Pile Driving: Hammers and Driving Methods

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The heart of any pile-driving system is the pile hammer. Modern contractors use impact types ranging from the "ancient" drop hammer, through single- and double-acting hammers, to differential hammers. Steam and air are still the basic sources of power for hammers, but lately diesel hammers and high-pressure hydraulics have gained acceptance. Because a constant energy source is seriously affected by pile cushions of varying characteristics, "permanent" cap blocks are now in widespread use. Low-frequency vibrators are used primarily for driving nonbearing piles and for extracting sheet piles. High-frequency (resonant) vibrators, though currently expensive to purchase and operate, have much wider fields of application including the driving of displacement bearing piles. Pile-driving systems of the future will include larger hammers (250,000 ft-lb or more) with self-contained power sources, both diesel and steam, and simple, less expensive but more reliable high-frequency, high-power vibrators.

•FOR THE PAST HUNDRED YEARS engineers have been struggling to convert the art of pile driving into a science. In the past 20 years or so its growth as a science has caused a demand for the improvement of old tools as well as the development of new, specialized equipment so that the practical side might keep pace with the theoretical. The heart of any pile-driving system is the pile hammer. Its history is as old as pile driving itself, having its beginning in the sledges of prehistoric man and the drop hammers of ancient Rome.

This paper is primarily concerned with the most common types of hammers in existence today, but some attention is given to those special systems that have seen limited use during the past decade and may be the nuclei of the driving systems of the future. Drop hammers are the oldest type of hammer and are still used today because of the simplicity of the pile rig required for their application. From the early beginnings of pile driving little changes were made in hammers until the steam age of the nineteenth century, when the single-acting steam hammer was developed. As the use of single-acting steam hammers became widespread, pile men felt the need for a power hammer that would strike a greater number of blows per minute, delivering energy at a faster rate. This lead to the development of the double-acting hammer. Because of the high-velocity, sometimes impractical blow of these hammers, engineers have been cautious about their application on bearing piles. This desire for driving speed coupled with a low-velocity blow lead to the development, 35 years ago, of the differential-acting hammer. Single-acting, double-acting, and differential-acting are the 3 major types of hammers in common use today. Although primarily designed as steam hammers, they are often used with air or hydraulic fluid as a source of power. The diesel hammer, developed prior to World War II, has come into prominence lately because of its self-contained power source.

This paper also discusses cap blocks, the cushion interposed between most pile hammers and the pile, and vibrators, both the low-frequency type commonly used to drive sheet piles and the high-frequency or resonant vibrators that caused quite a stir when introduced commercially 5 years ago.

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DROP HAMMERS

Pile hammers originated with the sledges of prehistoric man and the drop hammers of ancient Rome. Drop hammers are still in use today primarily because of their simplicity of operation. Their advantages are many. However, so are their disadvantages.

Among the advantages of a drop hammer is the simplicity of the operating system. The hammer requires no specialized power source but uses the main hoist of the pile rig. The lack of mechanical parts makes for the simplest of maintenance requirements. When the hammer is handled by an experienced operating engineer, the hoisting line is the only part requiring periodic replacement.

Except for the Franki pressure-injected footing system, the drop hammer sees little use on domestic pile jobs today. This is primarily because of its low frequency, 5 to 10 blows per minute, and the difficulties attendant to the delivery of a consistent, measurable blow. In the Franki system, where large strokes are common, variations of several inches of stroke have a minor effect on the energy of the delivered blow. When bearing piles are driven, however, experience, and of late theory, has shown that low-velocity blows are desirable, the acceptable maximum being 36 to 39 in. In these cases variations of several inches in the stroke can have a measurable effect on the energy of the blow.

The blow of drop hammers can also be adversely affected by other factors. For one, the drag exerted on the hammer by the handling line can vary from pile to pile depending on the friction in the hoisting system. For another, even an experienced operator will occasionally prematurely engage the friction on the hoisting drum, dampening the blow.

Drop hammers are commonly used overseas to drive bearing piles. The most common application is on precast, prestressed piles. The ability to "tap" the pile when little or no point resistance is present and thereby to avoid excessive tension stresses represents an advantage of this particular hammer.

Regardless of the simplicity of drop hammers, the economic demands placed on the modern pile contractor relegate it, at least in the United States, to a minor role.

SINGLE-ACTING HAMMERS

The single-acting hammer, a product of the steam age, has seen only superficial changes in design since the early 1900's. These hammers are simple and reliable, develop consistent energies when the stroke is adequately controlled, and possess, what from the contractor's standpoint is a major advantage, a large ratio of weight of ram to total weight of hammer. Most of the empirical pile-driving formulas in use today are based on this type of hammer.

The hammers are mechanically reliable. Years of experience have produced a series of low-maintenance designs that produce hammers that require little care on the part of the operator and little concern on the part of the engineer. They are moderate speed devices usually rated in the range of 60 to 75 blows per minute.

The single-acting hammer can be conveniently and economically short-stroked for the driving of precast and prestressed concrete piles. Mechanisms are now available to make it possible to remotely shift from a short to a long stroke in a matter of seconds. There is, however, the ever-present possibility of oversupplying short-stroked hammers with steam or air, and temporarily reduced energy blows are not to be considered reliable as to rated energy. Factors that may contribute to substandard operations of single-acting hammers are as follows:

1. Improper valve timing—This results in premature admission of steam (cushions the blow) and throttling of the exhaust (shortens the stroke). Usually improper valve timing results in decreased frequency of blows of the hammer. It should be noted, however, that there is really no direct relationship between the frequency of the hammer and the energy of the blow.

2. Excessive mechanical friction—There have been cases documented where the hammer ram has actually "hung-up" because of excessive packing friction. Adjustment of the gland beyond that required to just reduce excessive leakage can reduce hammer energy.

3. Variations in the location of the striking point—When the location of the striking point (the top of the cap block or cushion block) is too high, the valve of the hammer might not be thrown completely, and as a consequence the single-acting hammer will short-stroke. When the striking point is too low, the ram has to travel an excessive distance after the valve is thrown at the bottom of the stroke until it strikes the pile, and the blow can be cushioned by the upforce of steam. In spite of its age and shortcomings, the single-acting hammer is still the mainstay of today's pile contractor.

DOUBLE-ACTING HAMMERS

Double-acting hammers use steam or air to raise the striking parts and also to impart energy during the downstroke in addition to that supplied by gravity. The basic design was developed out of a desire on the part of engineers for a greater number of blows per minute. The double-acting hammers in common use today operate in a range of 100 to 250 blows per minute.

To provide higher frequencies double-acting hammers are usually designed with light rams. A large percentage of the energy rating of the hammer is due to steam force. These hammers are, therefore, extremely sensitive to system pressure.

Double-acting hammers strike a relatively high-velocity blow compared to single-acting hammers. Theoretical investigations have shown this to be extremely inefficient in the driving of heavy piles. Although contractors consider these hammers desirable because they have a high-energy rating compared to other hammers of equal total weight, they are not often used for the driving of bearing piles. Their use is commonly limited to the driving of sheet piles or soldier beams.

Because they are usually of the closed design where the ram is not visible, it is extremely difficult, if not impossible, to monitor the stroke of the hammer. Tables are, however, available indicating "rated energy" versus blows per minute for these hammers. Unfortunately, these are extremely unreliable because factors other than the energy of the blow affect the operating speed of these hammers. For example, (a) a hammer that short-strokes will usually produce a higher frequency of blows than one that delivers the rated stroke, and (b) double-acting hammers operating on a springy pile will usually increase in frequency as resistance increases, requiring the operator to throttle the hammer and consequently the blow.

The double-acting hammer has to be classed as a special-purpose tool. However, properly applied it becomes a necessary valuable part of the equipment of the pile-driving contractor.

DIFFERENTIAL-ACTING HAMMERS

Employment of relatively heavy rams in pile driving results in low-impact velocity blows that not only conserve more of the available energy, but also prevent undue damage to the pile. Because of this, as much as possible of the total weight of a hammer should be assigned to the striking parts in order to most efficiently utilize the maximum permissible equipment weight. It is also desirable to have a hammer strike as many blows per minute as possible in order to further reduce the cost of driving.

A single-acting hammer meets the heavy ram requirements. It lacks, however, the desirable high frequency of blows. A double-acting hammer operates with a rapid succession of blows; but, when compared with a single-acting hammer of the same total weight, its much higher velocity impact is less effective.

In the differential type of hammer the deficiencies of single- and double-acting hammers are overcome while the advantages are maintained. This is the result of its steam cycle that is different from that of any other hammer. This cycle makes the lifting area under the piston independent of the downward thrusting area above the piston. Therefore, regardless of how large a portion of the total weight is contained in the striking parts, sufficient force can be applied for lifting and accelerating these parts without affecting the deadweight needed to resist the reaction of the downward accelerating force.

An explanation of this is as follows: The upward steam force in the differential hammer can be increased by increasing the size of the larger piston. The reaction for this

force is carried through the hammer frame into the follower and head of the pile. The downward steam force uses for its reaction the entire deadweight of the frame of the hammer.

This produces an interesting characteristic of differential hammers. The maximum energy per blow that can be developed by a differential hammer is the total weight of the hammer times its stroke. The proof of this is straightforward. Hammer energy is equal to the total downforce times the stroke of the hammer. This downforce is made up of the weight of the striking parts times the stroke, plus the weight of the downward steam force times the stroke. The maximum limit for the steam force is that of the reaction furnished, or the deadweight of the nonstriking parts of the hammer. The maximum energy of the hammer is, therefore, the sum of weights of the striking parts and nonstriking parts times the stroke.

Differential hammers may be short-stroked in a manner similar to single-acting hammers. However, if the short-stroking is to be permanent, that is for the life of a job, economical hammer operation can only be ensured by putting a filler or "dummy" under the cylinder head. The reason is obvious if one realizes that in the differential hammer the amount of steam vented to exhaust on each stroke, and thereby "consumed" by the hammer, is the volume above the upper piston at the time the hammer strikes. A short-stroked differential hammer without a filler in the cylinder will exhaust the same volume of steam per blow as a full-stroke hammer. The results will be decreased energy output with the same energy input.

Fillers in the cylinders of short-stroked differential hammers offer another advantage besides economy of operation. They guarantee a mechanical limit for the hammer stroke and prevent accidental overdriving.

Differential hammers are today's hammers. Their economy of operation finds favor with owners and contractors. Their efficiency and reliability find favor with engineers.

HAMMER POWER SOURCES

Steam

Steam has been a prime power source for pile hammers since before the turn of the century. It is becoming increasingly difficult, however, to find qualified firemen, and boiler maintenance is in danger of becoming a lost "art." Coupled with these disadvantages are problems relating to local smoke ordinances that all but rule out contractor's boilers, the difficulties of cold weather operation, and the ever-present need for large quantities of clean water. On a commercial crane pile driver, a boiler represents a second power source, one that idles while the main hoist works; and the crane engine idles while the hammer works. All of this leads contractors and equipment manufacturers to search for other power sources.

Air

Modern air compressors answer many of the objections to contractor's boilers. A few years ago it was difficult to obtain portable compressors of adequate size and pressure rating. However, today, even the largest hammer can be operated by paralleling compressors when necessary. The modern compressor is a clean tool, and its maintenance and reliability are constantly being improved. It can be run by most operating engineers, requires little or no start-up time, and eliminates the need for large quantities of water. Winter operations of compressors have become commonplace. The efficiency of compressors for pile-hammer operation has been increased in recent years by the introduction of an after-heater system that uses the heat of the compressor engine exhaust gases to add energy to the air and thereby increase the output of the system. Compressors are, however, not without their disadvantages. The initial investment required can be 4 to 5 times that of a boiler with similar capacity. Operating costs are higher than those of a boiler, and compressor complexity adds to the contractor's maintenance work load. Finally, air compressors still represent a second power source on a pile driver.

Hydraulics

In the early 1960's the Raymond Concrete Pile Division of Raymond International, Inc., introduced a line of hydraulically powered differential hammers. Today over 25 of these are in operation. Their hydraulic power source offers the following advantages:

1. The pumps for the hammer system can be driven by the main engine of the pile driver. Because this engine would normally idle during most of an air- or steam-hammer driving cycle, the increased fuel and maintenance costs generated by the pump load are relatively insignificant.
2. The use of 5,000 psi pressure allows for small-sized hydraulic components, making possible completely built-in power pack systems.
3. The "closed loop" hydraulic system eliminates the external exhaust present in other pile hammers. No airborne contamination is generated, and hammer noise is appreciably reduced.
4. The hammer power pack can operate other pile-driver accessories such as drills for pre-excavating, hydraulic spotters, and auxiliary hydraulic hoists.

DIESEL HAMMERS

In recent years German, Japanese, and American equipment designers have produced bigger and better diesel hammers. When the diesel hammer was first introduced just prior to World War II, its mechanical reliability was questionable. Many times the hammer would not start. It was common for it to occasionally skip a blow. Most of these mechanical shortcomings have been overcome.

A diesel hammer is close to an ideal pile-driving package for the contractor. It gives him a single piece of equipment combining his power source and hammer. With a commercial crane, a light set of leaders, and a diesel hammer, he is in business.

There is apparently no limit to the size of diesel hammer that can be designed and built. Hammers with energy ratings of more than 100,000 ft-lb are available. There is, however, still some question about the blow delivered by diesel hammers. Arguments have been advanced for and against its special characteristics.

The blow of a diesel hammer is complex and starts with an initial force induced in the head of the pile by the compression of the air and fuel prior to ignition. The pre-compression force is followed by the actual blow of the ram that starts to accelerate the head of the pile downward. Almost simultaneously with the blow, diesel ignition occurs and the force of the explosion accelerates the ram upward and pushes the pile head downward. A lingering push is applied to the head of the pile as the products of combustion expand and continue to push the ram upward and the head of the pile downward.

Proponents of diesel hammers maintain that all of these factors contribute to a very efficient transfer of energy from a falling ram to a pile and that even the lingering force of explosion keeps the pile in motion and increases the penetration per blow. Opponents of the diesel hammer maintain that pre-ignition may cushion the blow of the hammer and that incomplete combustion can produce erratic hammer action.

Much is yet to be learned about these hammers. Several extensive test programs seem to indicate that the hammers deliver energies close to their rating. There are, however, other comparison driving tests that seem to indicate the contrary and cause many engineers to be extremely cautious about their application and use in connection with most "conventional" pile formulas. There is no doubt, however, that the diesel hammer is here to stay and that its reliability will soon be sufficiently improved and enough experience gained in its use for it to receive universal acceptance.

CAP BLOCKS

No discussion of driving systems would be complete without some mention of the cap block or cushion block commonly interposed between a hammer and the pile. This assembly performs 2 major functions: (a) It protects both the pile and the pile hammer; and (b) it modulates the blow of the hammer, eliminating extremely high, inefficient,

and possibly injurious peak forces, and transfers the energy of the moving ram to the pile more in terms of a push than a sharp rap.

Constant cap-block characteristics are almost a necessity when penetration per blow is used as a driving criteria. All of the empirical formulas used to determine the rate of penetration equivalent to a particular dynamic resistance assume that cap-block characteristics are constant.

For many years wood was the mainstay of the industry. It was found, however, that the type and the amount of wood used had an effect on the cushion's characteristic and that this characteristic further varied throughout the life of the block itself. This variable characteristic together with the high cost of the consumable wood block lead contractors to the development of the so-called permanent cap block. Typical of these is the micarta-aluminum combination developed by Raymond International, Inc. It not only possesses the springy constant found desirable in the old "standard" wooden cap block, but also has a higher coefficient of restitution: a measure of the efficiency with which the cushion can transmit the hammer blow to the pile.

VIBRATORS

Low-Frequency Vibrators

In a search for faster and more efficient means of installing piles, engineers began experimenting in the United States with the use of vibrations in the early 1950's. (In Russia and Germany experimental investigations were made prior to 1936.) Little came of this until the early 1960's when several low-frequency vibrators were introduced.

These vibrators operate in the range of 5 to 35 cycles per second and deliver their energy by lifting the entire pile and driving it downward on each cycle. The vibratory input tends to reduce the frictional grip of the soil on the pile and the pile itself is used to impact the soil and overcome point resistance. In recent years these tools have been increasingly used in the driving of "nondisplacement" piles. The application of the tool to closed-end pipe, shell, and precast piles has been very limited for 2 reasons: (a) Displacement piles are usually bearing piles and as yet no dynamic formula has been universally applied to make it possible to correlate either vibrator output or rate of penetration with dynamic pile capacity; and (b) the ability to overcome resistance under the pile point depends on the vibrator's maximum output force, the mass of the pile, and the amount of damping in terms of side friction that the soil presents. For most displacement piles the power required is beyond the capabilities of all but the largest vibrators.

The hammers have, however, been used extensively to drive and pull sheet piles, soldier beams, and open-end pipe. Almost every year new, larger units are available that cannot help increasing the vibrator's area of application.

High-Frequency (Resonant) Vibrators

In the early 1950's Bodine introduced the concept of resonant pile driving. This system utilizes oscillators having an operating range of 40 to 140 cycles per second. These oscillators make it possible to vibrate a pile at its natural frequency. The resonant theory holds that the mass of the pile does not dampen the oscillator's output but that the pile acts as a "transmission line" that maximizes the ability of the tip of the pile to do work on the soil. The vibratory imput also reduces or eliminates side friction.

A number of successful jobs have been completed by using this tool. Displacement piles over 100 ft in length have been successfully driven. The system offers the following advantages to the contractor and the engineer:

1. The ability to drive lighter section piles than can be driven with an impact hammer;
2. Increased speed of installation;
3. Elimination of the impacting noises present in conventional hammers; and
4. Operation far above the natural frequency of the soils on a particular site, eliminating or at least reducing the amount of vibrations felt by adjacent structures.

The system is not without its drawbacks. The cost of the equipment is high. The complex construction of the oscillator increases the maintenance cost of the tool and adversely affects its reliability. It is only a matter of time, however, before less complex high-frequency oscillators are developed that will eliminate these objections and increase the number of applications for resonant driving. Vibrators will probably, however, remain special-purpose tools.

DRIVING SYSTEMS OF THE FUTURE

For the short term the writer expects to see the following:

1. Diesel hammers—As their design is further refined, their reliability is increased, and a background of experience is developed, diesel hammers will be adopted by more pile contractors. Their "all-in-one-package" feature will make them especially attractive for the small jobs and highway work where many equipment moves are required. As diesel hammers of larger energy ratings become available, their use in driving heavy bearing piles for design loads of more than 100 tons should become common.
2. Large steam hammers—Only a few years ago piles of 70-ton design load capacity were considered exceptional. Today loads of 200 tons per pile are not uncommon. In a few years it is to be expected that piles loaded to 300, 400, and even 500 tons will be replacing expensive caissons for high-column loads. This will make the use of larger hammers mandatory.

In offshore construction, loads of 1,000 to 1,500 tons are already commonplace, and hammers with 60,000-lb rams and rated energies of more than 150,000 ft-lb are being used. Hammers with rams weighing 100,000 lb and ratings of more than 250,000 ft-lb are already on the drawing boards and will be introduced during the 1970's. As the design loads of dry-land piles are forced upward for economic reasons, it is only a matter of time before these large hammers move onshore.

3. Hydraulic hammers—The practicality of hydraulics as a source of power for pile hammers has been proven during the 1960's. To date the largest hydraulic hammer has a rated energy of 24,500 ft-lb. A 75,000 ft-lb hammer has already been designed. There seems to be no limit to the size of the hammer to which hydraulics is applicable. If the pile drivers of the 70's are to be as mobile as those of the 60's, and equipped with as many auxiliaries, hydraulic hammers are bound to see wider application.
4. Vibrators—Larger low-frequency vibrators and more reliable high-frequency vibrators are to be expected in the 1970's. Although these tools will probably always have limited application, they are just beginning to be applied. Oscillators of the high-frequency or resonant type will probably make use of linear hydraulics, and this should make for a high force output from a small package and minimize the number of moving parts in the system.

For the long term, who really knows just what driving systems will be developed? Nuclear power systems are a possibility. Another is single-package steam generators and hammers. Chemical generation of steam is now possible with convertors in the 70- to 100-hp range no larger than a roll of plans for some medium-sized job and those in the 250- to 1,000-hp range smaller than a 55-gal drum. Generators of this type directly mounted on a hammer will offer the same advantages in steam now enjoyed by diesel and yet not alter the operating characteristics of the steam hammer.

One thing we are sure of: The equipment conceived in the past and refined in the present will do the bulk of the work in the future.