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Drilled and Driven Piles in Seismic Regions

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A comparative Paper on the various types of piles used in seismic regions. Piles are not equal and performance, or the assurance of performance, will vary by pile type. This Paper outlines issues that need to be considered in selecting a pile type for a specific installation in a seismic area.

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1 Introduction

Piles provide foundations for structures that carry heavy loads or that are located on soils that do not have adequate bearing capacity. Piles are also used for marine applications where they may be free-standing over a significant part of their height. In this way they can obviate the need for a separate column.

Piles in some form have been used for almost as long as man has been building. Examples exist in primitive societies of houses built on "stilts" (i.e. piles) to keep clear of floodwaters or predators. The same principles have been used by less primitive societies. In the 10th Century AD, Venice was built in a lagoon for defensive reasons, and this required extensive use of piles. Some of the piles in Venice have been in service, under water, for over 1000 years (Caltrans, 1997).

Despite this long history, design and construction of piled foundations is still part science and part art. This is so partly because the foundation represents the interface between two engineering disciplines, partly because the soil properties are always subject to some uncertainty, and partly because inspection of the final product is difficult at best, and must be done by remote means. It is not surprising that many different types of piles exist (ASCE, 1984).

Perhaps the broadest distinction is between drilled and driven piles. In principle, drilled piles are constructed by drilling a hole in the ground, placing a reinforcing cage in it and filling it with site-cast concrete. By contrast, a driven pile consists of a prefabricated column, made from any one of a number of materials, that is pushed into the ground until it meets sufficient resistance to carry its intended load with an acceptable margin of safety. Variations on these broad distinctions exist. For example, a driven pile may be started by placing it in a short, drilled hole, or a Franki pile is placed by driving a plug of fresh concrete into the ground with a hammer, etc. Despite these exceptions, most piles fall clearly into the driven or drilled categories.

Displacement of the soils during pile installation is another distinguishing feature of different piling systems. It refers to the fact that the soil is displaced, by driving the pile or some other object into it, rather than removed by drilling. It is also influences bearing capacity, since it densifies the soil around the pile and consequently increases capacity. All driven piles are displacement piles. However, cast-in-situ displacement piles are sometimes constructed by driving a mandrel to form the hole, withdrawing it, and depositing the concrete.

Certain applications call naturally for one type of pile or the other. For example, the majority of marine piles are driven, because they can be made free-standing in a single operation. On the other hand, land-based piles that must be placed through very dense soil deposits, or those containing a significant number of boulders, are usually drilled, since the hard soil would require very heavy driving that might damage the piles. Maintaining alignment during driving is also more difficult in heavily-bouldered soils.

2 Drilled Piles

2.1 Types

Cast-in-drilled-hole (CIDH) piles (Figure 1) are self-explanatory. Other terms, such as *cast-in-place piles* or *bored piles* are also used. *Drilled shafts* are usually taken to mean large diameter CIDH piles. Several variations on the basic installation theme are used as necessary. In particular, a means for preventing collapse of the sides of the hole during drilling may be necessary in loose soils. One common method is the use of a steel casing tube, which holds up the sides during drilling but is removed after the concrete is in place. A second possibility is to use a liquid slurry, which holds up the walls during drilling and is subsequently displaced by the heavier concrete during casting.

Piles may also be formed by *auger-casting* (Figure 2). In this case, the auger that drills the hole has a hollow stem. The auger prevents the walls of the hole from caving in during drilling. When the hole has reached full depth, the auger is slowly withdrawn and cement grout is simultaneously pumped down the hollow stem to form the pile. Finally the reinforcing cage is lowered into the wet concrete. This method is usually restricted to relatively small diameter piles.

2.2 Bearing Capacity

Most piles derive their bearing capacity from a combination of bearing at the tip and friction on the sides. Usually one mechanism dominates so, for simplicity, piles are often referred to as either *end-bearing piles*, or *friction piles*. For example, piles extending down to bedrock are usually end-bearing, whereas piles drilled into deep clay deposits usually depend mainly on friction.

The bearing capacity of CIDH piles must be obtained by means of testing, since the installation procedure provides no verification of capacity.

2.3 Cast-in-Drilled Hole Piles - Details

2.3.1 Construction

The basic installation procedure is illustrated in Figure 1. In firm soils, it takes on its simplest form. A drilling rig drills a hole with an auger, the bottom of the hole is cleaned out with a cleanout bucket, a reinforcing cage is lowered into the hole, then concrete is deposited in it. In some cases a small quantity of concrete is placed in the bottom of the hole prior to lowering the cage, in order to ensure proper bottom cover.

The type of drilling auger is selected based on the conditions. Double-flight augers are better balanced than single-flights, so help to maintain alignment. The use of a long, continuous flight auger is convenient for deep holes, but short segments joined together may be necessary if headroom is limited. Different cutting bits are used for soft or hard material. The pitch of the flights influences their ability to lift soil to the surface without its slipping back into the hole. (Dry sands can slip off the auger back into the hole if the pitch is too steep).

The purpose of the clean-out bucket is to ensure a flat bottom to the hole, and thereby to achieve optimum bearing on hard soil or rock. It consists of a hollow steel cylinder with a largely closed bottom. Angled slots in the bottom of the bucket, similar to those in a cheese-grater, pick up loose soil as the bucket is rotated. It is used to lift loose material that may not have been picked up by the auger and that would otherwise detract from the bearing capacity of the pile.

The concrete should be deposited through a tremie tube, in order to avoid segregation. The end of the tremie should be kept well below the surface of the concrete. Vibration is usually not necessary, except in the top few feet of the pile, because the head of concrete consolidates it. The need for vibration also depends on the particulars of the concrete mix.

In loose soils, or if the pile must be installed at an angle to the vertical, there is a danger of the walls of the hole caving in. Such "cave-in" may be avoided by installing a steel casing tube in the region of the poor soil, and drilling inside it. The casing is withdrawn as the concrete is deposited. Alternatively, the hole may be filled with a liquid slurry during drilling. Besides applying hydrostatic pressure to the walls, the slurry coats the soil particles and provides a cementitious action as well. As the concrete is deposited through the tremie, it displaces the slurry which, being lighter, floats on the concrete. The slurry is collected in a sump at the head of the pile, and is then pumped to a filtration/cleansing unit prior to re-use.

2.3.2 Primary Advantages and Drawbacks of CIDH Piles

The primary advantages of CIDH piles are:

- Low noise and vibration. Pile driving can cause noise and vibration that are unacceptable either for human tolerance, or for fragile neighboring structures.

- Pile length can be changed on site. If the bearing layer is not as deep as anticipated, the pile can be shortened by drilling the hole less deep and the cage can easily be cut off to the required length. By contrast, a driven pile must be cut off after refusal. This may be more difficult than shortening a CIDH pile, especially with prestressed concrete piles.

- Piles can be drilled through dense or bouldered soil if a suitable cutting head is used. Driving a pile through such soil deposits could cause high temporary stresses and damage to the pile.

- Pile diameter is limited largely by auger availability. (A crane that can lift the reinforcing cage must be available). Driven piles are subject to constraints of transportation and handling and are seldom available in diameters larger than 5 ft.

- Use of a single, large-diameter, drilled shaft onto which a column is cast directly avoids the need for multiple piles and a pilecap.

The disadvantages of CIDH piles are:

- Quality of the final product depends strongly on the experience, abilities and quality control procedures of the contractor.

- Defects are largely invisible. In large piles, inspection tubes are usually installed to allow verticality and straightness to be checked, and to permit some acoustic testing. However, detecting local wall cave-ins is difficult. These can reduce the pile cross-section and can allow moisture to attack the reinforcement.

- Pulling a defective CIDH pile is very difficult at best, and is usually impossible.

- Bearing capacity must be established by testing.

- The lack of soil displacement in most CIDH piles reduces the bearing capacity.

- Drilling batter piles is difficult. Maintaining alignment is one problem. Wall cave-in (from the top face) is also rendered more likely by the batter.

- Disposal of drilling spoils from contaminated soils may attract additional environmental costs.

2.3.3 Common Problems and Solutions – CIDH Piles

The primary problems experienced with drilled piles are with cave-in of the walls. This can occur even when a casing is used. For example, if the casing is pulled when the concrete is still fresh, but it is pulled too fast, it may draw some of the concrete up with it, thereby causing suction in the concrete, which can pull the pile walls in or, if the concrete is allowed to set up too much before pulling the casing, the casing may drag on the concrete and cause cracks in the concrete. The hydrostatic head may or may not be sufficient to heal the cracks.

If a slurry is used, it must be appropriate for the soil in question. It must also be cleaned and filtered in accordance with the manufacturer's specifications. Some slurries are classed as hazardous materials, and must be disposed of properly when exhausted.

The bottom of the hole must also be cleaned out carefully, since it is the interface across which the bearing stresses are carried. If drilling spoils are left on the bottom, the pile is likely to settle as the spoils subsequently settle under pressure.

2.4 Auger-Cast Piles – Details

One of the main attractions of auger-cast piles is their low cost. Because they are usually smaller in diameter than traditional CIDH piles, the installation equipment is typically smaller and less expensive, thus opening the market to smaller firms and increasing competition. Because of the details of the construction sequence, fewer pieces of heavy equipment are usually needed. For example, when casting a CIDH pile, the inspection tubes must be kept straight by internal steel rods while the concrete is cast. The rods are often supported by a crane. Inspection tubes are seldom used in auger-cast piling, so there is no need for the additional crane.

The very features that lead to low cost also tend to lead to lower reliability. With only the auger to hold up the sides of the hole, the possibility of local cave-in is higher than with traditional CIDH piles. The skill of the operator in withdrawing the auger at a speed that ensures that the tip is always below the surface of the grout, and therefore to limit wall cave-in, is critical. Location of the reinforcing cage is also not ensured because the cage is pushed into the grout after casting, rather than being correctly located at an earlier stage when measures can be taken to ensure correct alignment. A misaligned cage can cause the flexural strength of the pile to be quite different in opposite directions. Furthermore, because of the difficulties of pushing a long cage into an already grouted hole, the cage may not extend the full depth of the hole, so the bottom part of the pile may be constructed of unreinforced grout. Inspection of the pile is almost impossible after casting, so verification of quality is extremely difficult. Because the pile's integrity affects its ability to resist lateral load, some authorities advise against any use of auger-cast piles in seismic regions.

3 Driven Piles

3.1 Materials

Driven piles are made from timber, steel, reinforced concrete or prestressed concrete. Timber piles are seldom used in large, land-based projects today. Even in marine facilities, present environmental restrictions on the preservatives that were used in the past often limit the use of timber piling.

Steel piles are often favored by contractors, because their ability to withstand tension stress makes them relatively forgiving during driving. Handling is generally straightforward, in that self-weight bending stresses during lifting into the leads are unlikely to reach critical values. Steel piles can also be cut off and added to relatively simply, by oxy-acetylene cutting equipment and welding. However, the material cost per pile is typically higher than for concrete piles. Corrosion must also be accounted for. This may be done either by adding sacrificial thickness or by galvanizing or coating the pile. These measures inevitably add to the cost.

While non-prestressed concrete piles can be used, they are at greater risk of cracking through tension stresses during driving. For that reason, prestressed concrete piles are more common. The prestressing normally takes the form of pretensioning. Precast piles can be made in sections and post-tensioned together on site, if handling conditions so require, but the need for post-tensioning equipment adds to the cost and complexity of the job.

Pretensioned piles are common on the west coast. They are widely used for both land-based and marine applications, and can be made in lengths up to about 200 ft. This is long enough for almost all applications, but obviously requires special arrangements for transportation. The prestressing helps to prevent cracking during handling and driving, and closes any flexural cracks that may occur during service. It is also effective in increasing the effective moment of inertia (by virtue of the fact that the section is uncracked) for service applications. This might be important, for example in marine applications where the pile is free-standing for much of its height and resistance to buckling is important. The piles are typically made from high-quality, well-consolidated concrete that is mixed, deposited, consolidated and cured under factory conditions.

3.2 Pile Driving

Driving is a critical operation for driven piles, because it is the time when the highest stresses occur. It is particularly important for concrete piles, both prestressed and reinforced.

The process is simple in principle (Figure 3), but many variations on the basic procedure exist. The pile is held in leads that maintain the alignment. A cushion block is placed on top of the pile to prevent local damage from the impact of the hammer. The hammer is lifted and dropped onto the top of the pile, thereby driving it into the ground. The major objectives are:

- Drive the pile as fast as possible (for economic reasons).
- Avoid excessive tension stress waves, which could cause horizontal cracks in the pile.
- Avoid excessive compression stress waves, which could crush the pile.

The parameters available for satisfying these objectives are the hammer weight and drop, and the properties of the cushion block. Many hammer types are available, each having its own characteristics, blow rate and energy efficiency. Cushion blocks are often made from stacks of plywood, but artificial materials, with controlled properties, are also used. During driving, the cushion block suffers permanent compression deformation, densifies, and so becomes stiffer. Changing it before it becomes too hard is essential if excessive driving stresses are to be avoided, because a stiff, non-absorbent cushion leads to a short duration impact and high transient stress.

As the hammer strikes the pile head, it induces a compression stress wave that travels down the pile (Figure 4). At the bottom, it is reflected back up. If the tip resistance is low (i.e. soft soil) the wave is reflected as a tension wave. If it is high (i.e beneath a pile that is near refusal), the reflected wave is compressive. The tension wave stress must not exceed the tension strength of the concrete plus the effective prestress. With a common maximum prestress of 1200 psi, and tension strength on the order of 500 psi, the total available tension resistance is approximately 1700 psi. The peak applied tension stress is a function of the hammer energy (weight times drop minus losses) and the energy absorbing properties of the cushion block. Lowering the hammer energy (lighter hammer or shorter drop) and increasing the duration of the impact (by choice of cushion block properties) both reduce the peak tension stress. Similar arguments apply to the peak compression stress. The compression capacity is controlled by the concrete strength. Various authorities, (e.g. Gerwick, 1993) suggest that temporary driving stresses in the range 0.60 to 0.85 f'_c may be used. The total applied compressive stress is the sum of the compression stress wave and the prestress.

3.3 Bearing Capacity – Driven Piles

The pile bearing capacity can be computed from the hammer energy and the movement, or "set", at each blow. Equating the potential energy of the hammer and the work done in driving the pile into the ground gives:

$$Wh = Rs$$

where

W = hammer weight
h = hammer drop
R = pile (bearing) resistance
s = displacement in one blow.

Since R is the only unknown, it can be computed from the other variables in the equation. However, this basic equation is too simplistic, because it ignores energy losses, which exist because of friction in the driving leads, energy loss in the cushion block, etc. Numerous modified equations have been produced, and are discussed, for example, by Whittaker and others. A simple, commonly used one, known as the "ENR equation" is

$$Wh = R(s + c/2)$$

where c = elastic displacement of the pile head

More sophisticated estimates of bearing capacity are available from consideration of the stress waves in the pile and the transient stresses that they cause. Some (e.g.

Anderson and Moustafa, 1971) have compiled charts to help accommodate the many variables. However, pile driving analysis (e.g. Goble, 1976), using instruments on the pile to determine the stresses from measured accelerations, rather than estimates based on assumed properties for the critical components, is being used more and more often.

Regardless of the details of the calculations that relate bearing capacity to driving conditions, the pile driving operation may be regarded as a test of the bearing capacity. It is the basis of the adage "Every driven pile is a tested pile".

3.4 Prestressed Concrete Piles - Details

3.4.1 Construction

Pretensioned piles are usually square, octagonal or circular. They may be solid or hollow (see Figure 5). Solid pretensioned piles are usually fabricated end-to-end in long beds. This procedure reduces labor costs by minimizing the number of stressing operations. End forms separate the individual piles and act as templates to maintain alignment of the strands, which pass through holes in them.

Hollow piles are used for large sizes, in order to reduce weight. They may be made by the mandrel method, in which a mandrel is drawn slowly and continuously through the pile during casting. This method imposes some constraints on the concrete mix that can be used, because the concrete must achieve sufficient strength and stiffness to maintain its own weight once the mandrel has passed. (The same principle is used in casting hollow-core slabs). Alternatively, a static void former may be used.

Spirals provide the confinement steel for the pile core. In order to maintain integrity during driving, the top and bottom of the pile are usually enclosed in heavy (approximately 1% or more by volume) spiral (Gerwick, 1993; PCI, 1993). Special care is need in hollow piles that are to be driven through soils that could cause a plug in the pile. High internal pressures can build up and can split the pile longitudinally if the spiral is not adequate to resist the forces. If service loads (e.g. seismic) require significant shear or confinement reinforcement elsewhere, spiral can easily be added.

3.4.2 Advantages and Drawbacks

The primary advantages of driven piles are:

- Factory-quality production of the piles.
- Driving provides an implicit test of every pile.
- Solid piles displace the soil, densifying it and in creasing bearing capacity.
- Battered piles can be driven.
- Driven piles can be partially free-standing, thereby forming the pile and column from a single element. This is common in marine applications.
- The pile can be pulled and replaced if it is found to be defective.
- Contaminated soils pose no special problems.

The primary disadvantages are:

- The noise and vibration during driving may be objectionable.
- Driving stresses must be controlled.
- Driven piles may not be viable in very hard, or heavily bouldered, ground, where driving stresses might prove excessive.
- Pile diameter is limited by weight.

3.4.3 Common Problems and Solutions

Most of the problems associated with driven piles arise during driving. Damage to the pile, by excessive tension or compression, or by longitudinal splitting of hollow piles, must be guarded against. Careful control of the hammer and cushion block properties is necessary. Maintaining alignment of very long driven piles, or battered piles, may also require particular care.

In prestressed concrete piles, the extent of the spiral at the head must allow for some variability in the final length of the pile. If refusal is reached earlier than expected, the pile head must be cut off, but the remaining region of heavy spiral must be adequate to provide the necessary confinement and shear resistance for in-situ loads. Alternatively the pile may be driven down to the planned depth using a higher energy hammer, but the viability of this approach will depend on the pile properties, including the spiral content.

4 Seismic Performance of Piles

4.1 Loading and Response

Piles experience lateral loading during an earthquake. In some instances, the seismic loading also cause significant axial load. If the load is tensile, the pile should be checked for tensile capacity, with respect to both skin friction capacity and the tension capacity of the pile itself.

The most common lateral loading occurs at the top of the pile, as shown in Figure 6. Then the shear and moment are both maximal at the same place, directly below the pile cap, if the connection between the pile and cap is a moment connection (Banerjee et al., 1987), as is usually the case. The moments and shears die out quite rapidly down the pile. Various authors (e.g. Davisson, 1963) provide methods of computation for elastic systems. In fact, the most influential, upper layers of soil may undergo inelastic action, including "gapping", in which case "p-y" curves, which relate the lateral load and displacement of the pile in a particular soil type, are used (Kramer, 1996).

A second possible source of seismic shear and moment in the pile is the existence of adjacent layers of soil with markedly different properties (Figure 7). At the interface, equilibrium requires that the shear stress is the same in each material, but, if the shear moduli differ, the shear stains will be different. This results in a kink in the pile and locally intense moment and shear. Under these circumstances, it is essential to maintain the axial capacity of the pile. In concrete piles, this means preventing shear (i.e. diagonal tension) failure; formation of a plastic hinge may not lead to loss of axial capacity provided that the spiral confines the concrete core and the surrounding soil prevents overall buckling.

The expected seismic capacity of different pile types merits consideration because inspection and repair of deep foundations is very expensive. While the engineer should not plan to locate the inelastic action in the foundation, and should therefore protect it by capacity design procedures, the piles should still be furnished with good resistance and some ductility in the face of shear and bending forces.

In steel pipe piles, the pipe wall must be prevented from buckling under bending load, since such local buckling reduces axial capacity. This is controlled by the wall thickness to pile diameter ratio. AISC recommends $D/t \leq 3300/F_y$.

Pretensioned concrete piles can be designed and fabricated with sufficient spiral steel to inhibit splitting during driving and to provide the shear resistance and confinement needed during a seismic event. They are precast, so the location of the longitudinal and transverse reinforcement is known precisely, as is the cross-section of the concrete. The prestressing tends to close any flexural cracks. If hollow piles are used, the effectiveness of the spiral in confining the "core" concrete is subject to question because the concrete can spall inwards into the void regardless of the amount of spiral supplied (Pizzano, 1983). An effective way of overcoming this uncertainty is, after driving, to fill the piles with concrete in those regions where plastic hinges could occur. The fill concrete does not need to have the same strength as that of the pile itself because it is completely confined by the precast body of the pile..

Cast-in-drilled-hole piles offer significantly less reliable quality, particularly if they are relatively small in diameter and if they are constructed by placing the steel cage after concreting, as is unavoidable with auger-cast piles. The small diameter is important because any local wall defects of a given size have a larger relative effect on smaller piles. A 4" collapse in the wall represents the loss of 20% of the section in a 16" pile, but only 7% in a 32" diameter pile. Placing the steel after concreting prevents good control of the steel location. If the longitudinal steel is out of position, the pile's moment resistance is impaired. If the transverse steel is out of position, the core is not properly confined and the shear resistance is also likely to be reduced. Checking the location of the cage anywhere except at the top of the pile is essentially impossible. CIDH and auger cast piles are also not prestressed, and are typically made from lower strength, less durable, concrete than are precast piles.

5 Conclusions

Many different pile types are available for use in seismic regions. There are fundamental differences between driven and drilled piles with respect to the way that they are constructed and the certainty over the final, installed product. When selecting a pile type for a given application, the engineer should take account of installation methods and potential problems, potential defects in the final product, expected product quality and operational constraints, in addition to cost.

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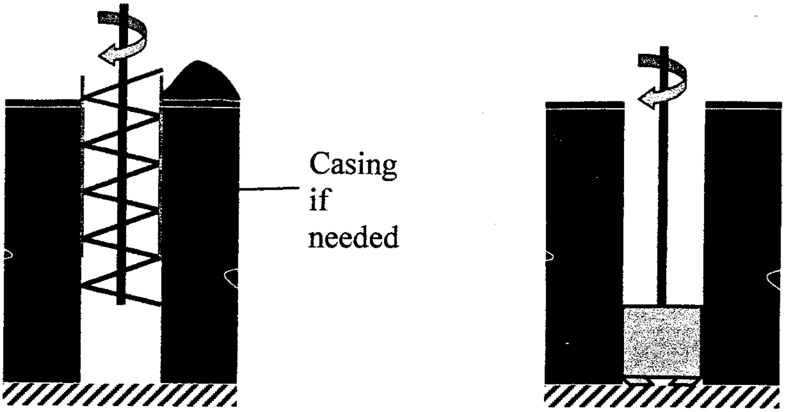
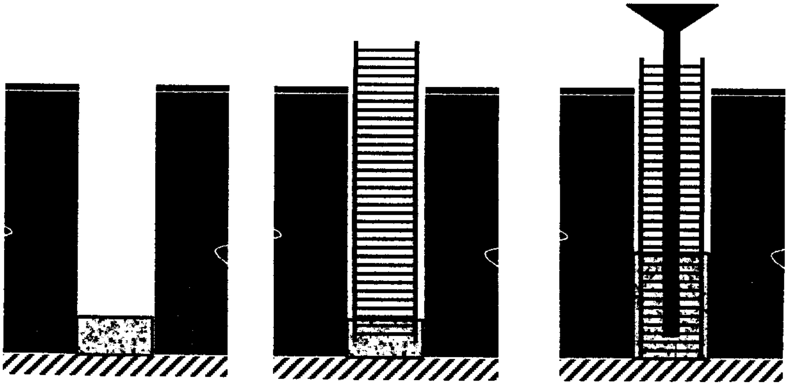


Drill with auger

Clean-out bucket



Concrete in bottom of shaft

Install rebar cage

Tremie concrete

Figure 1. **CIDH Piles – Installation Procedure.**

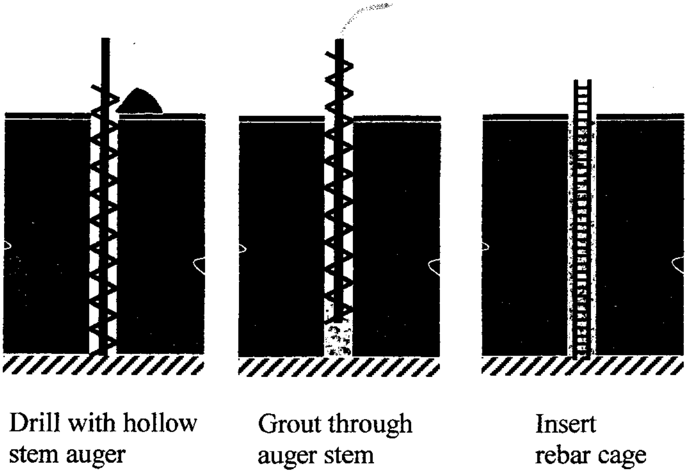


Figure 2. **Auger-cast Piles – Installation Procedure.**

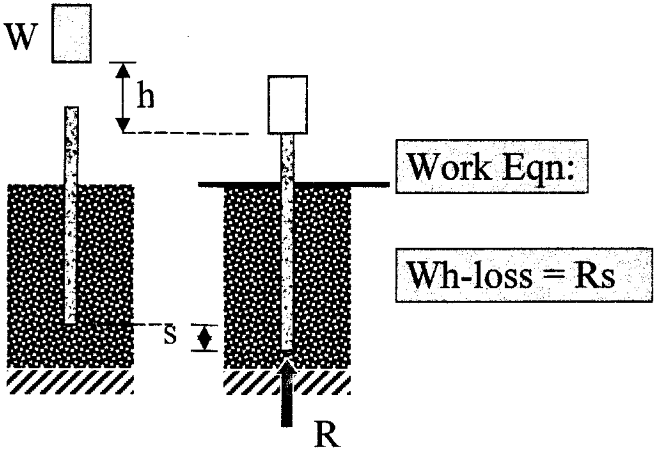


Figure 3. **Pile Driving.**

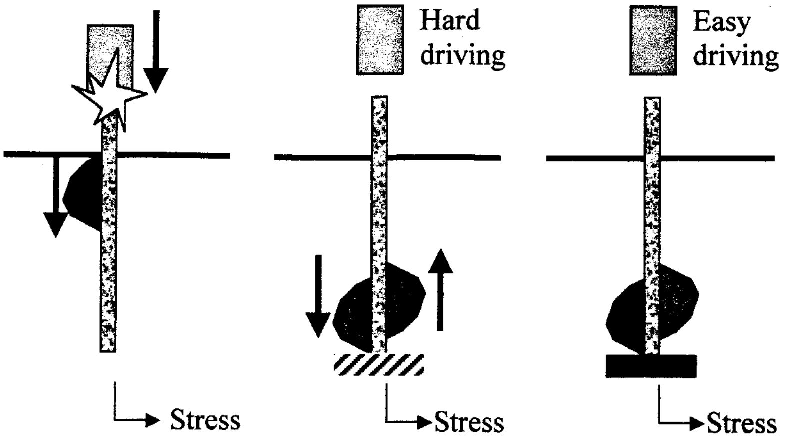


Figure 4. **Stress Waves in Driven Piles.**

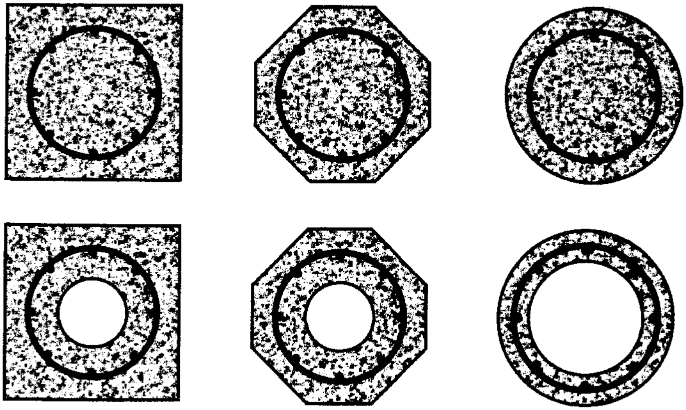


Figure 5. **Prestressed Concrete Pile Sections.**

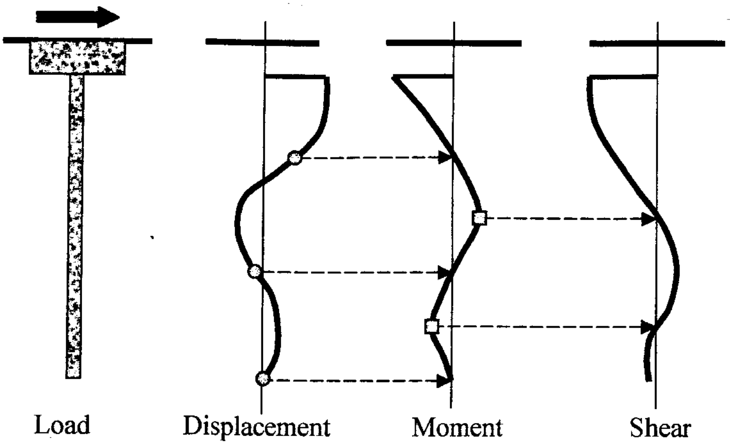


Figure 6. Lateral Loads on Piles: Top Loading

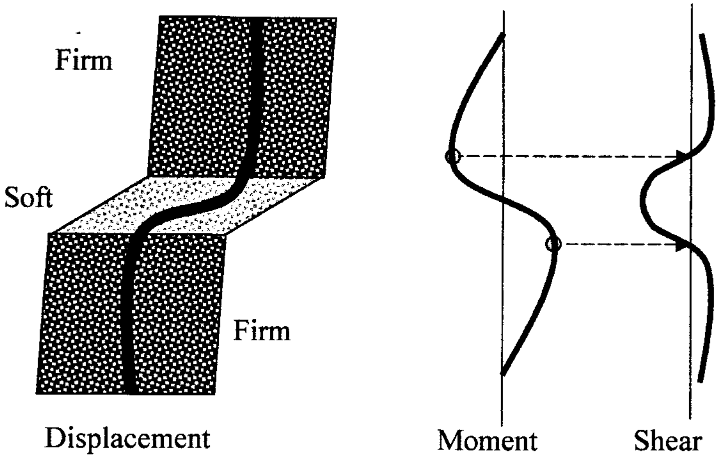


Figure 7. Lateral Loads on Piles: Soil Layer Loading