CHAPTER

7 Driven Piles

7-1 Introduction

Driving piles for structure foundations has occurred for centuries. Originally, timber was used for piles. In 1897, the first concrete piles were introduced in Europe, and the Raymond Pile Company drove the first concrete piles in America in 1904. These new concrete piles were designed for 30 tons and over. Currently, steel H-Piles and pipe piles are also used. These piles can be expensive but their ability to transfer greater loads has made them economical, particularly in large structures.

Pile driving is the operation of forcing a pile into the ground thereby displacing the soil mass across the whole cross section of the pile. Historically, the oldest method of driving a pile, and the method most often used today, is by use of an impact type hammer.

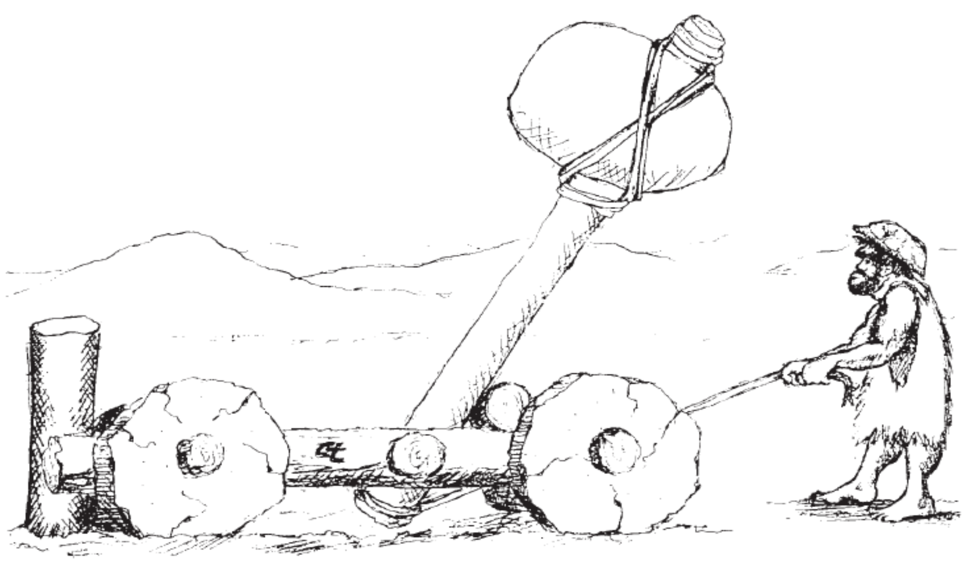

Figure 7-1. Early Pile Hammer.

The first hammers known to be used were drop hammers which were used exclusively until the invention of the steam engine, which eventually resulted in steam hammers. Subsequent technological advances have led to the development of air, diesel, hydraulic powered impact hammers, plus vibratory and sonic hammers. Modern day requirements for construction have also resulted in various adaptations of the aforementioned pile driving techniques.

This chapter is intended to outline specifications, equipment, techniques, and safety items that a bridge engineer can expect to encounter during typical pile driving operations.

7-2 General Specifications

The following is a partial list of some of the more important pile driving specifications. Before starting a project, the Engineer should thoroughly review the Standard Specifications for general requirements and the special provisions for information tailored to the needs of the specific project.

Typical sections of the Standard Specifications (SS) to be reviewed are as follows:

- *Earthwork* (SS, Section 19).
- *Piling* (SS, Section 49).
- *Wood and Plastic Lumber Structures* (SS, Section 57).

The following are taken from the Standard Specifications and should be reviewed as applicable:

- In embankment areas where piles are to be placed or driven, do not use material containing rocks, broken concrete, or other solid materials larger than 4 inches in greatest dimension.[1]
- For bridge footings to be constructed in embankment, construct the embankment to the grading plane elevation and extend the finished slope to the grading plane before:
  1. Excavating for footings.
  2. Driving piles or drilling holes for Cast-in-Place (CIP) piles.[2]
- Where an embankment settlement period is specified, and before the end of the settlement period, do not:
  1. Excavate for abutments, bent footings, wingwalls, or retaining wall footings.
  2. Drive foundation piles or drill holes for CIP piles.[3]
- Piling must have sufficient length to attain the specified trip elevation shown and extend into the pile cap or footing.[4]
- Install driven piles using an authorized impact hammer. The impact hammer must be:

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[1] 2010 SS, Section 19-6.02A, *Materials General,* or 2006 SS, Section 19-6.01, *Embankment Construction, Placing.*

[2] 2010 SS, Section 19-6.03A, *Construction General,* or 2006 SS, Section 19-6.01, *Placing.*

[3] 2010 SS, Section 19-6.03D, *Settlement Periods and Surcharges,* or 2006 SS, Section 19-6.025, *Settlement Period.*

[4] 2010 SS, Section 49-1.01D(1), *Quality Control and Assurance General,* or 2006 SS, Section 49-1.03, *Determination of Length.*

1. Steam, hydraulic, air, or diesel.
2. Able to develop sufficient energy to drive the pile at a penetration rate of not less than 1/8 inch per blow at the nominal driving resistance shown.[5]

- For piles to be driven through embankments constructed under the Contract, drive piles through predrilled holes where the depth of the new embankment at the pile location is in excess of five feet. The hole diameter must be at least 6 inches larger than the greatest dimension of the pile cross section. After driving the pile, fill the space around the pile to the ground surface with dry sand or pea gravel.[6]
- Except for piles to be load tested and sheet piles, drive piles to at least the nominal driving resistance and the specified tip elevation shown.[7]

The preceding specifications indicate that there are two different pile driving acceptance criteria: (1) A specific pile tip penetration, and (2) a prescribed bearing value. In all but a few cases, both of these criteria must be met in order to accept the pile.

7-3 Pile Driving Definitions

The following is a partial list of some of the definitions unique to the pile driving trade. These are the most common terms used and should be of benefit to those new to pile driving work. Refer to Figures 7-2 through 7-8 for the illustration of the defined terms.

Table 7-1. Pile Driving Terms and Definitions.

TERM	DEFINITION
Anvil	The bottom part of a hammer that receives the impact of the ram and transmits the energy to the pile.
Butt of Pile	The term commonly used in conjunction with the timber piles–the upper or larger end of the pile, the end closest to the hammer.
Cushion Blocks	Usually plywood pads placed on top of precast concrete piles to eliminate spalling.
Cushion Pad	A pad of resilient material or hardwood placed between the drive cap insert, or helmet, and drive cap adapter.
Drive Cap Adapter	A steel unit designed to connect specific type of pile to a specific hammer. It is usually connected to the hammer by steel cables.
Drive Cap Insert	The unit that fits over the top of pile, holding it in line and connecting it to the adapter.
Drive Cap System	The assembled components used to connect and transfer the energy from the hammer to the pile.
Follower	An extension used between the pile and the hammer that transmits blows to the pile when the pile head is either below the reach of the hammer (below the guides/leads) or under water. A follower is usually a section of pipe or "H" pile with connections that match both the pile hammer and the pile. Since the follower may absorb a

[5] 2010 SS, Section 49-2.01C(2), *Driving Equipment,* or 2006 SS, Section 49-1.05, *Driving Equipment.*
[6] 2010 SS, Section 49-2.01C(4), *Predrilled Holes,* or 2006 SS, Section 49-1.06, *Predrilled Holes.*
[7] 2010 SS, Section 49-2.01A(4)(b), *Pile Driving Acceptance Criteria,* or 2006 SS, Section 49-1.08, *Pile Driving Acceptance Criteria.*

TERM	DEFINITION
	percentage of the energy of the hammer, the contract specifications[8] require the first pile in any location be driven without the use of a follower so as to be able to make comparisons with operations utilizing a follower. In water, the first pile to be driven should be one sufficiently long to negate the need for the follower. The information from the first pile can be used as base information when using the follower on the rest of the piling. Beware of soil strata that may change throughout the length of a footing. Underwater hammers and extensions to the leads can be used as alternatives to driving with a follower.
Hammer Energy	The amount of energy available to be transmitted from the hammer to the pile. Usually measured in foot-pounds.
Leads	A wooden or steel frame with one or two parallel members for guiding the hammer and piles in the correct alignment. There are three basic types of leads: • Fixed, which are fixed to the pile rig at the top and bottom. Refer to Figure 7-4. • Swinging, which are supported at the top by a cable attached to the crane. Refer to Figure 7-5. • Semi-Fixed or Telescopic, which are allowed to translate vertically with relation to the boom tip. Refer to Figure 7-6.
Mandrel	A full-length steel core set inside a thin-shell casing. It increases the structural capacity of the casing so that it can be driven. It helps maintain pile alignment and prevents the casing from collapsing. It is removed after driving is completed and prior to placing reinforced concrete.
Moonbeam	A device attached to the end of a lead brace that allows a pile to be driven with a side batter.
Penetration	The downward movement of the pile per blow.
Pile Butt	A member of the pile crew other than the operator and oiler.
Pile Gate	A hinged section attached to the pile leads, at the lower end, which acts to keep the pile within the framework of the pile leads.
Pile Hammer	The unit that develops the energy used to drive piles, the two main parts of which are the ram and the anvil.
Pile Monkey	A device used to position the pile in the leads beneath the hammer.
Pile Rig	The crane used to support the leads and pile driving assembly during the driving operation.
Ram	The moving parts of the pile hammer, consisting of a piston and a driving head, or driving head only.
Rated Speed	The number of blows per minute of the hammer when operating at a particular maximum efficiency.
Spudding	Spudding is the driving of a short and stout section of pile-like material into the ground to punch through or break up hard ground strata to permit pile driving. Used extensively in the driving of timber piles.
Striker Plate	A steel plate placed immediately below the anvil. Also known as an anvil.
Stroke	The length of fall of the ram.
Tip of Pile	The first part of the pile to enter the ground.

[8] 2010 SS, Section 49-2.01C(2), *Driving Equipment,* or 2006 SS, Section 49-1.05, *Driving Equipment.*

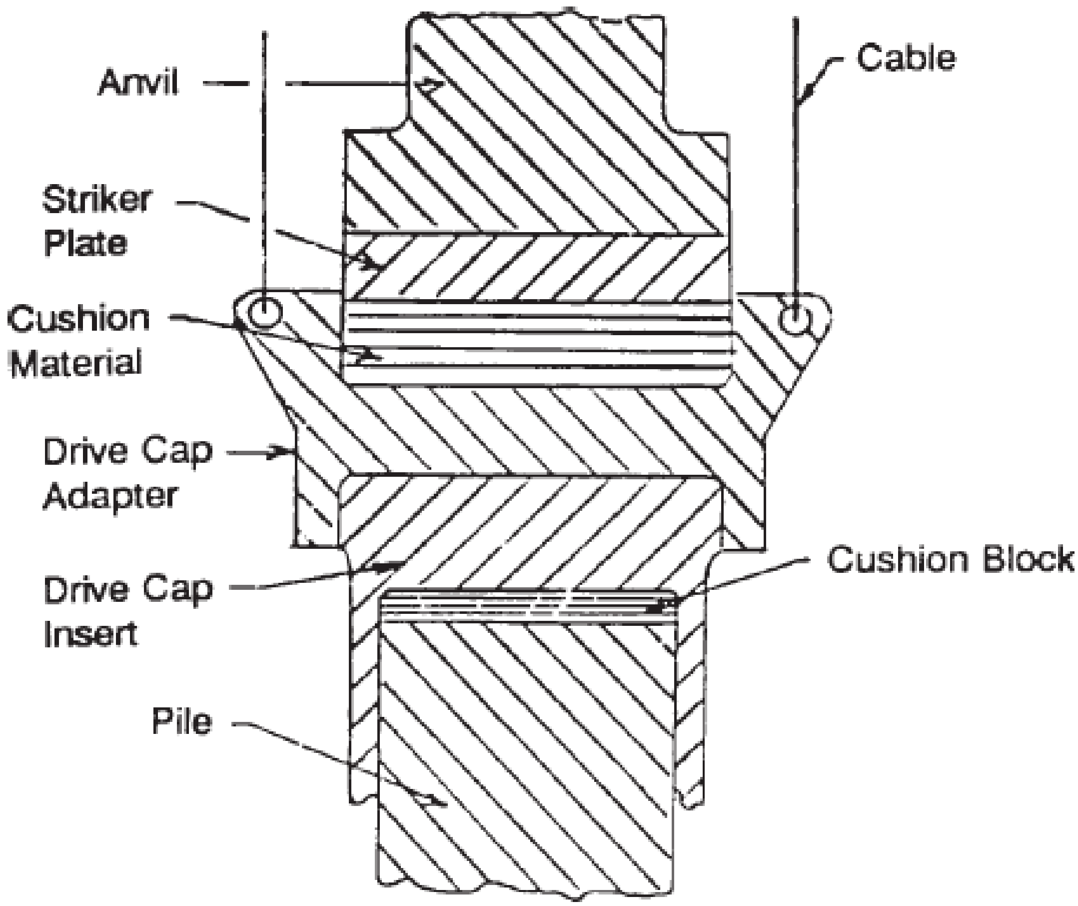

Figure 7-2. Drive Cap System.

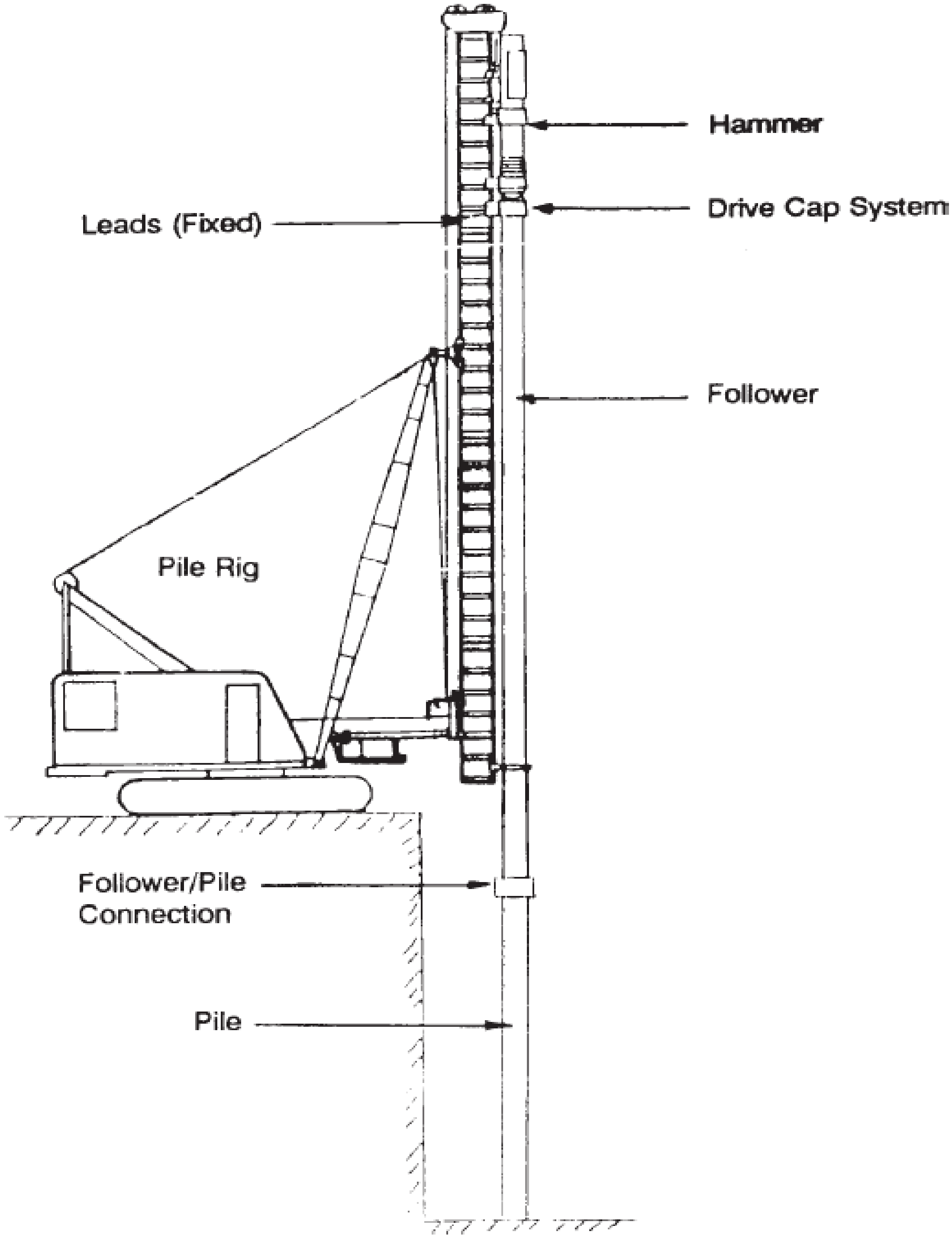

Figure 7-3. Typical Pile Rig Configuration.

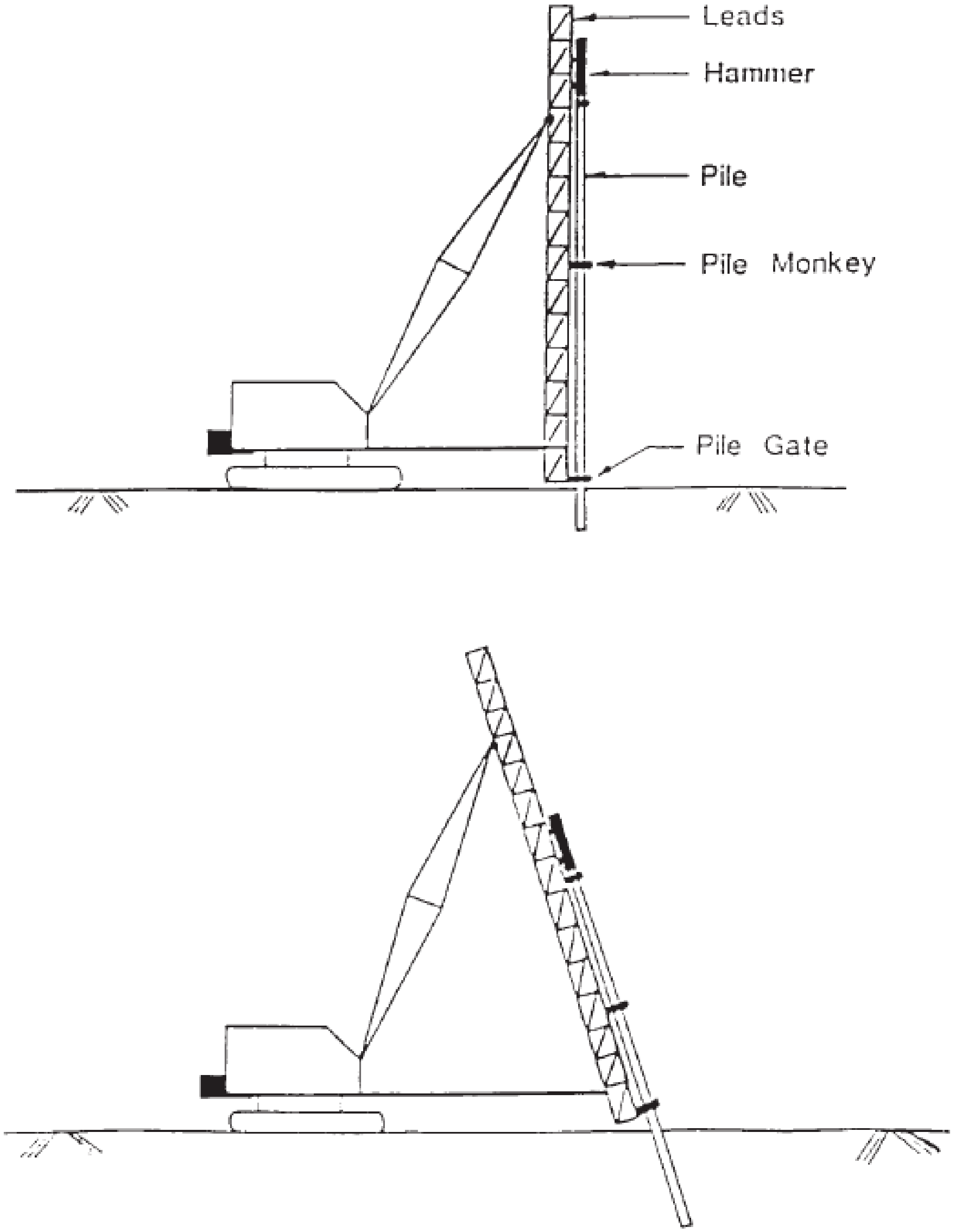

Figure 7-4. Fixed Lead System.

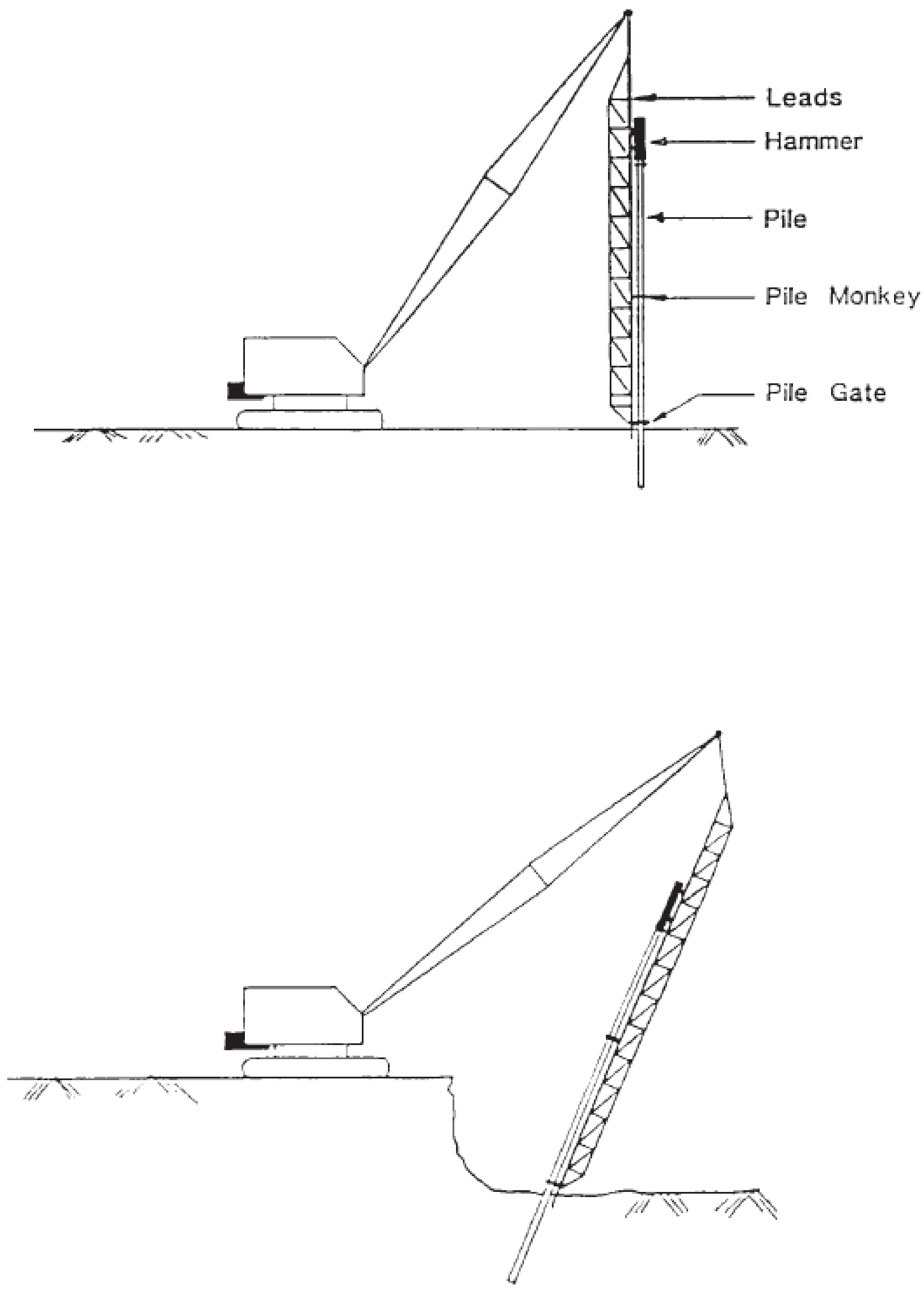

Figure 7-5. Swinging Lead System.

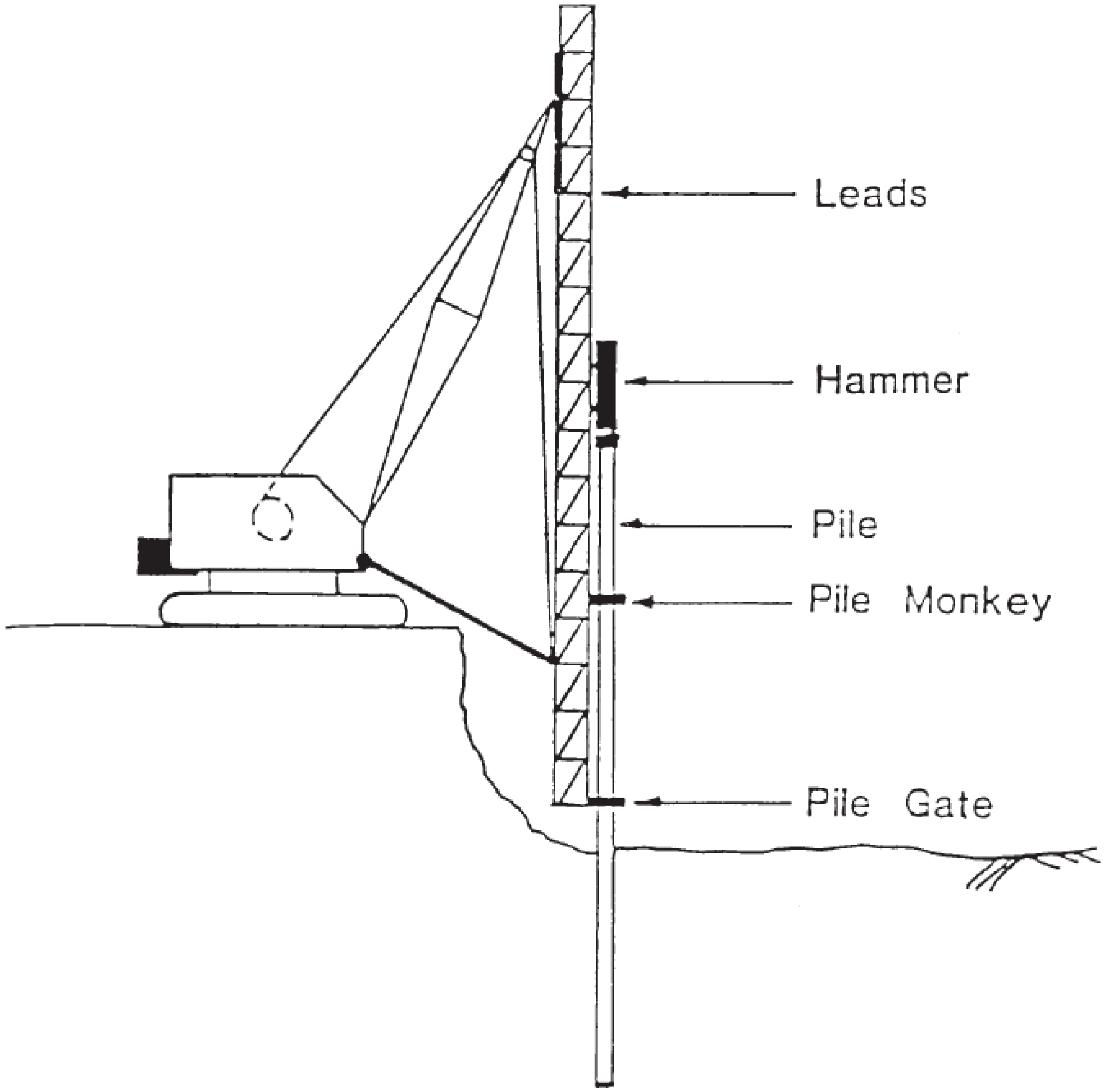

Figure 7-6. Semi-Fixed Lead System.

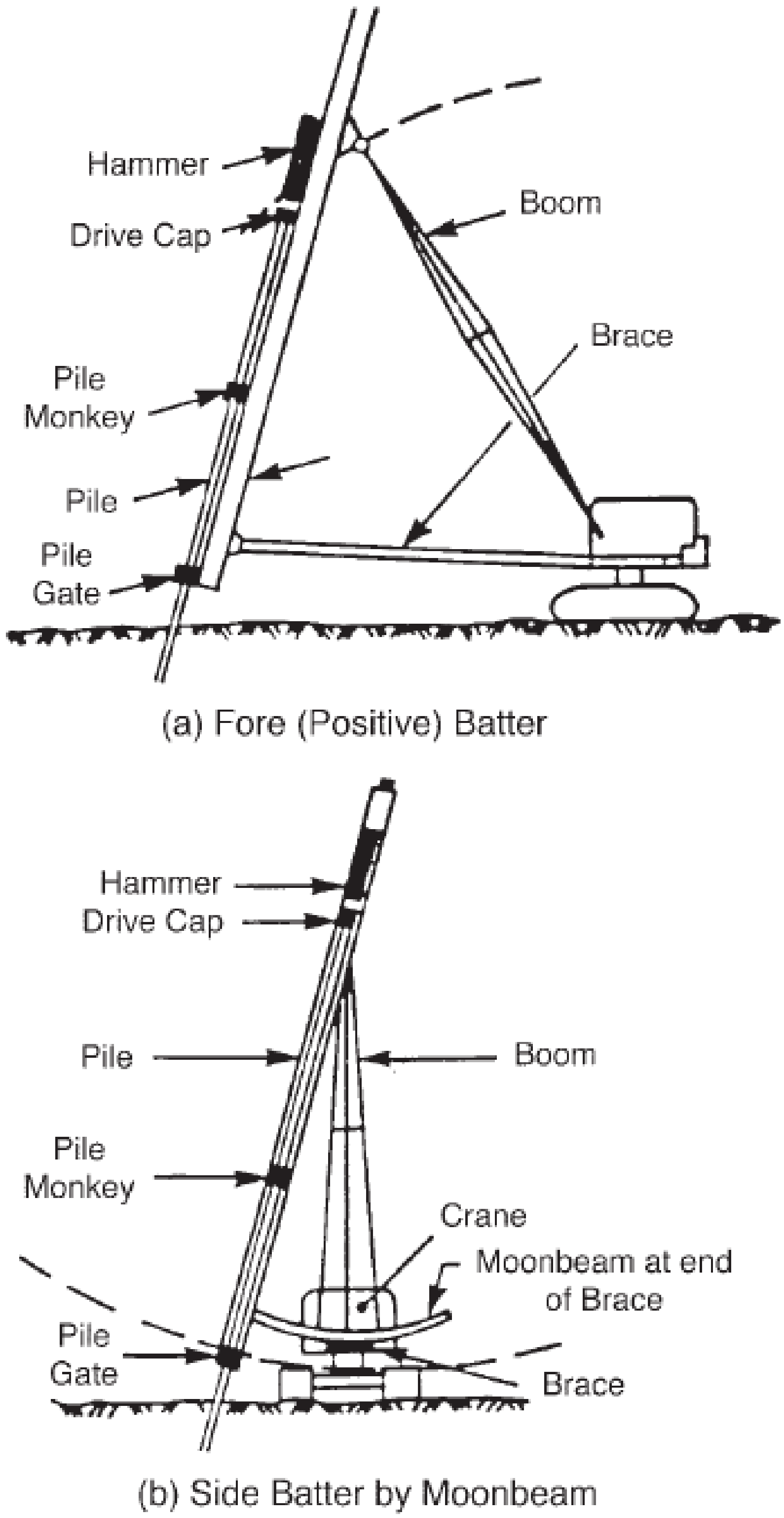

Figure 7-7. Lead Configurations for Battered Piles.

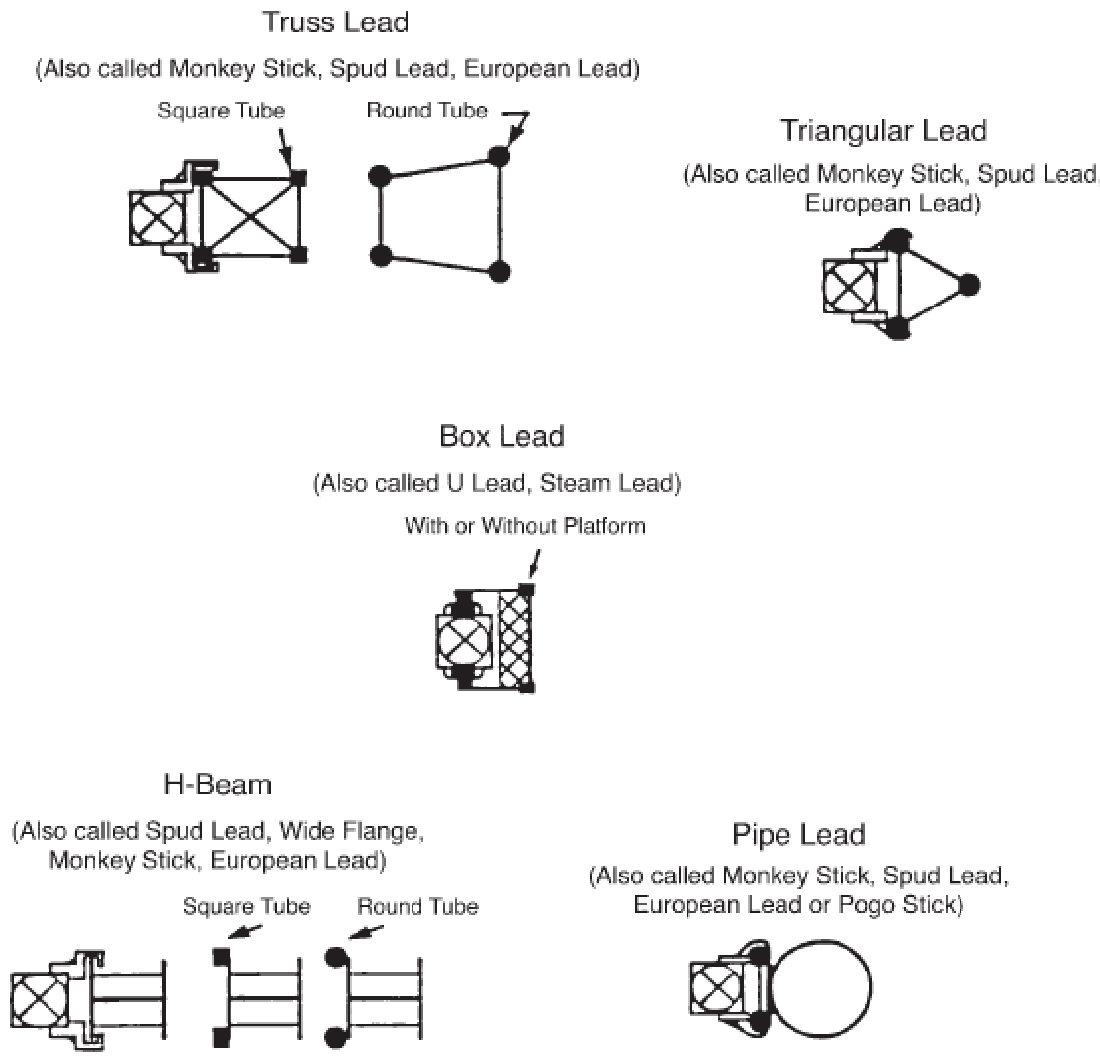

Figure 7-8. Lead Types.

7-4 Hammer Types

Many different types of pile driving hammers are used in the pile industry today. In the past, single acting diesel hammers were used on most projects. With the onset of retrofit work and new construction in areas with low overhead clearances, the use of double/differential acting hammers and hammers that require only a limited overhead clearance are finding their way to the job site. Site specific construction challenges, be it limited space, noise levels, or unusual tip or bearing requirements will tend to dictate the type of hammer used.

The pile hammer is not only the production tool for the Contractor, it is also a measuring device for the Engineer. The energy transmitted to the pile advances it toward the specified tip elevation. The amount of energy and the penetration per blow can be used to determine the bearing capacity of the pile. A working knowledge of pile hammers, their individual parts and accessories, and their basis for operation and the associated terminology is essential for the Engineer.

Following is a partial list of different types of hammers available today with a brief description of their limiting characteristics.

7-4.1 The Drop Hammer

Although the drop hammer was invented centuries ago, it is still in use today. Although modernized somewhat, the basic principle of operation remains the same. A weight is lifted a measured distance by means of a rope or cable and allowed to freefall, or drop, and strike a pile cap block. The available potential energy is calculated by multiplying the weight and the distance of the fall.

One variation of the drop hammer currently finding its way to the job site is one that requires only a minimal amount of headroom. The idea utilizes a closed-ended pipe pile with a large enough diameter to allow the drop hammer run inside the pipe's walls. The hammer impacts onto a "stop" built into the bottom, inside of the pipe pile. As the pile is driven, the impact occurs near the tip of the pile. In fact the pile is actually pulled down into position in lieu of being pushed. This configuration minimizes the need for the additional overhead clearance (leads, crane, etc.).

Drop hammers are not typically used and are permitted only when allowed by the special provisions.

When using a drop hammer the Engineer should:

Table 7-2. Drop Hammer Actions

NO.	ITEM DESCRIPTION
1	Ensure that you have the correct weight for the hammer being used. If in doubt, have it weighed.
2	Ensure the drop hammer lead sections are properly aligned and that all lead connections are properly tightened.
3	Ensure, while in use, that the hoist line is paying out freely.

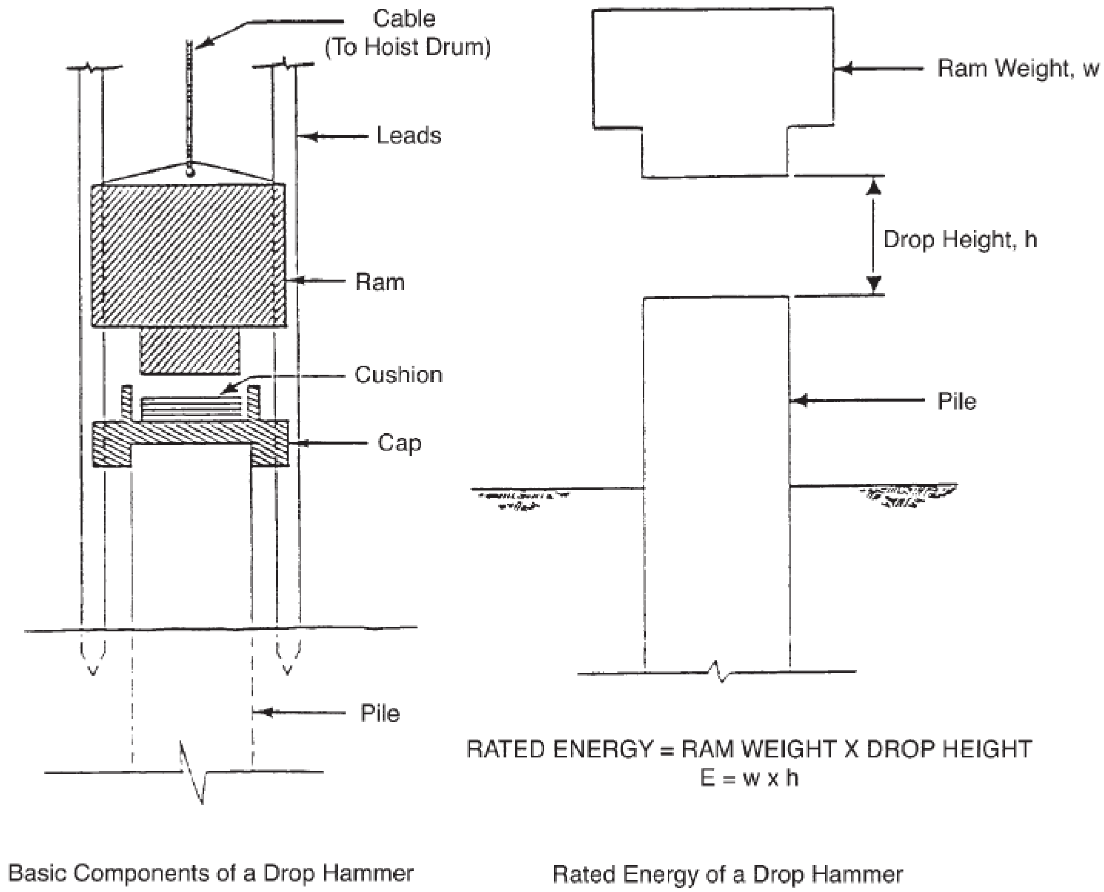

Figure 7-9. Drop Hammer.

7-4.2 Single Acting Steam/Air Hammer

The single acting steam/air hammer is the simplest powered hammer. Invented in England by James Nasmyth in 1845, it has been used in this country since 1875.

As shown in Figure 7-10, the hammer consists of a heavy ram connected to a piston enclosed in a chamber. Steam or air is supplied to lift the ram to a certain height. The lifting medium is then exhausted and the ram falls by its own weight. The rated energy of the single acting steam/air hammer is calculated by multiplying the ram weight (total weight of all moving parts: ram, piston rod, keys, slide bar, etc.) times the length of fall (stroke).

These hammers have a stroke of 30 to 40 inches and operate at 60 to 70 strokes per minute. They are rugged and deliver a relatively low velocity heavy blow. The only necessary changes in operation from steam to air are a change in the general lubrication and the hose line specification.

When using a single acting steam/ air hammer the Engineer should:

Table 7-3. Single Acting Steam/Air Hammer Actions.

NO.	ITEM DESCRIPTION
1	Have the manufacturer's current specifications for the type and model of hammer being used.
2	Ensure all required parts of the hammer are intact and in good operating condition.

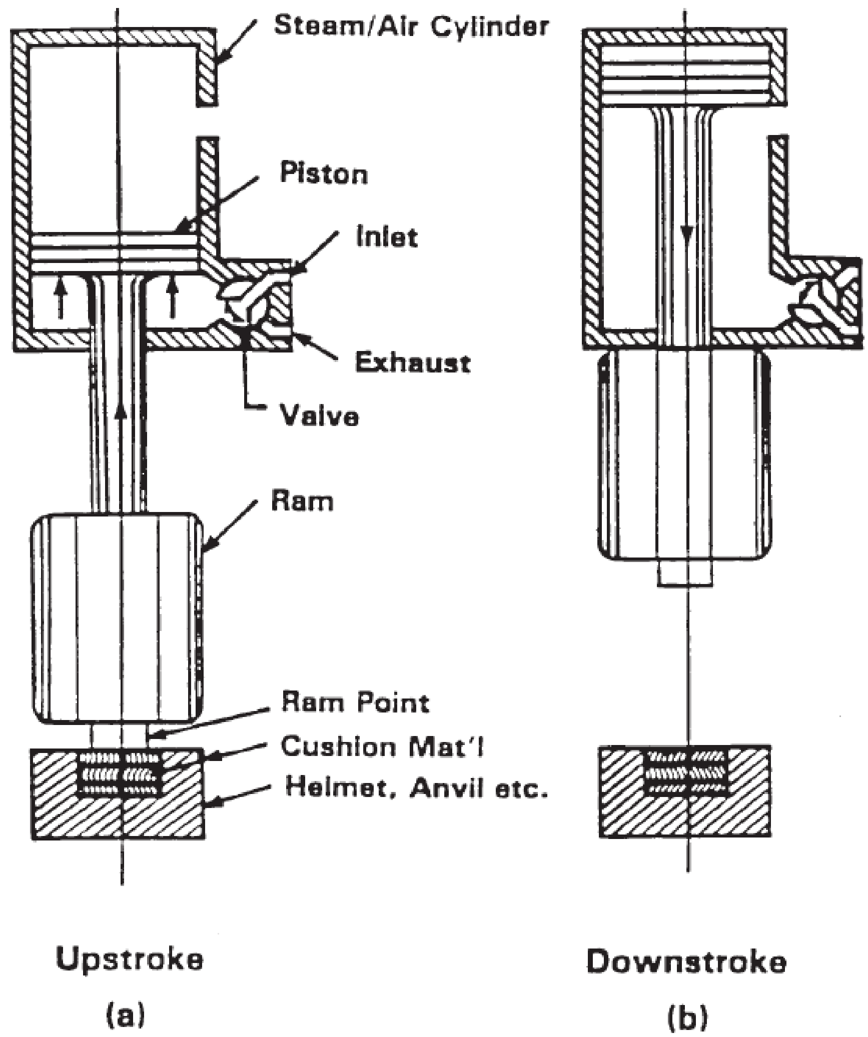

Figure 7-10. Single Acting Steam/Air Hammer.

7-4.3 Double Acting Steam/Air Hammer

The double acting steam/air hammer employs steam or air, not only to lift the piston to the top of its stroke, but also to accelerate the piston downward faster than by gravity alone. The additional energy put into the downward stroke by the compressed air/steam increases the effectiveness of the hammer. The advantage of the double-acting hammer is that stroke lengths can be reduced making them ideal in low overhead clearance situations. The stroke typically ranges from 10 to 20 inches, or about half that of a single-acting hammer. The blow rate is more rapid than the single acting hammer, somewhere between 120 and 240 blows per minute. Refer to Figure 7-11. The rated available energy of the double acting steam/air hammer is calculated by multiplying the ram weight times the length of stroke and adding the effective pressure acting on the piston head during the downstroke.

In addition to being an ideal hammer in low overhead situations, this type of hammer does not use a cushion block between the ram and the anvil block. Another advantage is that some of these hammers are entirely enclosed and can be operated submerged in water. With this type hammer, it is essential that the hammer is operating within the manufacturer's specifications. Since pressure is used to drive the hammer, it's imperative that operating pressures are known. The pressures recorded will correlate to an impact energy found on a chart/table provided with the hammer.

When using a double acting steam hammer the Engineer should:

Table 7-4. Double Acting Steam Hammer Actions.

NO.	ITEM DESCRIPTION
1	Have the manufacturer's current specifications for the type and model of hammer being used.
2	Ensure all required parts of the hammer are intact and in good operating condition.
3	Have chart available declaring rated energy vs. operating speed of hammer.

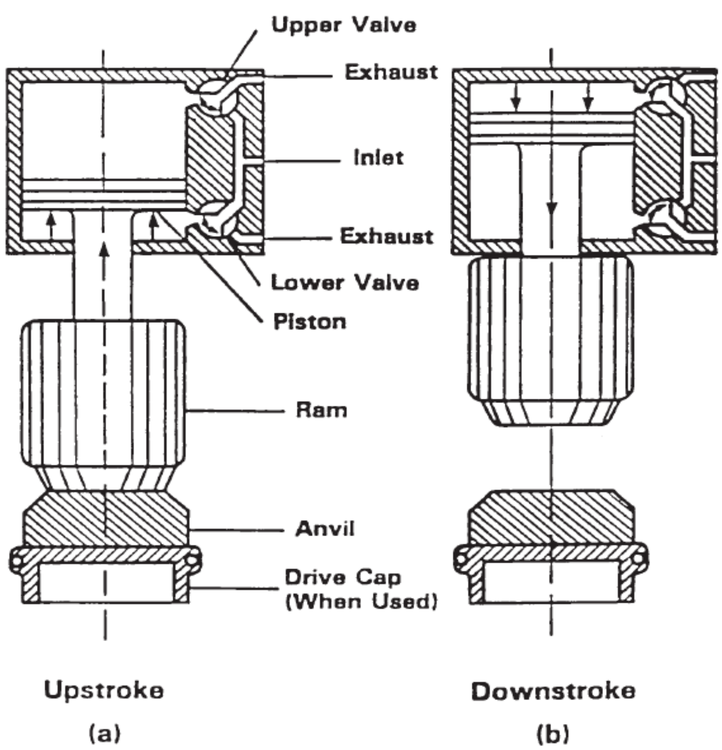

Figure 7-11. Double Acting Steam/Air Hammer.

7-4.4 Differential Acting Steam/Air Hammer (External Combustion Hammer)
The differential acting steam/air hammer is similar to a double acting hammer. Compressed air/steam is introduced between large and small piston heads to lift the ram to the top of its stroke. The valves are then switched so that the medium (motive fluid) used to lift the ram accelerates it in its down stroke. Refer to Figure 7-12. When hydraulic fluid is used as a motive fluid it is called a double/differential acting hydraulic hammer.

The rated striking energy delivered per blow by a differential acting steam/air hammer is calculated by (1) adding the differential force due to the motive fluid pressure acting over the large piston head (2) to the weight of the striking parts and (3) multiplying this sum by the length of the piston stroke in feet. The differential force results from the fluid pressure acting on the top piston head surface minus the same pressure in the annulus acting on the bottom surface and is equal to the area of the small piston head times the fluid pressure. This type of hammer uses a cushion block between the ram and the helmet.

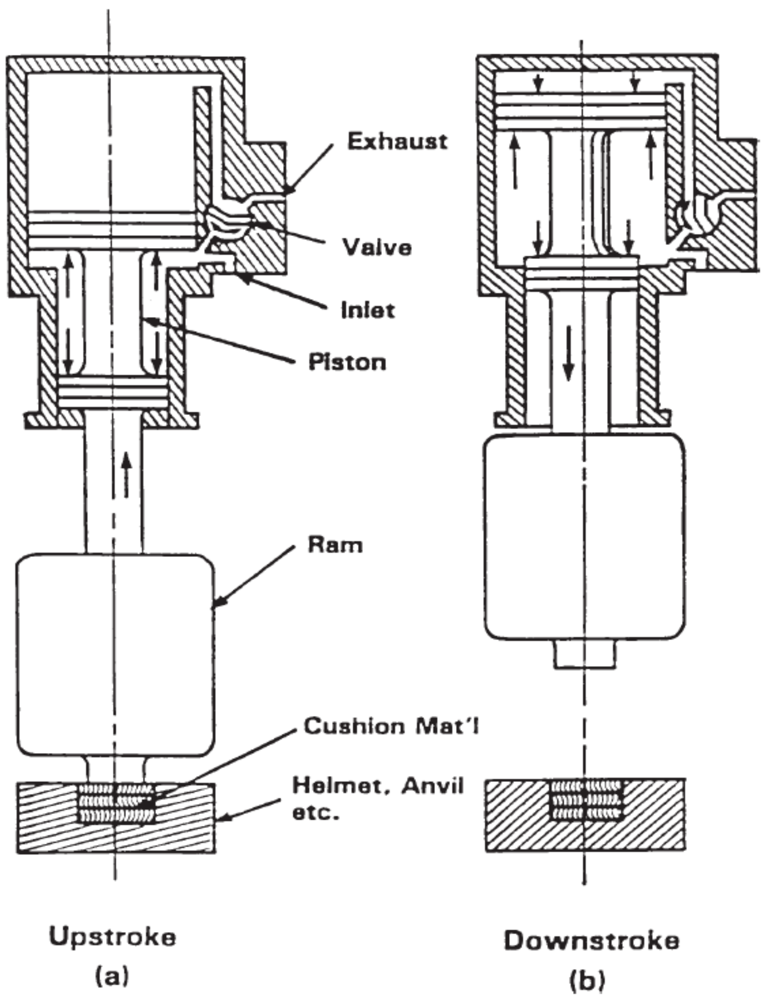

Figure 7-12. Differential Acting Steam/Air Hammer.

When using a differential acting steam/air hammer the Engineer should:

Table 7-5. Differential Acting Steam/Air Hammer Actions.

NO.	ITEM DESCRIPTION
1	Have the manufacturer's current specifications for the type and model of hammer being used.
2	Ensure all required parts of the hammer are intact and in good operating condition.
3	Have chart available declaring rated energy vs. operating speed of hammer.

7-4.5 Diesel Pile Hammer

In the early 1950's a new type of pile driving hammer was introduced - the Diesel Hammer. Basically, it is a rudimentary one-cylinder diesel engine. It is fed from a fuel tank. The tank and fuel pump are mounted directly on the hammer, in contrast to air and steam hammers, which require an external energy source. Simple to operate, diesel hammers are commonly used on most bridge contracts today.

7-4.5.1 Single Acting Diesel Hammers.

The fundamental makeup and operation of all diesel hammers are similar. They consist of a cylinder-encased ram, an anvil block, a lubrication system, and a fuel injection system that regulates the amount of fuel to each cycle. New models added a variable fuel metering system that can change the energy delivered by the ram, thereby making them more versatile for varying soil conditions. The energy imparted to the driven pile is developed from gravitational forces acting on the mass of the piston. Refer to Figure 7-13. The operational cycle of the single acting diesel hammer is shown on Figure 7-14 and is described in the following paragraphs.

To start operations, a cable from the crane lifts the ram. At the top of the stroke, the lifting attachment is "tripped" and the ram (piston), is allowed to drop. The ram falls by virtue of its own weight and activates the cam on the fuel injector that injects a set amount of fuel into the cup-shaped head of the impact block. As soon as the falling ram passes the exhaust ports, air is trapped in the cylinder ahead of the ram, and compression begins. The rapidly increasing compression pushes the impact block (anvil) and the helmet immediately below it against the pile head prior to the blow.

Upon striking the impact block with its spherically shaped leading end, the ram drives the pile into the ground and, at the same time atomizes the fuel which then escapes into the annular combustion chamber. The highly compressed hot air ignites the atomized fuel particles and the ensuing two-way expansion of gases continues to push on the moving pile while simultaneously recoiling the ram.

As the upward flying ram clears the exhaust ports, the gases are exhausted and pressure equalization in the cylinder takes place. As the ram continues its upward travel, fresh air is sucked in through the ports, thoroughly scavenging and cooling the cylinder. The cam on the fuel injector returns to its original position allowing new fuel to enter the injector for the next working cycle. The operator may stop the hammer manually by pulling a trigger, which deactivates the fuel supply.

The diesel hammer is difficult to keep operating when driving piles in soft material. Large downward displacements of the pile absorb most of the energy; therefore, little remains to lift the ram high enough to create sufficient compression in the next downstroke to ignite the fuel. To resume operation, the cable hoist must again raise the ram.

It is generally accepted that the energy output of an open-end diesel hammer is equal to the ram weight times the length of stroke. This combination ignores any component of the explosion that acts downward. In production pile driving, the stroke is really a function of the driving resistance, the pile rebound, and the combustion chamber pressure. The combustion chamber pressure is affected by the general condition of the hammer as well as the fuel timing and the efficiency of combustion. Accordingly, manufacturer's energy ratings are based upon the hammer operating at refusal with almost all the energy of combustion developing the upward ram stroke leaving just the weight of the ram and the stroke left to determine energy.

Diesel hammers are very versatile. They may be connected to almost any set of leads. They do not require an additional energy source, such as steam or air so the size of the pile crew can be reduced. On occasion, piles are driven with crews of as few as three workers, including the crane operator. These hammers typically operate within a speed of 40 to 60 blows per minute and can have strokes in excess of 10 feet. Although these hammers will drive any type of pile, their stroke is dependent on soil conditions. Hard driving in harder soils results in increasing stroke lengths, thus providing increasing hammer energies; while easy driving in softer soils results in lower stroke lengths and lower hammer energies. It should be noted that diesel hammers are deemed to be noisy and are viewed as environmentally unfriendly by some as they tend to spew oil and grease and emit "unsightly" exhaust.

When using a diesel hammer the Engineer should:

Table 7-6. Single Acting Diesel Hammer Actions.

NO.	ITEM DESCRIPTION
1	Have the manufacturer's current specifications for the type and model of hammer being used.
2	Ensure all required parts of the hammer are intact and in good operating condition.
3	Have chart available declaring rated energy vs. operating speed of hammer.
4	Be aware of the actual stroke of the hammer during driving and that it will vary depending on soil resistance.

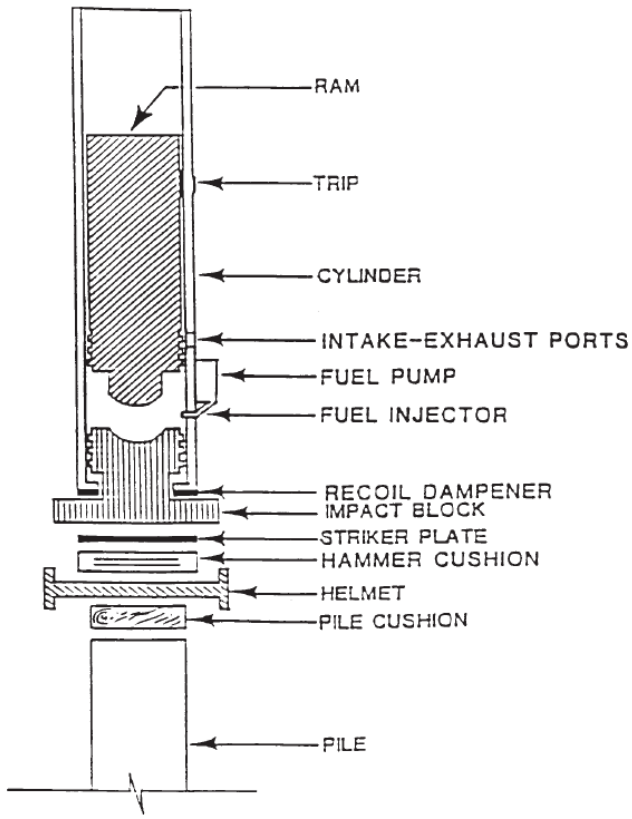

Figure 7-13. Single Acting Diesel Hammer.

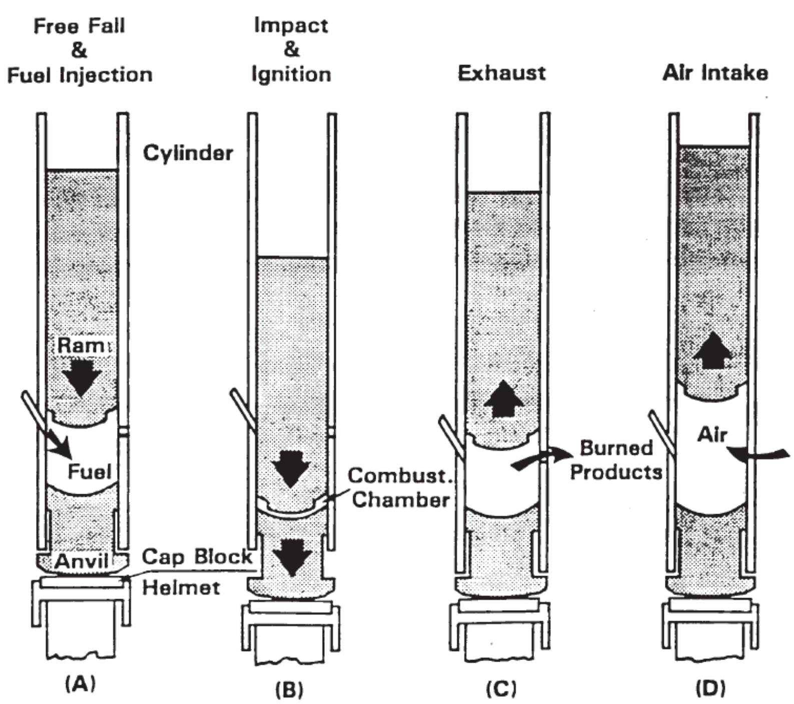

Figure 7-14. Operational Cycle for Single Acting Diesel Hammer.

7- 4.5.2 Double Acting Diesel Hammer

The double acting diesel hammer is similar in its operations to other double acting hammers. The top of the cylinder is capped so that pressures can be developed on the downward stroke. The energy transferred is more than just a function of gravity. As the ram nears the top of its upward stroke, air is compressed in a “bounce chamber”. This halts the upward flight of the ram as pressure increases. The downstroke energy now becomes a function of both gravity and the internal pressure generated in the “bounce chamber”. The hammers have a stroke that is typically around 3 to 4 feet and operate at a much higher/quicker blow rate compared to the single acting diesel hammer. Refer to Figure 7-15.

These hammers normally have a manually operated variable fuel injector, which is controlled by the crane operator. Unless the control is wide open, the energy delivered is difficult to determine. The rated energy needs to be computed from a formula incorporating the length of the free fall downstroke of the ram multiplied by the sum of its weight and adding the effects of changes in pressures and volumes of air in the bounce/scavenging chambers of the hammer. Manufacturers have plotted the solutions to the formulae for each model of hammer for various pressure readings in the bounce chamber.

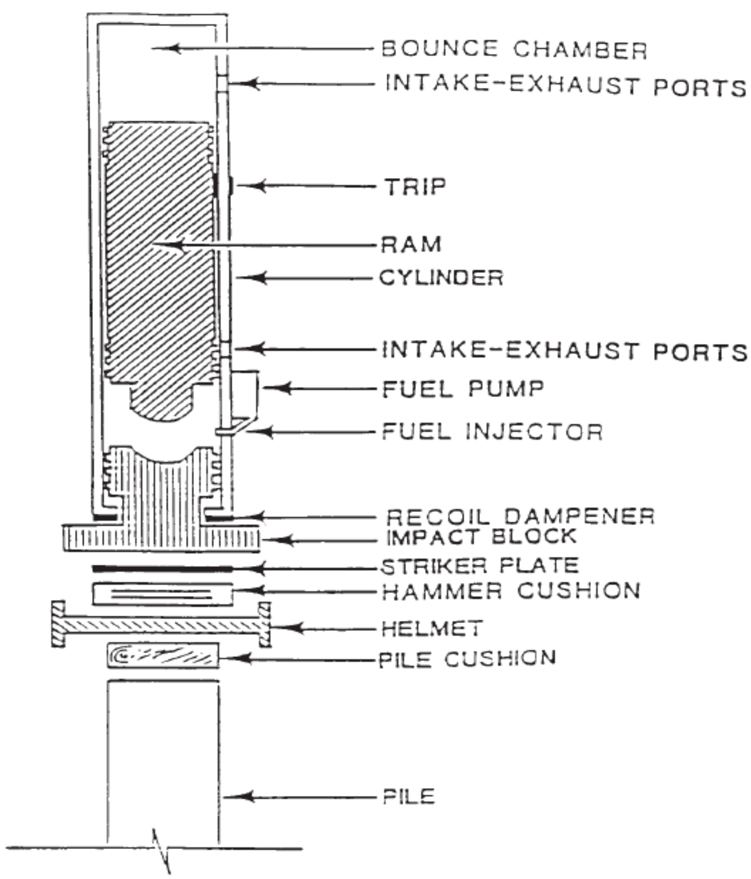

Figure 7-15. Double Acting Diesel Hammer.

When using a double acting diesel hammer the Engineer should:

Table 7-7. Double Acting Diesel Hammer Actions.

NO.	ITEM DESCRIPTION
1	Have the manufacturer's current specifications for the type and model of hammer being used.
2	Ensure all required parts of the hammer are intact and in good operating condition.
3	Ensure the energy chart made available by the manufacturer is the correct one for the model of hammer being used and that there has been a recent calibration or certification of the bounce chamber gauge.

7-4.6 Vibratory Driver/Extractor

Vibratory pile drivers/extractors could be likened to a mini-stroke, high blow rate hammers. However, the familiar vibratory pile drivers in standard use today do not contain linearly reciprocating weights or rams. Instead, they employ two balanced rotating weight sets, which are eccentric from their centers of rotation. Moving in opposite directions, they impart a vibration that is entirely vertical. This motion is transmitted to the pile through the hydraulic clamps of the driving head. The pile in turn transmits the vibratory action to the soil allowing the soil granules to be more readily displaced by the pile tip. The same action works even more effectively for extracting piles. Refer to Figure 7-16.

The effectiveness of a vibratory unit is dependent upon the interrelationship of the performance factors inherent to the unit. The larger the eccentric moment, the more potential vibratory force the driver possesses. In order to realize this potential force, the driver must operate with the proper frequency and amplitude.

With heavier piles, there is a higher vibratory weight supported by the hammer. This tends to reduce the amplitude. So as piles get larger, it is necessary to use drivers with larger eccentric moments. The non-vibratory weight has the effect of extra weight pushing the pile downward.

Vibratory drivers are most effective in granular soil conditions, but recent developments and new techniques have also made them effective in more cohesive soils. They can handle a variety of piling, including steel sheets, steel pipe, concrete, timber, wide flange sections, "H" piles, as well as caissons. They do not create a large amplitude ground vibration compared to impact pile hammers discussed previously. This makes the vibratory hammer desirable in areas where excessive ground motions could possibly cause damage to adjacent structures.

The contract specifications[9] prohibit the use of the vibratory hammer for driving permanent contract piles because there is no way to determine the amount of energy delivered to the pile. However, contractors frequently use vibratory hammers to install

[9] 2010 SS, Section 49-2.01C(2), *Driving Equipment,* or 2006 SS, Section 49-1.05, *Driving Equipment.*

temporary works (i.e. placing and extracting sheet piles for shoring, etc.). These hammers are also used to extract piles.

Although vibratory hammers cannot be used when there is a nominal driving resistance requirement, the vibratory hammer has occasionally been permitted to install a bearing pile to a point above the expected final penetration. An impact hammer authorized for this operation is then placed upon the pile to drive it to acceptable bearing and final penetration values. A situation where this technique is useful is where alignment of a pile is critical. The vibratory hammer allows the operator to minimize the rate of penetration of a pile, thereby allowing for more precise alignment of a pile as it gets started into the ground.

There have been comparisons made in the recent past indicating variances in bearing capacities of piles when comparing a pile driven to the same elevation with a vibratory hammer and one driven with an authorized impact hammer. Items of interest and discussion include the *set* of the pile and the disturbance of the soil mass. The vibration of the pile against the soil may reduce the amount of skin friction on the pile leading to lower nominal resistances than what would have occurred if the pile were driven without vibratory means. This condition may be temporary. Depending on the soil, the skin friction may return in full or in part as the soil remolds or sets over time.

When a request is made to use a vibratory hammer to start a pile, the Engineer should:

Table 7-8. Vibratory Hammer Actions.

NO.	ITEM DESCRIPTION
1	Be aware of specific pile requirements and limitations stated in the contract specifications.
2	Discuss the proposal with the Bridge Construction Engineer, the Designer, and the Geoprofessional.

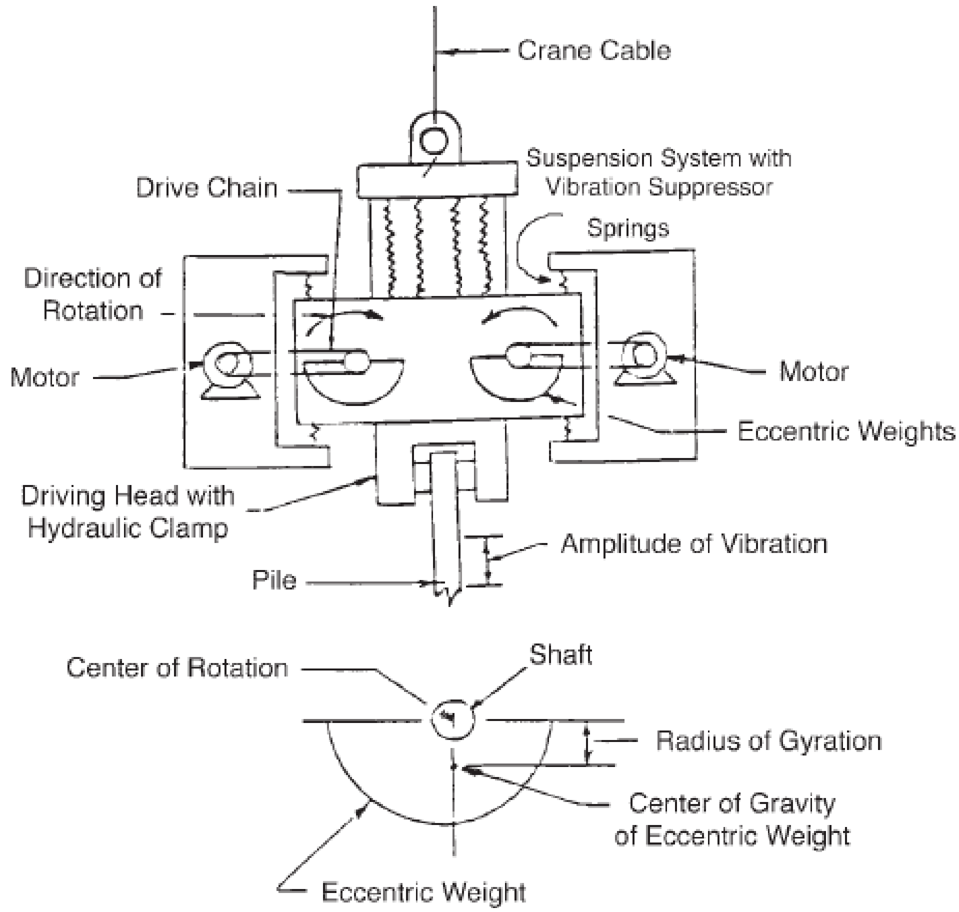

Figure 7-16. Vibratory Driver/Extractor.

7-4.7 Hydraulic Hammers

A hydraulic hammer incorporates an external energy source to lift the hammer to the top of its stroke. For the single acting hydraulic hammer, the free-falling piston provides the energy induced into the pile, much the same as a drop hammer or a single acting diesel hammer. The rated energy for the differential acting hydraulic hammer is found by means similar to other differential acting hammers. Refer to the previous section on differential acting steam/air hammers.

The theories of energy delivery and transfer vary between differential hydraulic hammers. For example, one particular hydraulic hammer manufacturer utilizes a ram made of composite material. In this case, it is made of lead wrapped in steel. The theory behind the lead ram is that a heavier weight falling a similar distance should produce blows with longer impact durations. This longer impact duration produces a compression wave that is low in amplitude and long in duration. It is thought that this type of blow is more efficient in terms of delivering driving energy to the tip of the pile (relative to a lightweight hammer with a longer stroke).

The hydraulic hammer has a variable stroke, which is readily controlled from a detached control box either located in the cab with the crane operator or otherwise. With the control box the stroke can be varied, finitely (reported to be in the centimeter range), such that the stroke can be optimized so that it matches the dynamic spring constant of the hammer and pile. Manufacturers have stated that the ability to vary the stroke and frequency enables these hammers to perform more efficiently than other types of hammers.

The general theory behind the hammer is as follows: Every ram body, depending on material and cross sectional area, has its own dynamic spring constant. Likewise, each pile, based on different materials and sizes, has its own dynamic spring constant or acoustic impedance. As the dynamic spring constants for the pile and the hammer converge, higher efficiencies can be achieved. Energy will be transmitted through the pile to the tip with fewer losses and at lower internal stresses. Essentially all the hammer energy will go into moving the pile since the losses in the pile were minimized. The greatest efficiency is achieved when the hammer impedance is the same as the pile impedance. If this were to occur, a pile cushion would be unnecessary and driving would be further optimized.

The manufacturer data sheets for these types of hammers state the following:

Table 7-9. Hydraulic Hammer Manufacturer Claims.

NO.	ITEM DESCRIPTION
1	Hammer efficiencies in the range of 80% to 98%, while saying that diesel hammers have efficiency in the range of 30% to 40%.
2	Due to the increased efficiency of the hammers and because more energy is transmitted through the hammer, there is less internal stress of the pile, less pile damage, etc.
3	They claim the operation to be quieter than the typical diesel hammer.
4	The typical exhaust of the diesel hammer is eliminated, since only the motor driving the hydraulics is the source of exhaust.
5	Avoids diesel hammer problems of soft ground starting and operating in extreme climates.

7-4.8 General Hammer Information

The contract specifications[10] require the Contractor furnish an authorized hammer with sufficient energy to drive piles at a penetration rate of not less than 1/8-inch per blow at the required bearing value. In effect, this specification places a lower limit on the hammer size because hammer size, in most cases, is related to energy. An upper limit is not specified; however some hammers may be too large for the intended use and may damage the pile during installation.

Economics often dictate the selection of hammer size and type. Large hammers provide vast amounts of energy that will advance the pile quickly and reduce driving time. They also help achieve specified tip elevations when hard driving is encountered, thus enabling

[10] 2010 SS, Section 49-2.01C(2), *Driving Equipment,* or 2006 SS, Section 49-1.05, *Driving Equipment.*

completion of the work without the need of supplemental measures such as jetting or drilling. On the other hand, heavy hammers require heavy leads and heavy cranes; the result being decreased mobility and increased equipment costs. Another consideration is that larger hammers deliver more energy to the pile. Hence, the probability of pile damage (heavy spalling, buckling, or other) increases as the hammer size increases. Ram impact velocity is another important factor. In general, a large ram weight with a short stroke and low velocity at impact will not produce the magnitude of pile stress that a light ram with a long stroke and high velocity will induce. Generally, at constant driving energy, the driving stress on the pile will decrease as the ram weight increases. Though there are situations where the *bigger hammer* may be too big and will overstress the pile. However, the option to run a bigger hammer at less than the maximum capacity, with a shortened stroke, may help, as the impact durations are different. Refer to the section on hydraulic hammers for more information on impact duration.

7-5 Nominal Resistance/Bearing Capacity

Pile driving formulas have been developed over the years to determine the nominal resistance of driven piles. There are many different (at least 450) pile driving formulas, the more notable of these being the Gates, Hiley, Pacific Coast Uniform Building Code, Janbu, and the ENR. Refer to Appendix E for examples. They have been empirically developed through testing and research. They utilize known information such as the energy delivered per blow, the resistance to the movement of the pile per blow, pile penetration, and some acknowledgement or estimates of the unknown or unquantifiable that serves to drive and/or resist the pile. All of the driving formulas make use of the conservation of energy theory:

(HAMMER ENERGY) – (ENERGY LOSSES) = (WORK PERFORMED)

Soil resistance multiplied by pile penetration represents work performed, hammer stroke multiplied by ram weight represents hammer energy, and various factors and/or constants in driving formulas are derived to represent energy losses in the piling system. The desired objective is to account for the most significant energy losses so that soil resistance can be estimated. Some of the energy losses associated with pile driving are hammer combustion and mechanical inefficiency, hammer and pile cushion restitution, dynamic soil resistance and pile flexibility. No pile driving formula accounts for all energy losses, and the major difference between formulas is which losses each considers.

The contract specifications[11] require the bearing value of driven piles be determined using the Gates formula as follows (Refer to Appendix E, *Driven Piles,* for examples):

[11] 2010 SS, Section 49-2.01A(4)(b), *Pile Driving Acceptance Criteria,* or 2006 SS, Section 49-1.08, *Pile Driving Acceptance Criteria.*

$$R_u = (1.83 \times (E_r)^{1/2} \times \log_{10}(0.83 \times N)) - 124$$

Where:
R_u = the nominal resistance in kips.
E_r = the manufacturer's rating for foot-pounds of energy developed by the hammer at the observed field drop height.
N = the number of hammer blows in the last foot (maximum value for N is 96).

This formula is appropriate for piles with a nominal driving resistance of 600 kips or less. Acceptance criteria for piles that require higher capacities than the Standard Plan piles may be determined by other methods. The other methods for determining the load-bearing capacity of a pile depend on detailed knowledge of how energy is transmitted to a pile during driving. These exercises are much more detailed than the pile driving formulas. These methods and procedures typically obtain more accurate representations of the pile's bearing capacity and can be categorized into three areas: (1) Pile Load Testing, (2) Wave Equation Analysis of pile driving, and (3) Dynamic Pile Driving Analysis (PDA). The processes are explained in detail in the next chapter but a brief description of each one follows.

7-5.1 Pile Load Testing

The most accurate way to determine the axial capacity of a pile is to perform a static load test on it. The method is time consuming and expensive so it is reserved for locations where the underlying geology is variable and complex. Load tests are useful in determining the capacities of large diameter piles as the traditional method of using pile-driving formulas loses accuracy as the diameter of the pile increases. Typically, the load test pile is pushed and pulled by hydraulics that are attached to a resisting beam to a point were design loads or ultimate capacity is achieved. Refer to Chapter 8, *Static Pile Load Testing and Pile Dynamic Analysis,* for information that is more detailed.

7-5.2 Dynamic Analysis by Wave Equation

Wave equation analysis is used to create site-specific model of the interaction of the pile, hammer and soil. It is a one-dimensional finite difference analysis method, which models the transmission of a hammer's impact wave down a pile and into the soil. Several versions of the program are available. The program used by Caltrans is one of the most widely used. It was developed by a company called GRL and is called Wave Equation Analysis of Piles (GRL WEAP).

Wave equation analysis models the pile and the driving system as well as the different soil lenses that the pile is expected to drive through. The soil is modeled as a series of elastic plastic springs and linear dashpots. The relative sizes of the springs and masses depend on the actual soil properties as shown on the *Log of Test Borings (LOTB).* Driving system characteristics are embedded in the program and pile characteristics, such as diameter and wall thickness are input by the user. After modeling, a dynamic analysis is performed. Wave equation analysis has been used for drivability studies, hammer acceptance studies, and to develop site-specific curves that relate nominal resistance with pile blow counts and energy. The wave equation analysis method has been shown to provide a more accurate indication of actual nominal resistance than by pile driving equations.

7-5.2.1 Drivability Study

The wave equation analysis can be used as a drivability study during the design phase to validate design assumptions for wall thickness on pipe piles and hammer sizes and types. Geoprofessionals from Geotechnical Services, Foundation Testing Branch, create the driving system model. The input information consists of soil characteristics taken from the *Log of Test Borings*, pile length, and other material properties of the pile obtained from the Designer. In addition, hammer data, such as type and cushion properties for the different hammers likely to be used in the actual construction operations, is input.

The output information provides the internal stresses of the pile as it travels through the varying strata and as it approaches the specified tip elevation. The output also gives information on driving rates for specific hammers through the different soil strata. The model is run using several different hammer sizes and types. The results are presented in a report that shows how the different hammers will drive piles through the different soil strata. This analysis also offers the Designer the opportunity to change pile types, sizes, or thicknesses should the drive analysis show that pile-driving difficulties could be overcome with changes in the pile characteristics.

7-5.2.2 Hammer Acceptance Study

Hammer Acceptance studies are done after the contract is awarded. The *Standard Specifications*[12] require the Contractor to submit information and wave equation analysis for driving systems proposed for use on the project under two circumstances; (1) when the *Special Provisions* require a driving system submittal, or (2) if the ram stroke for the proposed hammer is not visible during driving. This information is used by the Foundation Testing Branch to perform wave equation analysis for comparison. Essentially a drivability study is performed using the actual hammer information instead of assumed values. From this information, the Engineer can decide if the proposed driving systems will drive the pile to the specified tip elevation and reach the nominal resistance without overstressing the pile during driving. The results of the study might also show that the chosen driving system is not efficient. Either way the results of the drivability study are used by the Engineer as a basis for authorizing the hammer submittal.

7-5.2.3 Acceptance Curve Study

The studies described above use theoretical or empirical information to develop a model that gives a pretty accurate indication of what is likely to be encountered in the field. Gathering additional information while driving an actual pile can refine this model. Pile Dynamic Analysis (PDA) equipment can be used to record and process information

[12] 2010 SS, Section 49-2.01A(3)(b), *Driving System Submittal,* or Special Provisions for contracts using 2006 SS.

gathered from stress and strain gauges attached directly to the pile. The information can be recorded during initial driving and during re-drives to determine increased capacities over time. The information from the PDA can be analyzed using the Case Pile Wave Analysis Program (CAPWAP) to estimate capacity. On some larger projects with complex soils, a static load test might also be performed to refine CAPWAP even further. The pile capacity as determined by CAPWAP is used to refine the original WAVE model.

Acceptance curves are developed from outputs of the refined models. The curves correlate pile capacity to blow counts and hammer energy/driving rate. They are site specific and may even be foundation specific. The Engineer uses the curves in the field to determine the nominal resistance of a driven pile. The curves are used in place of the acceptance criteria outlined in the contract specifications[13]. The curves may also be used to provide criteria for field revisions to the specified tip elevation when compression controls the design. Refer to Appendix E, *Driven Piles,* for samples of acceptance curves.

Another situation where acceptance curves are useful is in situations where the ground conditions during driving are not what controls the design. Examples of these are foundations that require the installation of driven piles in scour sensitive areas, through liquefiable soils, or through large layers of re-moldable clays. In these instances, piles need to be driven through materials that will provide skin friction resistance during driving but not under the extreme event limit state. If driving through re-moldable clays, skin friction is lost during the driving operation, but then returns over time.

Pile load tests, WAVE analysis and CAPWAP runs have been performed in the design phase and the construction phase to provide additional information and confidence to the Designer and Geoprofessional. These types of analysis are normally done on large projects but in recent years have been done on projects that use large diameter piles. The correlation of nominal resistance to pile driving formulas is not very effective for large diameter piles so these additional measures are needed.

Piles driven in re-moldable clays, such as Bay Mud found in the San Francisco Bay Area, lose virtually all their skin friction during driving. The skin friction returns with time as the pore water pressures are redistributed. The driven pile will actually achieve greater capacity over time as the skin friction returns. As such, piles driven to specified tip on the day of driving might not achieve nominal resistance but may do so days and sometimes hours later. Acceptance curves provide new criteria for the piles thereby eliminating the need to perform expensive and time consuming re-drives or the need to extend the piles.

During the process to develop acceptance curves it may become apparent that there is a need or opportunity to revise the specified tip elevations shown on the contract plans. When this is done during construction, the special provisions will outline the

[13] 2010 SS, Section 49-2.01A(4)(b), *Pile Acceptance Criteria,* or 2006 SS, Section 49-1.08, *Pile Acceptance Criteria.*

administrative process to be followed. Often the special provisions prohibit the procurement of piles until pile load tests are completed and revised tip elevations are provided. That way piles and rebar cages can be fabricated to the correct length and any required splices kept to a minimum.

7-5.3 Manufacturer's Energy Ratings

Generally each manufacturer publishes a catalog or brochure for their hammers. It outlines operating specifications, including any specific equipment that is required for the safe operation of the hammer. Manufacturer's specifications such as ram weight, stroke, blows per minute, and the minimum required steam or air pressure are important as they all relate to the energy that the hammer is capable of delivering under ideal conditions. Manufacturers calculate hammer energy differently. Some use ram weight multiplied by the stroke. At one time, Delmag calculated a hammer's energy as a function of the amount of fuel injected but now use the weight of the ram times the stroke. Other manufacturers include the effects of additional parameters such as fuel ignited and the effect of the bounce chamber. In any case, a hammer's rated maximum energy is the rating when the pile hammer is operating at or near refusal. It does not consider losses and is essentially the amount of potential energy, in foot-pounds, capable of being delivered by any one blow.

The Engineer uses the manufacturer's maximum rated energy, for a given stoke, as an indication of the driving capability of the hammer. It is used in the Gates formula as required by the contract specifications. It is important to know that the manufacturer's given energy rating should not be used "blindly". The actual potential energy needs to be verified by measuring the stroke of single acting diesel hammers and by comparing the operations of the hammer with the manufacturer's operating specifications for other hammer types. Just because a hammer is operating properly doesn't mean that it is operating at maximum efficiency.

As stated previously, manufacturers rate their hammers by determining the amount of energy that can potentially be transferred to the pile. They do not specify the amount of kinetic energy that is actually delivered by a hammer at the head of the pile after undergoing losses. These losses occur in the transfer of energy through the driving system and can vary from hammer to hammer. The ratio of the maximum rated energy provided by the manufacturer to the actual energy delivered to the pile is the hammer's efficiency. An accurate determination of the actual available energy of any given hammer is difficult as there are many things that can have an effect on the efficiency of the system. Factors such as wear and tear, age, type of cushion, improper adjustment of valve gear, poor lubrication, fuel setting, unusually long hoses, minor hose leaks, binding in guides, and minor drops in steam or air pressure can all affect the performance of a hammer.

It is necessary to have a working knowledge of hammer operations. The Engineer must ensure that the accepted hammer on the job is operating properly and is capable of producing the manufacturer's "rated energy" (or potential energy, at the top of its stroke).

Material presented in this manual and material found in other technical publications will supplement this knowledge. However, there is no substitute for field experience. The Engineer is advised to look into the mechanical aspects of the pile driving operation when the Contractor starts assembling the equipment and driving begins.

7-5.4 Battered Piles

Adjustments must be made when driving battered piles since the path of the ram is not plumb. One method of adjusting for battered piles is to use the modified Excel spreadsheet shown in Appendix E, which incorporates the pile batter into the Blows vs Stroke chart. Another method is to adjust the ram stroke to represent the vertical fall. For example, an observed ram stroke of 7 feet for a 1:3 battered pile indicates the ram is moving 7 feet along the path of the pile. The vertical fall height is less, only 6.64 feet (7 feet x 3/3.162). It is mathematically incorrect to apply the correction to the hammer blows, since the relationship between ram stroke and hammer blows is not linear. Refer to the examples in Appendix E, *Driven Piles*.

A similar adjustment must be made for double acting and differential hammers. However, in determining the change in energy due to the batter, compensate only for that portion of the energy attributed to the free fall of the ram. Energy delivered by differential action or pressure imparted on the downward stroke should remain constant.

7-6 Preparing to Drive Piles

A *Driven Piling Construction Checklist* is presented in Appendix K-1 to assist field personnel in preparing documents and inspecting fieldwork to ensure compliance with contract requirements.

Pile driving techniques (including solutions to problems) are normally developed with time and experience. It is the intent of this section to provide some insight into the areas where problems can develop. With this potential knowledge, the Engineer is thus enabled to potentially eliminate them prior to their occurrence.

The Engineer should review the following lists before pile driving begins and while pile driving is underway. These lists are by no means complete, as new and different construction challenges will develop with each and every project.

Advance preparation to begin well before mobilization of pile driving equipment:

Table 7-10. Advance Preparation Tasks Prior to Driving Piles

NO.	ITEM DESCRIPTION
1	Review the plans, special provisions, *Standard Specifications*, and *Foundation Report* for requirements on pile type, required bearing and penetration, drilling or predrilling depths, (critical with tension piles as well as compression piles), tip protection, pile lugs and limitations on hammer types, or other specific limitations or requirements.

NO.	ITEM DESCRIPTION
2	Check for Form TL-29, *Release of Materials*.
3	Check Welding Quality Control Plan (WQCP) and welder certification requirements.
4	Prepare the pile layout sheet. (Form SC-4806), *Pile Layout Sheet*
5	Prepare the pile log forms. (Form SC-4805), *Log Pile Sheet*
6	Advance preparation of a chart, table, or graph that correlates the blow count, stroke, blow rate, etc., to the bearing value is suggested for each hammer. An example is included in Appendix E. Verify the hammer is an authorized hammer in accordance with the requirements of Bridge Construction Memo 130-4.0, *Pile Driving Acceptance Criteria,* and is able to develop sufficient energy to drive the piles at a penetration rate of not less than 1/8 inch per blow at the required bearing value. Refer to the *Verification of Hammer Energy* section later in this chapter.
7	Review the mechanics of the hammer type to be used for further verification of components in the field.
8	Obtain the necessary safety equipment (Refer to the *Safety* section later in this Chapter) and inspection tools (tape measure, paint, stopwatch, etc.)
9	Prior to driving, discuss with the design team what to do if the piles go long or fall short of specified tip,

Once out in the field, prior to startup of pile driving:

Table 7-11. Field Preparation Tasks Prior to Driving Piles.

NO.	ITEM DESCRIPTION
1	Confirm pile layout and batter requirements. The Contractor is to locate the position of the piles in the footing. The Engineer is to check the layout only. Do not lay out piles for the Contractor.
2	Confirm pile materials, tips, and lugs. Refer to the *Materials Checklist* later in this chapter.
3	Confirm the hammer type. If the hammer has a variable energy setting, check the setting to ensure the proper energy will be obtained. Some of the newer diesel hammers have four settings giving a range of 46% to 100% maximum energy. Ultimately the fuel setting is up to the Contractor. However, the Engineer should be aware of what the setting is and why it is in place.
4	Verify the reference elevation.
5	Layout and mark piles for logging. Mark additional reference points near the anticipated tip elevations so that monitoring can take place at smaller increments.
6	Locate a good place to inspect operations. Notify the pile foreman of location and signals to be used.

When pile driving starts:

Table 7-12. Field Preparation Tasks When Pile Driving Starts.

NO.	ITEM DESCRIPTION
1	Verify the pile location at the start of driving.
2	Verify plumbness or batter of the pile at the start of and during driving.
3	Monitor and log the blow count, stroke, and penetration (Refer to the *Logging of Piles* section later in this chapter).
4	Stop driving at proper bearing and penetration.
5	Be prepared to stop the driving if it appears that additional driving will damage the pile or if it appears the piles may run long.

After completion of driving piles:

Table 7-13. Field Tasks After Completion of Pile Driving.

NO.	ITEM DESCRIPTION
1	Verify proper pile cutoff.
2	Prepare copies of pile logs to be sent to Structure Construction in Sacramento in accordance with Bridge Construction Memo 3-7.0, *Pile Records*.

7-6.1 Verification of Hammer Energy

Several verification methods are available in the field to determine the amount of hammer energy that a hammer delivers to a pile in any one blow or over a short period of time. For single acting diesel, steam, or air hammers, the simplest method is to measure the stroke of the hammer and multiply this by the weight of the ram. While this method may underestimate the complexities of pile driving and energy transfer, it is the simplest method available for use in the field. To determine the stroke for diesel hammers, measure the depth of ram below the top of the cylinder before driving and add that to the height the top of the ram rises above the cylinder during driving. To determine this height, paint is often applied in one-foot intervals on the trip carriage above the cylinder. However, some hammers have rams with identifiable rings that are visible during driving. The location of the rings normally is shown on the manufacturer's brochure.

The maximum rated stroke for maximum rated energy for many hammers can be found on pile hammer manufacturer websites.

Another method of determining the actual ram stroke of an open-end diesel hammer is accomplished by measuring the ram stroke from the blow rate. The equation involved with this method is sometimes called the Saximeter equation. Saximeter is a trade name for a device used for remote measuring of the stroke of an open-end diesel hammer or the measurement of the hammer speed. This method is simplified by simply counting the blows per minute. An example is available in Appendix E.

For Air and Steam hammers, check the boiler or air capacity of the outside energy sources. This should be equal to or greater than that specified by the hammer manufacturer. Gages that indicate steam and air pressures are required by the contract specifications[14]. Verify the system is using the proper hose size recommended for the particular steam and air hammers. The hoses should comply with the manufacturer's specifications. All hoses should be in good condition (no leaks).

[14] 2010 SS, Section 49-2.01C(2), *Driving Equipment,* or 2006 SS, Section 49-1.05, *Driving Equipment.*

7-6.2 Materials Checklist

7-6.2.1 Precast Concrete Piles

Table 7-14. Precast Concrete Piles Checklist.

CHECK ITEM	CHECK DESCRIPTION
1	Check for damage, cracks, chips, etc. Check the date the pile was cast. This date is written, along with the release number, directly on the surface of the pile. The contract specifications[15] require piles be at least 14 days old before driving.
2	Lifting anchors for piles in a corrosive environment are to be removed to a depth of one inch and the hole filled with epoxy. Piles driven in a non-corrosive environment must have the anchors removed along the portion of pile above the final ground line in accordance with the contract specifications[16].

Discuss with the Contractor the type and method of rigging planned to lift precast prestressed concrete piles. The Contractor is to provide the necessary equipment so as to avoid appreciable bending of the pile or cracking of the concrete. If the Contractor materially damages the pile, the pile must be replaced at the Contractor's expense in accordance with the contract specifications[17].

Check the lifting procedure to ensure that the pile is not overstressed at any time during picking. The maximum permissible allowable stress is as follows:

Allowable Stress $= 5\sqrt{f'c}$ PSI tension

Measure piles and paint the necessary one-foot marks so blow counts can be determined. Check the ends of the piles. Prestressing steel should be flush with the pile head and covered with zinc primer. The head of the pile should be square.

When driving concrete piles, make sure that the cushion blocks are maintained in good condition. Failure to do so may increase the risk of damaging the piles during driving. If the driving is hard, the cushions may need to be changed once or twice per pile.

7-6.2.2 Steel Piles

If the piles are to be spliced, the Contractor must have welder(s) qualified prior to performing the welds. They must be qualified in accordance with the Welding Quality Control Plan and the AWS D1.1, *Structural Welding Code*. Assistance may be obtained by calling Materials Engineering and Testing Services (METS).

[15] 2010 SS, Section 49-2.04C(1), *Construction General,* or 2006 SS, Section 49-1.07, *Driving.*
[16] 2010 SS, Section 49-2.04B(2), *Fabrication,* or 2006 SS, Section 49-3.01, *Precast Prestressed Concrete Piles Description.*
[17] 2010 SS, Section 49-2.04C(2), *Handling,* or 2006 SS, Section 49-3.03, *Handling.*

Some welders will have qualification tests that were performed by a private testing laboratory. Prequalification can be accomplished in this instance by forwarding a copy of the test reports to the nearest Transportation Laboratory office where they will verify the welder's qualifications.

It is obvious that all of the aforementioned takes time. Hence, it is extremely important that determination of welder qualification be made as early as possible. Keep in mind that just because a person holds a welding certification, it does not mean you do not have to inspect the welding work.

Early contact with METS representatives in Los Angeles, Vallejo, or Sacramento is encouraged, as they can be very helpful. Reference should also be made to Section 180, (*Welding*), of the *Bridge Construction Records and Procedures Manual*.

Table 7-15. Steel Piles Checklist.

CHECK ITEM	CHECK DESCRIPTION
1	Check for proper diameter, pipe pile thickness or flange and web dimensions. Paint one-foot marks and lengths on the piles. The Contractor may assist in this.
2	Check welded joints for any sign of improper welding. When piles are to be spliced, a Welding Quality Control Plan will be required in accordance with the contract specifications[18].

7-6.2.3 Timber Piles

Check the butt and tip diameters to ensure compliance with the contract plans. Treated timber piles must be driven within 6 months after treatment.

Piles must have protective steel straps at 10-foot centers. Three additional straps are placed at the tip and two at the butt. Straps are to be approximately 1-1/4 inches wide and 0.03 inch in nominal thickness per the contract plans.

The Contractor is also required to restrain the pile during driving from lateral movement at intervals not exceeding 20 feet measured between the head and the ground surface. Make sure the Contractor is equipped for this.

7-6.3 Logging of Piles

Structure Construction practice is to log at least one pile, in its entirety, per footing. There are advantages to doing a more comprehensive logging of the piles. One situation is when, during easy driving, the piles are not achieving the necessary blow counts at specified tip. The Contractor will request to restrike or re-tap them later. A good log of the piles within the footing will help the Engineer to determine how many piles might require a restrike or re-tap to prove bearing. If all the piles drove in a similar manner, it might be possible to restrike or re-tap as few as 10% of the piles that did not originally

[18] 2010 SS, Section 11-3.02, *Welding Quality Control,* or Special Provisions for contracts using 2006 SS.

achieve bearing. If the piles all drove differently, a restrike or re-tap of all of the piles may be required. The following is a discussion of factors affecting pile log data. Typically when pile driving begins, the driving resistance of the pile is very low. The stroke of the hammer will be proportional to this pile resistance (low resistance equals low rebound energy). As a result, the energy delivered to the pile will be different from the manufacturer's rated energy value. Keeping careful track of blows per foot and actual stroke is necessary. If this difference is not taken into account, the log will be misleading when the values are put in the Gates Formula and bearing values are computed at various depths of driving. This procedure should be followed all the way to the final tip penetration.

With double acting steam or air hammers, check the gages for proper pressure during the driving operation. In addition to measuring the actual stroke, it is important that the blow rate be verified.

Underwater and *closed* system hammers are difficult to inspect and can be throttled by the operator. The full open position should be used to obtain maximum energy. Be sure to pick a fixed reference point as close to the pile as practical when logging piles or determining final blow count. This can be accomplished several ways:

1. Mark the pile with one foot marks and note the blows passing a fixed point near the pile (leads, reference point, lath driven near the pile, water surface, or other).
2. Mark the lower part of the leads with one foot marks and observe passage of a fixed point of the pile.

Site conditions often dictate how this is done, so improvise as necessary. Modifications must also be made to obtain blow counts over smaller increments.

If a precast concrete pile is undergoing hard driving and experiences a sudden drop or movement, this could indicate a fracture of the pile below ground. Driving should stop and an investigation of the soundness of the pile should be made. Piles that are damaged should be extracted. However, this is not always possible. Frequently, driving a replacement pile next to the rejected one can solve this problem. However, the effect of this change could impact the footing design so the Designer should be consulted when this option is used.

Be aware of the water level in the pile when driving hollow pipe piles in water. A phenomenon known as a water hammer can develop during driving. The increase in pressure from the water hammer could split the pile. To prevent this, the pile may need to be pumped free of water after seating and before driving.

Another problem that can occur with pipe piles has to do with what is called a soil plug. When driving hollow piles, there is a tendency for the soil to plug within the pile as it is being driven. This is common in cohesive materials. When this does occur the pile will drive as if it is a displacement (closed-end) pile. There are many implications if this happens. Among the possibilities include the possible overstressing of a pile as well as misleading blow counts. Center relief drilling may be needed to remove the plug so that the specified tip elevation can be reached.

7-7 Driving Challenges

Problems with driving can vary in nature and cause. In general there are three categories of problems: (1) hard driving, (2) easy driving, and (3) pile alignment. The causes typically are the soil is too hard or soft, the type of hammer used is inappropriate for the soils encountered, or the pile type being used is inappropriate. The following is an outline of various driving problems that can be encountered. The types of problems described are, by no means, a complete listing of all possible problems.

7-7.1 Difficult or Hard Driving

Hard driving is a term used to describe piles that have achieved nominal resistance but have difficulty reaching the specified tip elevation. This may happen when the soils are dense or when the hammer size or type cannot penetrate a particular soil lens or is inappropriate for the work in general. A review of the special provisions*, Foundation Report, and LOTB s*hould give an indication as to whether or not hard driving is to be expected. The pile placement plan should address the means and methods proposed to address hard driving.

The *Standard Specifications* and special provisions discuss what can be done to address this condition. For example, the contract specifications[19] state: *If necessary to attain the specified tip elevation shown and where authorized, you may drill holes with a diameter not greater than the least dimension of the pile to the specified depth before driving the piles*. For driven piles, shells, or casings, the contract specifications[20] also require the use of special driving tips, heavier pile sections, or other measures authorized by the Engineer, to assist in driving or prevent damage to a pile through a hard layer of material.

Hard driving and pile refusal are often interrelated as refusal can be considered the ultimate form of hard driving. Unfortunately, there are many definitions for the term *refusal*. Some popular interpretations range from:

1. Twice the required blow count.
2. Ten or more blows per inch.
3. No penetration of the pile under maximum driving energy.

Regardless of any specific definition, refusal is essentially the point where additional measures are needed to advance the pile to the specified tip elevation. These measures can be as simple as verifying the efficient operation of the hammer or more time-consuming like drilling or spudding.

[19] 2010 SS, Section 49-2.01C(3), *Drilling,* or 2006 SS, Section 49-1.05, *Driving Equipment.*
[20] 2010 SS, Section 49-2.01C(5), *Driving,* or 2006 SS, Section 49-1.05, *Driving Equipment.*

The size and type of hammer used to drive the pile play a part in having and/or resolving a hard driving issue. One should keep in mind that proper hammer sizing is not accomplished simply by meeting the minimum energy requirement required to drive the piles to the nominal driving resistance. It is important to be aware that the hammer needs to overcome the anticipated soil resistance and impedance to achieve the specified tip elevation. Other issues, such as the dynamic response of soils and the relative weights of the hammer and the pile, if not properly considered, may be the root cause of hard driving. A Wave Equation Analysis can capture many of these parameters and is often required on projects driving high capacity piles.

Hard driving is not always a permanent condition and can also be the result of a pressure bulb that has developed near the pile tip. This can occur in saturated sandy materials when pore water pressures build up during driving, but can dissipate over a relatively short period of time. Driving these types of piles in stages may remedy this situation.

Sometimes the means and methods of construction may increase the likelihood of experiencing hard driving. Soil densification or consolidation can occur when driving displacement piles in a cluster for a building or bridge footing or abutment. A revised driving sequence will often alleviate this problem. This can often be a trial and error process. Driving from one side of the footing in a uniform heading helps as does driving from the center in a uniform outward pattern. Both of these procedures should mitigate the issue and increase the likelihood of driving piles without issues.

Sometimes other construction methodologies are required to address hard driving. These methods include drilling, attaching driving tips, and spudding. These methods are typically used when economics dictate this to be the best solution or when larger hammers cannot be utilized because of their potential to overstress the pile.

Drilling a *starter hole* to facilitate the advancement of a driven pile is known as drilling to assist driving. The contract specifications[21] state the hole drilled must not be larger than the least dimension of the pile to be driven. This method has the potential to impact pile capacity, particularly for those that utilize skin friction. Often the amount or depth of drilling is limited to address this. There should be information in the plans, the *Foundation Report* or the special provisions that outlines these restrictions.

Driving tips strengthen the tip of the pile so that it can penetrate through obstructions and dense soil lenses. Cutting shoes are another form of driving tip that allows piles with thinner wall thicknesses to be driven through dense soil lenses. Closed ended steel pile may require a conical tip to facilitate driving and mitigate damage to the pile.

Spudding is another method used to assist the penetration of piles through dense lenses of material. It involves the use of a heavy or stout section to drive, break, or cut through a

[21] 2010 SS, Section 49-2.01C(3), *Drilling,* or 2006 SS, Section 49-1.05, *Driving Equipment.*

lens of hard material. The spud is removed after this is achieved and the production pile driven in its place to the specified tip elevation.

Except for timber piles, the term *hard driving* or *difficult driving* may be subject to individual interpretation as there is no language in the specifications that defines it. Steel or concrete piles have no measures specified to mitigate hard driving at predetermined blow count levels. However, the Contractor is required to employ the measures described above to obtain the required penetration and is also required to use equipment that will not result in damage to the pile.

For projects utilizing the 2006 or older *Standard Specifications*, the contract specifications[22] outline what to do when hard driving is encountered in timber piles. When the blow count for timber piles exceeds either 2 times the blow count required in one-foot, or 3 times the blow count required in 3-inches for the nominal driving resistance, additional means are required to achieve the specified tip elevation. These may include drilling or changing hammers to one with a heavy ram striking at a low velocity.

Physical damage to the pile, even when it is below ground, is fairly easy to determine. Impending damage and/or high driving stresses are not as easy to pinpoint. In situations of high driving resistance, the Engineer is advised to investigate pile stresses. This can be done with Pile Driving Analysis (PDA) equipment.

Because of the many variables involved, each hard driving issue must be evaluated on its own merit. There is no substitute for engineering judgment in this area. It should also be remembered that these issues are somewhat common and there is a broad base of experience within Structure Construction.

Piles typically are designed to meet four different design criteria: tension, compression, lateral, and scour. When compression controls the design, the Engineer has the flexibility to raise tip elevations to address hard driving. However, these tips should only be revised to the elevation of the next controlling criteria, and as confirmed by the Design Team, as discussed in Chapter 3, *Contract Administration*.

While it may be important to make a distinction between hard driving that was anticipated and what was not, it is in the best interest of all parties to work toward resolution of the issue quickly and efficiently in order to mitigate impacts to the project. There have been occasions where pile penetration to the specified tip elevation cannot be accomplished, despite everyone's best efforts. When this situation occurs, the Engineer needs to be proactive in finding an alternative solution. This includes conversation and meetings with Structure Design and Geotechnical Services to find an alternative tip elevation, method or design to address the challenge.

[22] 2006 SS, Section 49-1.07, *Driving.*

7-7.2 Soft Piles and Re-Drive

The *Standard Specifications* require the Contractor to satisfy requirements for minimum nominal driving resistance and specified tip elevation. A pile that drove *soft* is a pile that has been driven to the specified tip elevation but has not obtained the minimum driving nominal resistance. There are several options that can be explored when this occurs:

- Continue driving until the minimal nominal penetration can be achieved.
- Install pile lugs on H-Piles as discussed in Bridge Construction Memo 130-5.0, *Steel H Pile Lugs*.
- The pile can be *re-driven* sometime after initial driving, typically a matter of days, with the expectation that the pile has *set up* over time.

There are advantages and disadvantages to selecting any of these options. The first two options require field welding of steel piles so a welding quality control plan will most likely need to be created or revised for this work. Another issue is that the locations of field splices in piles may be limited to certain zones along the pile. Some pile designs have a no-splice zone or a no-field splice zone in the upper portion of the pile. This is because the loads and subsequent risks of plastic hinging are high. As such, the contract plans or special provisions may not allow field welding an extension on to a pile as the splice may fall within this zone.

The third option is a re-drive, also known as a re-strike or re-tap, of the pile. To do this, pile driving is stopped when the pile is several inches to one foot above the specified tip elevation. The pile is then driven the remaining distance at a later time. This allows the soil time to *set-up* around the pile. The time required for *set-up* depends on the soil and is anywhere from a day to a week. This option is effective in cohesive soils but not so much in submerged and saturated sands and gravels as there is little cohesion in these soil structures.

The Gates formula is still used for pile acceptance during a re-drive. However, it is important to note that the formula uses the number of hammer blows it takes to drive the last foot to determine nominal driving resistance. Typically piles can only be driven several inches before *set-up* is lost. Since the distance driven in a re-drive is less than one foot, the number of blows per foot used in the Gates formula will need to be extrapolated from the field results based on the number of blows over the driven length of the re-drive before *set-up* is lost. The number of blows to complete driving the pile to specified tip after *set-up* is lost are not counted. The extrapolated blows-per-foot value will be used to determine nominal driving resistance in the Gates formula.

Following are some ground conditions and the expected outcome after re-driving to address soft piles:

Table 7-16. Ground Conditions and Expected Re-Drive Outcomes.

CONDITION	DESCRIPTION
1	Loose submerged fine uniform sand. Driving temporarily produces a quick condition. Re-drive will probably not indicate any change in capacity.
2	Cohesive soil. Driving temporarily breaks down the soil structure, causing it to lose a part of its compressive strength and shear value. Re-drive should indicate increased capacity.
3	Saturated coarse-grained pervious material. May display high driving resistance, but on re-drive will lose capacity as compared to the initial driving. This could be due to changes in pore water pressure within the soil mass.

On contracts where soft driving in clay materials is anticipated, specific re-drive guidelines are frequently given in the special provisions. The *set-up* period is usually set at a minimum of 12 hours. In addition, only a fixed percentage of the piles are re-driven (10% or a minimum of 2 per footing). However, when re-drive requirements are not listed in the special provisions, the Engineer can still utilize this methodology. Ultimately, the Engineer must be satisfied that all of the piles have achieved the bearing capacity, and should therefore re-drive a sufficient number of piles to ensure this.

Re-driving is a tool that the Engineer can use in an attempt to obtain an acceptable pile even though the contract specifications may not discuss re-drives or specify elapsed time before attempting a re-drive. Trial and error methods may have to be employed to figure out the appropriate time to wait before re-driving. It is the Engineer's responsibility to determine what criteria will be used to determine pile acceptability. At times piles will not attain minimum bearing at specified tip, even when re-driven. When this happens the only option is to splice on additional length and continue driving to a point where the nominal driving resistance is achieved.

Issues with soft piles frequently occur in steel *H* piles. When overdriving is excessive, lugs or "stoppers" can be welded on the pile to mitigate the problem. If lugs are not required by the contract, they can be added by change order. Bridge Construction Memo 130-5.0, *Steel H Pile Lugs,* covers this in detail.

7-7.3 Alignment of Piles

The Engineer needs to verify that each pile is placed in the correct location and that the alignment is plumb or at the required batter. This should occur often during the first part of the drilling or driving of each pile and periodically thereafter. This is extremely important when swinging leads are used for pile driving as these leads lack the guides that fixed leads have. Alignment corrections should be made if the pile begins to move out of line. In certain instances, driving may need to be stopped so that the pile can be pulled and re-driven correctly.

While the contract specifications[23] state, *The Engineer rejects piles materially out of line*, there is no tolerance provided in the specification that define when a pile truly is *materially out of line*. Some contracts have specific tolerances outlined in the *Special Provisions* that define the criteria for acceptable alignment and/or plumbness of the piles. This is usually due to special considerations in the design of the structure and to clarify the Designer's intent. Each situation should be analyzed separately and *engineering judgment* used in making final determination as to the acceptability of any misaligned piles.

7-7.4 Overdriving

Occasionally the Contractor will want to overdrive prefabricated piles to avoid cutting piles to grade. This can be allowed in most circumstances. However, no payment is allowed for the additional length driven below the specified tip elevation unless it is part of an ordered change to the specified tip elevation. This subject is discussed in Bridge Construction Memo 130-6.0, *Measurement and Payment for Piling*.

7-8 Safety

The potential for accidents to occur during pile driving operations may be greater than for any other construction operation. The pile driving crane rigged with a set of heavy leads and a hammer is unwieldy enough; add to it a long pile and a high potential for danger exists. These risks increase when the hammer is in operation as all the parts are moving and support equipment such as a steam or high-pressure line are at capacity.

The following are some of the items that individuals inspecting piles should be aware of, especially personnel new to construction:

Table 7-17. Safety Items.

ITEM NO.	DESCRIPTION
1	Stand away from the pile when it is being picked and placed in the leads. Sometimes the pile when dragged will move in a direction not anticipated.
2	Stand as far away from the operation as practical while still inspecting the work.
3	Keep clear of any steam, air, or hydraulic lines.
4	Watch the swing of the rig so as not to be hit by the counterweight.
5	Wear safety glasses. There is a high incident of flying debris during the driving operation (dirt from piles, concrete from piles and steel chips).
6	Keep an eye on the operation in progress. Look out for falling tools and materials from the pile butts. Watch the rig in case the leads start to fall or the rig starts to tip.
7	Hearing protection is required due to high noise levels.
8	Have a planned route for rapid escape. If required to move quickly there will not be time to look around first.

[23] 2010 SS, Section 49-2.01C(5), *Driving,* or 2006 SS, Section 49-1.07, *Driving.*

ITEM NO.	DESCRIPTION
9	Wear old clothes. Park your car and stand upwind when possible. Diesel oil does not wash out of clothes!
10	Look where you are walking. The protective covers may not be securely in place over the predrilled holes.
11	Welding must not be viewed with the naked eye. Shield eyes when in the vicinity of a welding operation and wear appropriate shaded eye protection when near this work.