway crossing a Louisiana lake. The steel pipe was driven below mudline and thus only the concrete pile portion was exposed to the water. The wider concrete section also provided lateral resistance while the pipe was responsible for taking the axial loads into deeper more competent materials. Similarly, a timber pile is sometimes used underneath concrete again where the concrete is thought to provide better, long-term durability. Concrete encapsulated timber has also been encountered.

Spin Fin Piles

Along the west coast of the United States and Canada, this pile type has recently come into use. The pile is practically a pipe with an outside thread made of fins that very gradually wind around the pipe. During driving, the pile turns. Preventing the pile twist during uplift loading causes a plugging effect above the fins which, according to the promoters, increases the pile's uplift capacity.

SPECIAL PILE DETAILS

Pile Splicing

Pile splicing on nearshore steel piles is done by welding and is, of course, no problem. Whether or not an increased corrosion potential exists on welded splices should be checked and protective measures taken.

Timber piles should always be chosen with the proper length so that splicing is unnecessary.

Concrete pile splicing is sometimes necessary and often difficult. However, a variety of splice types have been proposed (Bruce and Hebert, 1974). Splicing may be anticipated and planned for a certain depth. A mechanical splice may then be used with two matching steel parts held together by pins, wedges, bolts, welds or other devices. When splicing is not anticipated and a splice has not been cast into the top of the bottom pile section, then an epoxy splice appears to be best suited (Figure 3). However, this splice is somewhat brittle and therefore care should be exercised when driving a pile spliced in this manner.

Regionally, different splice types have come into practice. In Florida, for example, a splice has been used which assures a full concrete section at the spliced section. The bottom of the upper extension consists of a hollow square concrete section (Figure 3). This massive splice is probably the most costly and some difficulties may occur where high resistance exists in the soil into which the splice is driven. On the other hand, even though it is not elegant, this type of splice performs well and is insensitive to corrosion. In Louisiana, the can splice is often employed which is the male end of the bottom section fitting into a steel sleeve of the extension. This splice does not transmit tension and thus sometimes protects the upper section from tensile cracking during driving. On the other hand, the splice cannot support uplift loads.

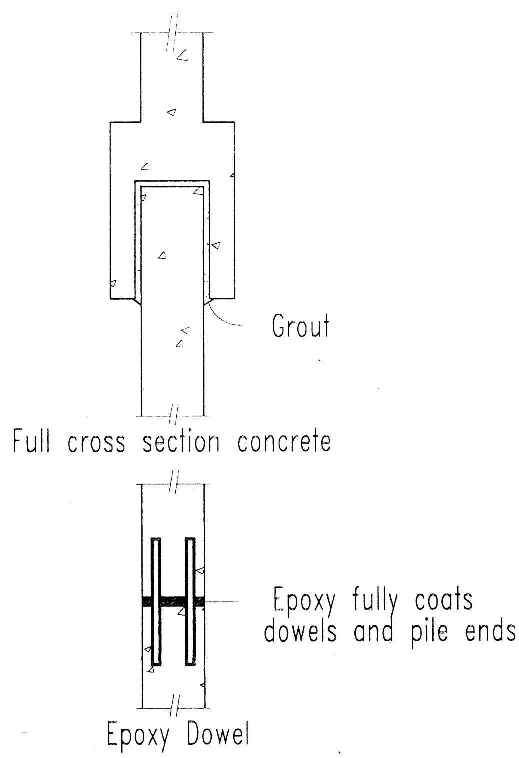

Figure 3. Special Splices for Prestressed Concrete Piles

Pile Protective Measures

Nearshore, similar devices might be considered for pile protection as on land. For example, timber pile tips are sometimes protected with steel strap points. Also common are toe protective castings for both simple H-piles and composite concrete piles with H-pile stingers.

For open ended pipe piles toe (and sometimes top) protection consists of an increased wall thickness. Large diameter, closed end pipes (say more than 900 mm diameter) require bracing for the end plate. Small diameter pipes are often protected by and closed with a conical tip.

For concrete piles the only protection is usually the pile top cushion. It serves to spread the impact forces uniformly over the pile top surface and to reduce the peak of the impact force. Thus far, plywood cushioning still appears best suited. Green oak boards are sometimes used and a combination plywood/Hamortex (consisting of aluminum backed tightly wound paper) is also occasionally employed. Plywood pile cushions can take up to 1500 blows before they start to burn or disintegrate. Unfortunately, for concrete piling it is often difficult or nearly impossible to exchange the pile cushion under water. Therefore, regardless of follower or under water hammer use, concrete pile driving underwater may be a real challenge.

The best pile protective measure is dynamic monitoring (Hannigan, 1990). It gives the engineer for each hammer blow the stress maxima and also often provides indications of developing damage.

HAMMERS, LEADS, FOLLOWERS

Today, most hammer types are used in the nearshore environment. Where cranes can be barge mounted, often large hammers come into use such as air hammers with 15 Mg or more ram mass. Air/steam hammers now have strokes up to 1.5 m which makes the rated energies easily 200 kJ or more. Diesel hammers are also a very good solution, providing high energies with relatively low weights. Rams with 4.5 or 6 Mg mass are not uncommon, providing typical rated energies of 120 or more kJ.

In recent years, a variety of hydraulic hammers have been developed. One group of these hammers is particularly useful for driving concrete piling with large ram masses and small fall heights. Others are fully enclosed and double acting and therefore can be used under water. Ratings range from as little as 30 kJ to as much as 2000 kJ.

For hammer selection it is always useful to perform a wave equation analysis (Goble, Rausche and Likins, 1993). Performing this analysis is particularly important for any work over water where mistakes in equipment selection can have rather costly consequences. Selections should be made based on allowable blow counts and stresses. In general, the anticipated blow count should be less than 75 blows for 250 mm for friction piles and less than 100 blows per 250 mm penetration for end bearing piles. Dynamic driving stresses should be kept within the limits suggested by AASHTO (1992). For example, the compressive driving stresses of steel (concrete) piles should not exceed 90% (85%) of the pile material's yield (compressive) strength. For tension in concrete piles, the allowable stresses include consideration of the prestress. The driveability investigations should include estimates of changes of soil resistance due to the dynamic effects of pile driving.

For steel and timber usually all hammer types are adequate. For concrete pile driving, diesel hammers are generally a good choice since they hit gently during easy driving when tensile stresses easily reach dangerous levels. However, any low stroke, high ram mass hammer should also work well for concrete pile driving. Those hammers whose energy output can be adjusted are preferred.

The nearshore pile installation technology is often very similar to offshore pile driving: a template provides guidance for the piles and an offshore leader aligns hammer with pile. Large projects with large hammers and large piles are very spectacular, however, where smaller piles are installed, the same basic considerations have to be made: How to guide the pile and how to align the hammer with the pile. Water depth is often the deciding factor for equipment selection.

For shallower depth, a normal fixed lead arrangement may be used on a crawler crane which is driven onto a barge and which may be operated with diesel or hydraulic hammers. In any event, it is hoped that the contractor chooses a barge large enough such that waves from nearby boat traffic do not cause excessive barge motions which have, on occasion, resulted in damage of concrete piles.

For larger projects, truck canes and even crane barges with permanently installed high capacity cranes may be found in the nearshore environment. Often, particularly for greater water depths, they are equipped with offshore leads which align the hammer with the pile. The pile itself is guided by a template.

Owing to frequently soft soil conditions below mudline, vibratory hammers are also used on large diameter pipes (small end bearing) particularly if the piles are driven only to provide lateral loads. It is often economical to start the piles with vibratory driving and finish them with an impact hammer.

Underwater driving has become simpler with the availability of sealed hydraulic hammers. This avoids the use of followers where piles have to be driven below the water surface. Although follower design is not difficult (for an example see Figure 4), questions often exist as to the energy efficiency of followers. Moreover, followers tend to require expensive maintenance because of fatigue causing stress cycles. It is therefore recommended to keep the follower impedance as high as possible (*e.g.*, twice the pile impedance; higher follower impedances may be uneconomical due to high energy reflections or high pile stresses).

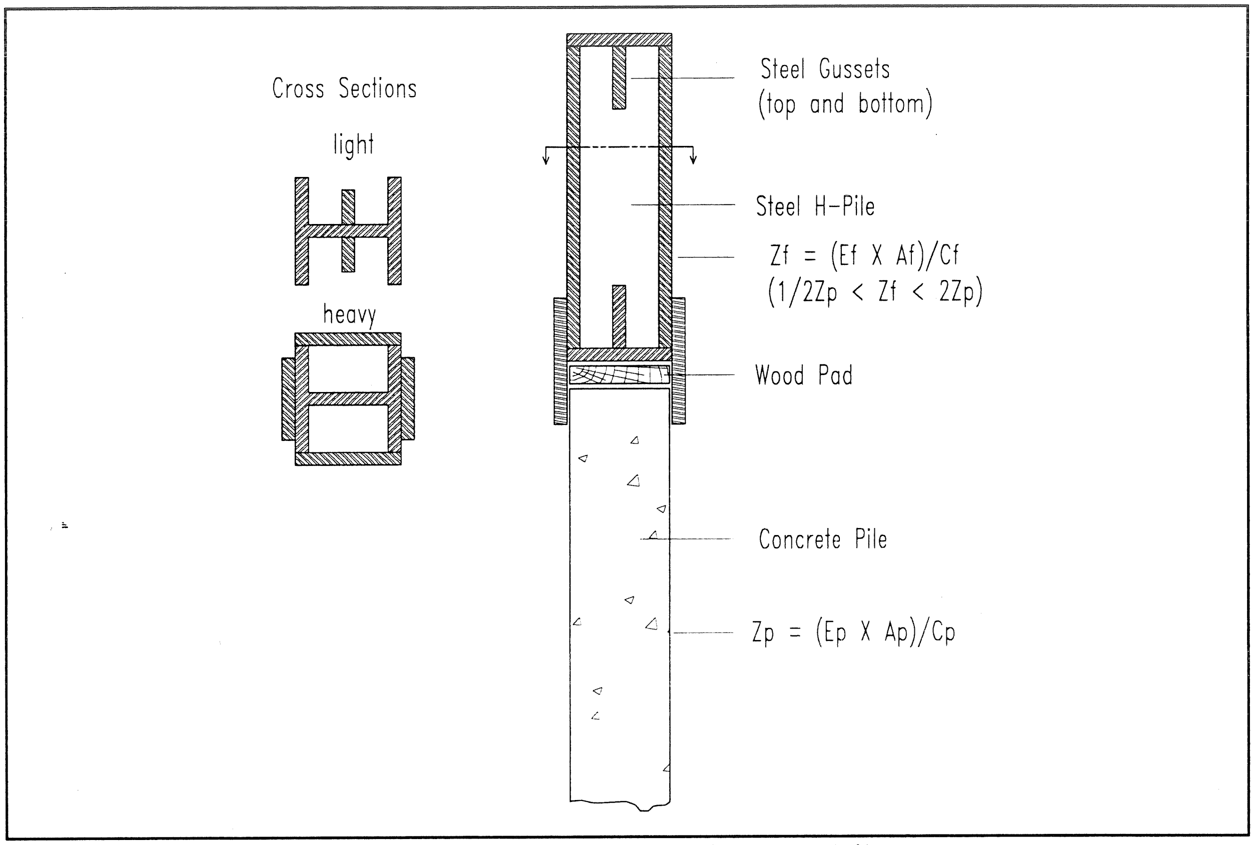

Figure 4. Follower for Concrete Pile

CORROSION CONSIDERATIONS

Below the water table, where there is no free oxygen or chemically corrosive materials, the three major pile materials exist without major deterioration. There is probably no difference between nearshore and on-land construction.

For piles exposed to the air, in the humid and salty nearshore sea environment, concrete does relatively well, even though chloride penetration occurs to some degree and at a rate that depends on the concrete quality. It is therefore advisable to use epoxy coated reinforcement bars.

In the nearshore environment, pressure treated timber is expected to last 50 years in northern areas with cold climates and fewer years in the south.

Steel piles on the average loose approximately 1/10 mm thickness per year in salty air (Coburn, 1988). Twice as much corrosion may be expected in the splash zone. Cathodic protection, a precaution extensively used in the offshore construction environment is also sometimes installed in nearshore construction projects.

TESTING

Testing prior to construction and testing during construction is done to meet several objectives. First, the bearing capacity of the foundation elements has to be checked. Second, the adequacy of the installation procedure and equipment must be monitored. Third, installation records must be collected. Finally, whenever unforeseen events occur, a resolution of disputes must be possible, based on objective test results.

Static pile testing is often difficult and even dangerous over water. Therefore, when a static pile test is needed, it may be desirable to select an equivalent test site on nearby land. Of course, there will always be some question as to the applicability of the replacement test site to the originally intended nearshore site; however, given proper dynamic monitoring during driving and restriking of land test piles and nearshore construction piles, doubts can be strongly reduced.

Dynamic testing by the Pile Driving Analyzer® (PDA) is an ideal solution because of its convenience and economy in nearshore situations (Goble and Hussein, 1994). Driven piles always require the mobilization of a hammer which can be used as the test loading device. Thus, bearing capacity is very often evaluated by dynamic testing on nearshore sites. Dynamic testing is also particularly useful when installing concrete piles for both economy and damage prevention. Economy can be achieved by optimizing cushions and damage can be minimized by continuously observing compressive and tensile stress levels.

It can be expected that nearshore piles are usually driven in saturated soils. Particularly for large displacement piles it was noted that dynamic soil resistance parameters are quite different from static ones. In particular the so-called quakes are often very large, making pile installation difficult (Likins, 1983). Other, often encountered soil conditions include silts and clays with a strong soil set-up potential. In those soils, driving is relatively easy and it is important to stop early enough and wait a few days before restrike testing to include the full soil strength in the test result. Relying on the end-of-driving blow counts or PDA indicated capacities would be very uneconomical. Similar set-up potential exists in the limestones of Florida and the corral strata of the Caribbean islands.

A FEW SAFETY CONSIDERATIONS

All of the land construction site safety concerns apply. However, over water loads are usually greater than on land and barges are always moving. This means that crane hooks sway, so do loads including piles, leads and hammers. In addition, everyone on a barge has to consider the danger of falling into the water after being knocked unconscious. Life jackets are therefore always required. Worse yet, the water is sometimes so cold that only a maximum 5 minute survival is possible without protective clothing. Also, falling between barges may mean that one is squeezed to death.

EXAMPLES

The following examples are only intended to give the reader a general review of piling solutions in various areas and for a number of different types of projects. They are not intended to provide complete case studies.

Timber Pile Jobs

Along the east coast of the United States large numbers of timber piles are driven often for the support of 2 or 3 story apartment buildings, single family residences, pier and board walks. Piles are often only 2 or 3 m long and 200 mm diameter along the beach and longer and larger if they form the foundation over water. Of course, many piers are built from timber piles. They are always pressure treated. Dynamic testing includes both bearing capacity evaluations and integrity assessments of both new and old foundations. Timber pile testing is sometimes more complicated than testing of other piles because of variable material properties. It is important not only to measure individual wave speeds, but also to weigh samples from several piles for an accurate assessment of material properties.

In the south-eastern United States, railroad trestles are still being maintained by driving and replacing old timber piles.

Steel H-pile Jobs

This pile type is very commonly used in the northeastern United States. For example, for the **Schuylkill River** sledge barge docking facility in Philadelphia, HP 10x42 piles were driven in water for a walkway. In Connecticut, for the **Poquepanuck River** railroad bridge, HP 14x102 piles were installed. Similarly, in **Holyoke**, Massachusetts a bridge was founded on H-piles driven during low water in the river bed.

Open End Steel Pipe Piles

Hudson River, New York, 1978; pipe piles were driven through soft cohesive soils into a dense granular layer as part of a preconstruction test program for a large bridge. Dynamic monitoring revealed very low capacities in the design layer and therefore it was decided to drive H-piles to bedrock.

At the **Cooper River Bridge**, large diameter steel pipes (48x1 inch) were driven in the river for the support of the center span. An MH 72B open end diesel hammer was used for installation and testing. The bridge, being located in Charleston, South Carolina had to be founded in the Cooper Marl. A similar project was the **Pugett Island Bridge** where 48 inch diameter steel pipes, spiral welded, were driven and continuously monitored to avoid pile damage and the attainment of sufficient bearing capacity. For a pier at the **Navy Ammunition Depot** in Leonardo, New Jersey, the open ended pipe piles were of 36 inch diameter and driven by an MH 72B diesel hammer.

A 72 inch diameter **Dolphin** in the Port of **Hamburg** actually was used more as a permanent test pile for large hammer development than for tying up ships. Sandy soils gave this pile very high capacities.

Open ended large diameter pipes for oil and coal loading and/or unloading platforms in **Korea, Israel and Columbia** may also be classified as offshore structures. They were constructed like platforms with large steel jackets forming the pier supports with large diameter (48 and 60 inches) pipe piles holding them in place.

Concrete Cylinder Pile Jobs

These large piles are particularly suitable in the nearshore environment where heavy loads can be handled from barges and where piles are driven through and extend above water such that a separately formed and poured pier is unnecessary. It is not easy to install these piles because of the need to avoid internal water or soil pressures which could produce vertical cracks. Some of the construction specifications therefore require that at certain intervals the driving is interrupted, the internal soil plug removed by jetting and the water bailed out. Very often, the specifications also call for dynamic monitoring, primarily to check hammer performance and pile stresses.

A very early example is the **Lake Chautauqua Bridge (New York)**. A preconstruction test program involved static and dynamic tests of 54 inch diameter concrete cylinder piles driven and tested over water to 500 tons. Reaction loads were provided by water filled barges. When the static test did not reach the required 500 tons rather than redriving the piles, they were statically jacked until they reached the required capacity. As part of this preconstruction test program, dynamic restrike measurements were also taken and analyzed by CAPWAP®. For environmental reasons the project was interrupted for several years.

In Maryland, New Jersey and Virginia several large bridges were built with cylinder piles. Among them are **Nantaco, Choptank, Bohemia, Severn River an Chesapeake Parallel Bridge** (under construction). Cylinder piles of 900 and 1350 mm diameter were also driven for the **Penang Bridge** in Malaysia.

Octagonal Concrete Piles

In the early 1980s, the West-Seattle freeway bridge was founded on hollow 24 inch octagonal concrete piles in silty soils; the piles were tested during installation. Difficulties were encountered with high tension stresses in the presence of high blow counts. This was caused by a so-called high quake situation, *i.e.*, a high soil flexibility which makes the driving progress very slow and which can easily result in pile damage.

Foundations for the **Anacis Island moveable bridge** were driven through water into fine sands with a diesel hammer. The piles consisted of 24 inch octagonal concrete sections of typically 25 m length. A follower study was conducted with various follower designs being tested for the highest energy transfer efficiency. The study included both wave equation analyses and measurements using a PDA on the pile and follower. It was concluded that a follower does not necessarily reduce the energy transfer. However, difficulties with cushion deterioration and the then necessary cushion exchange were experienced when long underwater driving sequences were required. PDA measurements and CAPWAP analyses also indicated unexpectedly low bearing capacities. They were confirmed by a static load test.

Square Prestressed Concrete Piles
In the **Port of Baltimore** a major improvement project (Seagirt Marine Terminal) required the driving of 20 inch square prestressed concrete piles. For an apartment complex in the same area, 12 inch square concrete piles were driven. Both diesel and air hammers were used and dynamic and static testing was employed.

A major construction project for the Trident Submarine base in **Kings Bay, Georgia** required the driving of 24 and 30 inch square prestressed concrete piles for various piers. For uplift capacity the piles were sometimes fitted with a steel stinger. Driving was extremely hard and for that reason, square holes were prejetted to within a few feet of the design tip elevation. The pile was then inserted in these holes and driven with a heavy air hammer. Occasional pile monitoring revealed pile damage in a few cases which may have been the result of tension cracks. Also some toe damage was noted probably due to high and uneven compressive toe stresses.

In Florida, mile long approaches to center spans or bay crossings require the driving of large numbers of prestressed concrete piles, typically 18, 24 and 30 inch square. The 30 inch piles typically are hollow. Their lengths may reach nearly 60 m. Because of increased ship impact loads and larger spans (in recent years typically 30 to 40 m) battered piles are not uncommon. The widely varying soil conditions ranging from limestone to silt and clay make pile length prediction extremely difficult. Restrike testing is usually necessary to confirm soil set-up. Typical pile loads are 1250 to 2500 kN. A common procedure for pile testing and pile length ordering is the preconstruction test of single piles in a pier. Splicing is then sometimes necessary. The test pile is monitored by the PDA. A driving criterion, including required transferred energy, and a pile length is then established. The test barge then moves on to the next pier while the installation barge follows, driving the production piles. Usually, when the test barge reaches the other side of the bridge, the bridge deck is already installed at that bridge side where construction started.

At the **Sunshine Skyway Bridge**, between St. Petersburg and Sarasota, when certain piles within a pier did not reach the established driving criterion, underwater restrike testing was conducted. To accomplish this, a pneumatic drill was used by a diver and waterproof strain transducers and accelerometers were then installed. The difficulty was then to accurately align the hammer with the pile top to avoid pile damage during restrike testing. By measuring first under a light hammer blow, the strain values on the piles sides over and under the batter (these are the sides experiencing the highest bending stresses), adjustments were made to the hammer alignment. The following restrike test was then performed without any damage problems. At the Sunshine Skyway Bridge, an extensive study was also made on how to improve the life of pile top cushions while driving under water. Plywood sheets and both aluminum and steel plates were sandwiched to help extract the heat from the cushion thereby preventing premature burning. Also, it was hoped that the metal plates would reinforce the cushion and thus reduce their deformations. Unfortunately, it had to be concluded that no significant increase in the cushion life could be achieved with such measures.

Another example, among many bridges of similar length and foundation, is the **Howard Frankland** between Tampa and St. Petersburg. The bridge is approximately 5 km long and required 30 km of piles. They were 24 and 30 inch square and lengths between 50 and 150 ft depending on the soil conditions at the individual piers. Typically one preconstruction test pile was driven in each one of the 120 piers.

In the **Ports of Los Angeles and of Long Beach** the typical southern California harbor pile consists of 24 inch square prestressed concrete. It is usually driven into fine silts and sands. Driving resistances are often very high. Monitoring primarily assures damage free installation and satisfactory hammer performance.

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