Keynote lecture: Pile driving equipment: Capabilities and properties

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ABSTRACT: Deep foundations are expensive: they are labor and equipment intensive and pile material is costly. If they are necessary, they become a significant part of the total cost of a project. For this reason, new installation methods and associated machinery are continuously being developed. For prefabricated piles, the installation method is still the age old hammering with or without driving aids such as jetting, spudding or predrilling. Vibratory hammer installation is a newer development that promises great improvements in productivity. For cast-in-place piles the development has gone to larger equipment with more powerful drills and automatic casing machines or improved wet drilling techniques. However, this paper will only examine the current state of the art of impact and vibratory pile driving equipment, summarizing what is available today, what additional improvements can be expected in the near future and how this equipment can be selected to optimize installation and return on investment.

1 HISTORY OF PILE DRIVING EQUIPMENT

In the beginning there was the drop hammer. Pulled up by humans (Fig. 1), horses or other creatures it was suddenly released and then pulled up again. Guides or leads for the piles were always an important part of the driving equipment.

The nineteenth century saw the general adaptation of steam engines to a variety of tasks, including pile driving. A first development the replacement of human or animal power by steam power to pull the rams up with a winch. Today, there are still many winch driven drop hammers in use, typically with ram weights between 1 and 5 tonnes. However, steam power has generally been replaced by electric motors, diesel or gasoline engines.

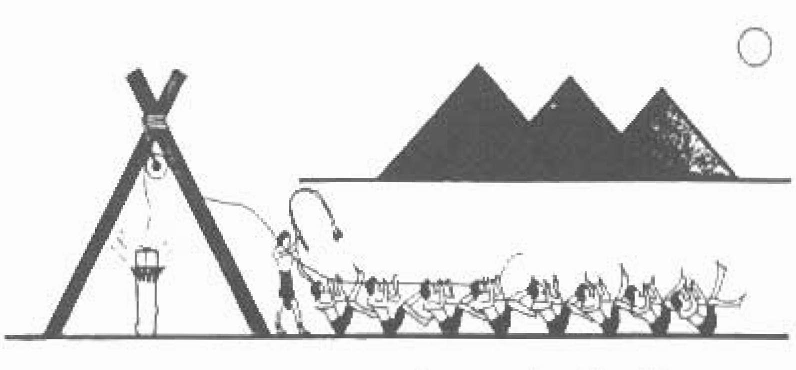


Figure 1. Artist's concept of an early pile driver.

At the end of the 19th century, the mechanical hammer was born. Steam pressure pushed against a a piston attached to the ram. Then, after tripping a valve, the steam pressure was vented and this allowed the ram to coast up to its highest point and then fall with relatively little energy loss. Even today steam is still being used as a power source for large hammers with ram weights up to almost 200 tonnes. However, more convenient air compressors gradually replaced the steam boilers on hammers with typically less than 15 or 20 tonnes ram weight.

Following the developments in general machine industries, it was obvious that double acting steam hammers should be built. They increased the operating speed of the hammer, but also wasted a lot of power. The differential hammer reduced that problem. Ram weights of double or differential acting hammers were limited to approximately 10 tonnes.

Adapting steam driven hammers to the more convenient compressed air operation required little change of the basic mechanical hammer. In contrast, the next development, using hydraulic power, required some new thinking. Merely replacing steam or compressed air by pressurized hydraulic fluid did not succeed because the "venting" of hydraulic fluid was not as simple as that of air or steam. Such hammers suffered pre-admission problems, meaning the motive fluid was admitted into the chamber before the hammer impacted, thereby self cushioning the ram.

The first successful hydraulic hammers were developed in Scandinavia in the 1960s for the installation of regularly reinforced piles. The best machine that met this objective had a heavy ram and a short stroke. This was accomplished with a simple hydraulic jack for a short upward ram motion (typically at most 1 meter) and then a free fall of the ram after quickly pulling the jack downward. These machines have ram weights of nearly 20 tonnes. They are being built by Banut, Uddcomp and others.

A parallel hammer development was engineered in Holland and Germany for the offshore hammer market. Their innovative design approach created a computer controlled double acting hydraulic hammer. The computer is provided with sensor information of ram position and ram speed and accordingly adjusts the hydraulic pressure for an operator selected ram impact energy.

Self-monitored hydraulic hammers have been built with ram weights reaching 150 tonnes by IHC and Menck. Being fully enclosed, they can be used underwater which requires solving a variety of additional problems as described below.

A variety of hydraulic hammers which either incorporate features of both the drop hammer and the computer controlled type or which cannot be strictly put in either of those two categories have also been developed. Some of these hammers are only optionally fitted with sensors for computer control or they are drop hammers with some downward pressure assistance. Manufacturers of these hydraulic hammers are BSP, HPSI, ICE, Junttan and others.

Diesel hammers replaced the external power source winch, steam, air or hydraulic fluid with an internal combustion underneath the ram. Starting in the 1920s in Germany, the first diesel powered rams typically had a mass of ½ or 1 Mg. Today, ram masses of single acting hammers range from 0.2 to 20 Mg.

A double acting diesel hammer that limited the high diesel hammer strokes and improved hammer speed by creating a passive air pressure chamber at the top of the hammer was also developed in the United States after World War II. Today closed end diesel hammers are built by ICE with ram weights up to 5 tonnes.

The vibratory hammer was developed in the Soviet Union prior to and during World War II. These hammers were first built with relatively low frequencies (less than 20 vibrations per second[VPS]) and were electrically powered. (After the war US, French and other companies further developed the low frequency hammers which today generate centrifugal forces of up to 4000 kN and now use hydraulic power almost exclusively.) The latest development allows for a gradual increase of the eccentric moment which is advantageous during the start-up of the hammer.

A French and later US development was the Bodine hammer, a diesel engine driven Sonic Pile Driver with 60 and higher VPS. Such frequencies created resonance in piles with length of 20m or more. Resonance in turn would greatly improve the speed of pile penetration. Because of mechanical problems this concept is still somewhat like a utopian dream.

For the sake of completeness the Silent Pile Driver which was developed in the last decades of the 20th century should also be mentioned. It is really a static machine which uses hydraulic pressure to push piles into the ground. The required reaction forces must be provided by previously installed neighboring piles. The system is therefore advantageous to sheet pile installation.

The so-called driving system includes a hammer cushion, helmet with inserts (cap) and pile cushion. While softwood and straw have been practically abandoned for hammer cushions and pile cushions respectively, little other progress has been made to improve driving systems. Exception is made to the systems that have eliminated hammer cushions entirely.

The guiding systems also have undergone some important development. Dedicated systems prior to World War II were often barge or skid mounted and had little freedom for adjustment. European developments combined carrier and leads into a dedicated system that requires little set-up time. This was particularly advantageous where pile sizes and lengths did not vary much, such as was the case with the European segmental reinforced piles. In the US, a greater variety of pile and hammer types made the combination of simple pile guide with a general purpose crane (often rented) more feasible. In the nearshore and offshore environment, free riding leads are used almost exclusively to align hammer and pile while a template or jacket provide support for pile and hammer.

Throughout the history of pile driving, a great deal of creativity was expended on the development of driving aids. The objective was the saving of pile material while improving driveability. Mandrels, jets, spuds, pre-augers, friction reducers and other means were developed, improved, optimized and occasionally abandoned.

2 MECHANICS OF IMPACT PILE DRIVING

Pile driving hammers are generally classified by their potential energy prior to the ram beginning its downward movement. The kinetic energy available to do work on driving system, pile and soil is a certain fraction of that potential energy. The ratio of kinetic to potential energy is the hammer efficiency. This concept of rating the hammer by a potential energy and calculating the available kinetic energy using a reduction factor has been replaced by a measured kinetic energy for those hammers that monitor ram position and speed immediately prior to impact.

Energy is not the sole quantity that defines the ability of a hammer to move the pile into the ground. An alternate measure would be its momentum or the product of ram mass and impact velocity. While this physical quantity would better indicate the maximum force that the ram can generate in the pile and therefore the soil resistance force that it can overcome, it is a measure that is only useful for comparing hammer capability in very hard driving cases.

Impact velocity is, however, one of the most important parameters of the impact event. In the absence of a cushion and helmet mass between ram and pile top, the particles of the pile assume the same velocity, v_i, as the ram during the first instant of the impact event. The corresponding force can be calculated from

$$F = v_i Z \qquad (1)$$

where Z is the pile impedance Z given by

$$Z = E A / c \qquad (2)$$

with E being the pile's elastic modulus, A its cross sectional area and c its wave speed given by

$$c = (E / \rho)^{1/2} \qquad (3)$$

with ρ being the mass density of the pile material.

The presence of a cushion reduces the peak force over time and spreads it over a greater time. A helmet mass has a similar effect (Rausche et al. 1972). Even so, the maximum force in the pile at the beginning of the impact event is primarily dependent on the impact velocity.

The greater the mass of the hammer, the greater its ability to maintain the pile top force near the maximum impact force. Therefore, a small hammer will only generate a short force pulse which may be ineffective in maintaining a sustained downward movement and therefore pile penetration. On the other hand, a slowly falling ram does not generate the force necessary to overcome soil resistance.

Piles are relatively long, slender elastic bodies and for this reason, their dynamic behavior is governed by wave effects. In other words, in the first instance after the ram has impacted, only the top of the pile moves downward. It takes a certain time, the wave travel time L/c (L is the pile length) before other pile particles further down the pile start to move. At the pile toe a reflection occurs that depends on the resistance that the material at the pile toe offers. If there is no resistance at all the pile toe will move twice the distance that the top moved during impact and it will then pull the upper pile particles downward. This creates a tension force which is potentially damaging to concrete piles. If there is an extremely high soil resistance such that the pile toe cannot move then the force at the pile toe will be twice the force that the pile top experienced during the impact event. Theoretically, therefore, the hammer can overcome a force which is twice the impact force of Equation 1. In practice, because of the need for all materials to compress before they can exhibit resistance, the limit of the soil resistance is about 1.4 for piles with predominant end bearing piles and 1.0 for shaft resistance piles.

In the case of the high toe resistance a strong compressive wave reflection occurs which pushes the upper pile particles upwards. For large ram weights, the ram will still have downward momentum when the reflected wave reaches the pile top. In the case of the hard driving pile it is possible that another compressive reflection occurs at the pile top which may cause the pile top force to grow above its initial peak. (In addition, a new wave will cause downward pile motions.) The benefit of a large ram is therefore a longer lasting downward motion of the pile, a further increase of the pile toe force and the chance for additional permanent pile penetration into the ground.

Since it is uneconomical to use very large ram weights, we normally do not see cases where the soil resistance is much greater than twice the impact force. However, damage at the pile toe when it is on rock can easily happen when either the impact force is very high or the ram mass is large.

Calculation of pile penetrations into the ground and stresses along the pile are difficult and inaccurate when considering simplified systems and employing wave propagation theory. It is better to use a wave equation computer program, such as GRLWEAP (GRL 1999) to realistically model hammer, driving system, pile and soil, and mathematically simulate the pile driving process. Obviously, such models require assumptions regarding the performance of the individual components of the system and it is therefore best to measure forces and velocities at the pile top and calculate the desired quantities based on these measurements using CAPWAP (GRL 1996).

3 HAMMER PERFORMANCE MEASUREMENTS

Pile Driving Analyzer®

The basis for the results calculated by the PDA are pile top strain and acceleration measurements which are converted to force and velocity records, respectively. The PDA conditions, calibrates and displays these signals and immediately computes average pile force, F(t), and velocity, v(t), thereby eliminating bending effects. The PDA calculates a variety of results for each hammer blow, including pile bearing capacity, pile stresses, pile integrity and other important pile quality parameters using closed form Case Method solutions based on the one-dimensional linear wave equation.

The PDA also calculates the energy transferred to the pile top from:

$$E(t) = \int_0^t F(\tau)v(\tau)\, d\tau \qquad (4a)$$

The maximum of the E(t) curve is the most important information for an overall evaluation of the performance of a hammer and driving system. This EMX value, also called ENTHRU, allows for a classification of the hammer's performance when presented as the rated transfer efficiency, e_T, also called energy transfer ratio (ETR), system efficiency or global efficiency:

$$e_T = EMX/E_R \qquad (4b)$$

where E_R is the manufacturer's rated energy value.

Hammer Performance Analyzer ™

The ram velocity may be directly obtained using radar technology in the Hammer Performance Analyzer (HPA). For the HPA to work the ram must be visible. The impact velocity results can be automatically processed with a PC or recorded on a strip chart. The result of the HPA is the velocity immediately preceding impact. The kinetic energy can be calculated directly from this measurement (see appendix).

Saximeter ™

For open end diesel hammers, the time between two impacts indicates the magnitude of the ram fall height or stroke. This information is not only measured and calculated by the PDA but also by the convenient, hand-held Saximeter.

Both Saximeter and PDA calculate the stroke (STK) of an open end diesel hammer using

$$STK = (g/8)\, T_B^2 - h_L \qquad (5)$$

where

g is the earth gravitational acceleration,
T_B is the time between two hammer blows,
h_L is a stroke loss value due to gas compression and time losses during impact (usually 0.3 ft or 0.1 m).

A modification of the Saximeter is the Saximeter-E which accepts timing signals from two proximity switches installed in the hammer such that the time between these two signals is a measure of the ram velocity immediately preceding impact. Again, this measurement can be simply converted to hammer kinetic energy. The signals from the proximity switches are sent to the Saximeter-E using telemetry.

Pile Installation Recorder ™ for Driven Piles (PIR-D)

The PIR-D accepts signals from a variety of sensors, among them time of occurrence of hammer blow, time when ram passes two positions just before impact (as for Saximeter-E), pile depth of penetration, bounce chamber pressure. These signals are evaluated and plotted vs depth as follows:

- stroke for open end diesels,
- impact velocity of all types of hammers, and
- bounce chamber pressure for closed end diesel hammers as an indirect measure of stroke.

4 TECHNICAL DETAILS OF IMPACT HAMMERS

Cable suspended drop hammers

The system generally uses a crane mounted winch for ram raising. Releasing the brake on the winch causes the ram to drop. Of course, the falling ram has to pull the winch cable and therefore accelerate the winch which costs energy. Immediately prior to impact, the crane driver is often tempted to reapply the brake to prevent a spilling of the winch cable. This action cushions the impact. It therefore must be expected that approximately 50% of the potential hammer energy is lost. Up to 3 m drops are not uncommon. In general, these hammers apply impacts of inconsistent magnitudes. Considering nominal fall height times ram weight the full energy, then energy losses are due to

- inaccurate drop height,
- friction,
- winch drum inertia,
- early catching of the ram, and
- misalignment.

Free release drop hammers

Such a hammer is probably only found for special applications, e.g. dynamic load testing. Free release devices, although not a real technical problem, are not a practical solution for normal pile driving tasks. In fact it is advisable to transfer the support of the ram from the crane to a stiff device such as the leads prior to releasing the ram to avoid damage to the crane. In this way a precise hammer fall height can be achieved. Of course, the hammer efficiency would be expected to be higher than that of the winch brake released hammer. The energy losses are then only due to

- guide friction and
- misalignment.

The hammer efficiency therefore may be assumed to be quite high, e.g. 95%.

For those involved in dynamic load testing, the development of free release devices has frequently been of interest. The following solutions have been encountered:

- cam hook,
- Spread hooks, and
- cut-off (torch, hydraulic shear) support cable.

Depending on the height, angle and friction factor of the cam, the force to release the weight will be a small percentage of the drop weight. Up to certain loads such devices are commercially available.

The tests described by Seidel et al. (1982) utilized a double hook device from which a 20 tonnes load could be released by hand.

As mentioned earlier, whenever a heavy ram is suddenly released, care must be taken that the energy stored in the supporting carrier is carefully released. In a winch release this is automatically the case because the weight is only gradually released. However, a sudden free release should either be done after the support of the weight is transferred from crane to ram guide or by utilizing a ballast between release device and crane hook. The inertia force of the ballast slows the release of the energy stored in the crane system.

Single acting air/steam hammer

It was the mechanical steam hammer that simplified the hammering process significantly. The ram was simply attached to a single acting steam engine that pulled the ram up. Near the top of the upward motion the valves were switched, releasing the upward pressure by venting the chamber. The ram would coast upwards an additional distance before it started to fall under gravity. Shortly before the downfall ended the valves were switched again. This allowed motive fluid to enter the chamber, generate an upward directed force on the ram and produce a new upcycle. Of course, allowing the motive fluid to enter the chamber too early would effectively cushion the impact of the ram prior to impact (preadmission). This effect is equivalent to the operator of a drop hammer applying the break too early. If all settings are carefully adjusted the losses would be small, however, losses due to preadmission are also possible if the cushion block were too thin allowing for a longer than design drop after the valves had been switched. On the other hand, a very thick cushion block would reduce the stroke and, in the worst case, prevent switching of the valves. Then the hammer would not run at all. It should also be mentioned that a sufficient air/steam pressure is important such that the ram coasts up to the nominal fall height after the valves have vented the chamber. In fact, in easy driving the upward ram motion is sometimes so low that the hammer short strokes (but in that case it is not a problem.).

There are two different arrangements of the steam engine. One type attaches the piston directly to the ram (Vulcan, Conmaco, MKT) and makes the cylinder stationary. The other one uses a hollow ram making it a movable cylinder while the piston is stationary (Menck MRBS). There is another difference between these two hammer types: The former maintains constant pressure under the piston until the chamber is vented; the latter works with a constant volume of steam charge which is then allowed to expand. Obviously, the former wastes more energy but is faster, while the latter is more economical.

Single acting air hammers are not much different from steam hammers except that steam is hot and compressed air is colder. The different temperatures of these two motive fluids require that manufacturing of piston and cylinder is done with different tolerances because of the differences in thermal expansion.

It is important that air/steam hammers are lubricated both internally with a lubricant injected into the motive fluid and externally along the ram guides. Energy losses primarily occur because of:

- guide and piston/cylinder friction,
- low stroke in easy driving,
- less than rated stroke when pressure is low,
- preadmission, and
- misalignment.

Typically, hammer efficiencies are assumed to be 67% for these hammers for wave equation analyses. Transfer efficiencies recorded at the end of driving average 55% on steel and 40% on concrete, and timber piles (Figs. 2-3).

Drop heights of single acting air hammers typically vary between 900 mm and 1500 mm. The stroke of the hammer is generally controlled by a

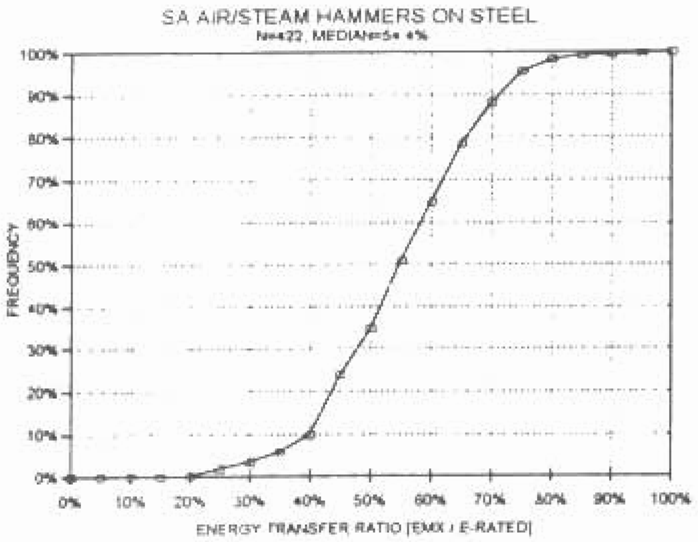


Figure 2. Transfer efficiencies of single acting air/steam hammers on steel piles at the end of driving.

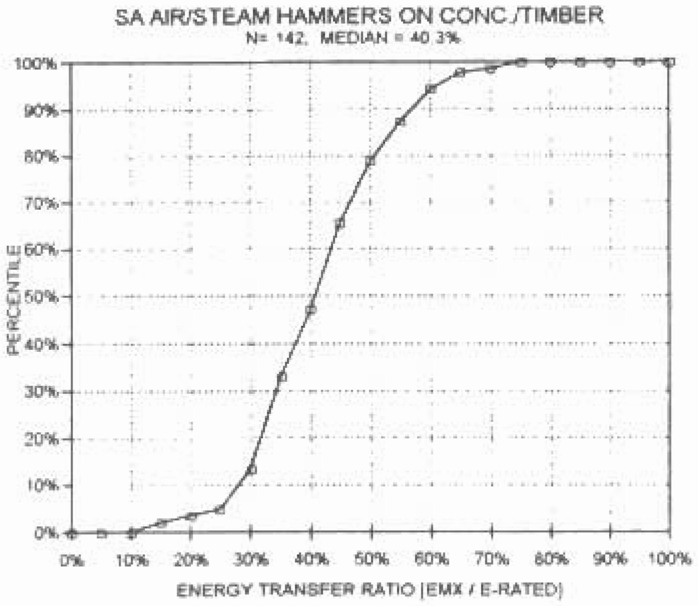


Figure 3. Transfer efficiencies of single acting air/steam hammers on concrete and timber piles at the end of driving.

slide bar which is attached to the moving ram. Several of these hammers have been equipped with a variable stroke attachment which allows for alternating between two different strokes. This is particularly useful for concrete pile driving where tender care is required in easy driving and high energies are needed in hard driving. It is not uncommon that the hammer overstrokes on the short stroke and therefore operates at apparently higher efficiency. It is therefore reasonable to increase the hammer efficiency (e.g. to 0.75 from 0.67) of short stroked hammers in a wave equation analysis.

Double and differential acting air/steam hammers

In order to generate hammer blows in quicker succession it is desirable to shorten the stroke and accelerate the ram on its downward motion by pushing downward with active pressure. This has been accomplished in double or differential acting hammers. The difference between these two engine types is subtle for the civil engineer: the former being somewhat more power intensive than the latter. While single acting hammers run typically at 50 to 60 blows per minute, double or differential hammers run at 100 blows per minute or more.

There is an obvious limitation on the amount of pressure that can be exerted onto the ram. If this pressure would create a force in excess of the weight of the hammer assembly itself (total hammer weight minus ram weight) then the hammer would lift off from the pile and an unstable driving situation would result. Thus, hammer weight and operating pressure must be matched.

During hard driving when the pile rebounds strongly, the ram obtains a high upward velocity which necessitates reduction of the operating pressure. This means that the pressure is also reduced during the downward cycle, causing a reduced energy of the impacting ram. For this reason, this type of hammer has on the average a lower efficiency at the end of driving (when driving is relatively hard) than other hammer types. The following energy losses have to be expected:

- guide friction and friction on piston in cylinder,
- reduced stroke in easy driving,
- reduced stroke due to reduced pressure in hard driving,
- reduced ram velocity due to reduced pressure,
- preadmission, and
- misalignment.

Normally, for wave equation analyses a hammer efficiency of 0.5 is therefore reasonable. Transferred energies average 35% on steel piles and 30% on concrete piles (Figs. 4-5).

These hammers run vary rapidly and have been made very small for many purposes, such as jack hammering. For pile driving their ram weights vary typically between 2 kN and 90 kN.

Diesel hammers

In the 1920s, DELMAG built the first open end diesel hammer which utilized diesel combustion underneath the ram to provide the energy for the upward ram motion. Thus, the ram serves as the piston of a 2-cycle diesel engine. The advantage of this hammer is a relatively light weight, sturdy construction and no need for an additional external power supply.

The hammer consists of four parts: a cylinder, a ram or piston, an impact block that closes the bottom of the cylinder and a fuel pump that injects fuel into the cylinder prior to impact. There are four phases that this hammer type undergoes prior to, during and

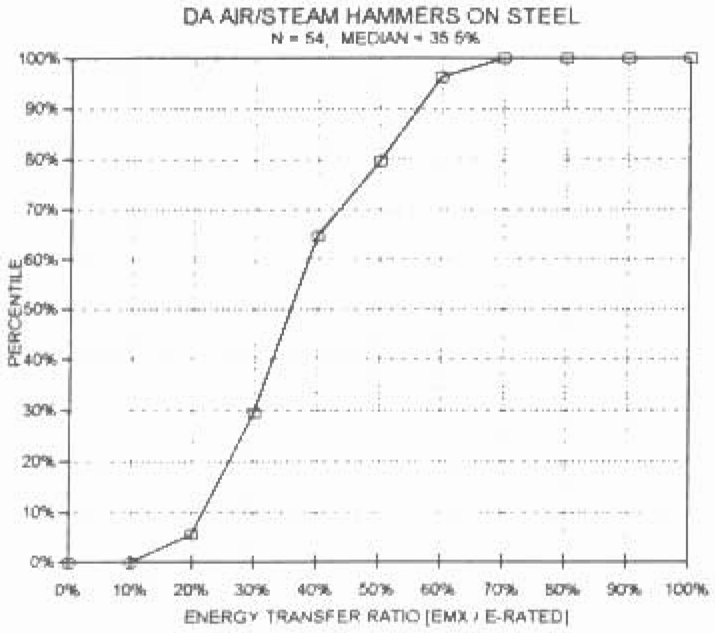


Figure 4. Transfer efficiencies of double acting air/steam hammers on steel piles from end of drive measurements.

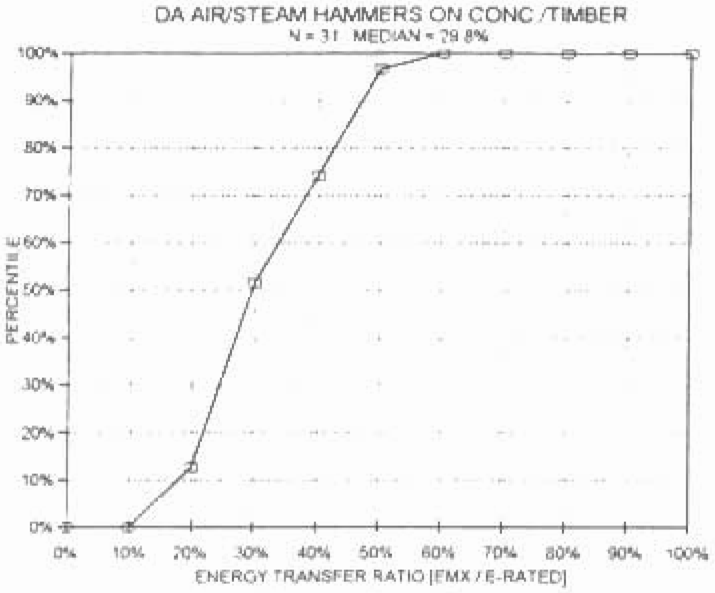


Figure 5. Transfer efficiencies of double acting air/steam hammers on concrete piles from end of drive measurements.

after the hammer impact. During the first phase the ram first rises and then falls only subject to gravity. When on the downstroke the ram closes the exhaust ports. The air underneath the ram is being compressed, and thus raises its temperature. This is the second or compression phase. Impact occurs and injected fuel combusts in the third, the impact and combustion phase. Finally, the ram is driven upwards during the expansion phase that ends when the excess pressure is vented through the exhaust ports and new air is sucked into the cylinder during the ram's upward motion which - being only subject to gravity - is part of the first phase of the next hammer blow.

Open end diesel hammers are made or distributed by APE, Berminghammer, DELMAG, and ICE. Other makes still exist but they are no longer manufactured.

Closing the top of the cylinder traps air above the piston which causes the ram to move up and down more rapidly (typically 80 blows per minute vs 40 blows per minute for the open end diesel hammer). Like double acting air/steam hammers, the maximum pressure on the piston is limited by the hammer weight. Therefore the maximum stroke is limited to that value that corresponds to a pressure that causes an uplift condition. The manufacturer rates closed end hammers somewhat below an open end diesel of the same ram weight. Double acting diesel hammers are made by ICE and MKT.

The behavior of diesel hammers is not as simply predicted as that of other mechanical hammers. To a much greater extent than air/steam hammers the ram drop height of diesel hammers is dependent on the resistance that the soil offers. Typically in a refusal situation the ram reaches its highest potential energy. This is actually a desirable quality, since the hammer strikes rather gently when driving is easy. In fact, it maintains a certain minimum compressive pressure on the pile from either gas compression or expansion that protects concrete piles against damaging tension stresses. However, the stroke variability also complicates the prediction of energy output. Another complication is that the compression of the air charge (phase two) requires energy that is temporarily stored in the compressed air and later released, together with the combustion energy, during the upward motion of the ram. The energy stored in the compressed air is a function of the compression ratio of the hammer, typically ranging between 12 and 15. Typically, the compression energy is between 20 and 30% of the potential hammer energy. It may be much higher if the hammer pre-ignites, which may happen if the hammer is poorly maintained or overheats to such a degree that either the fuel oil or the lubrication oil combusts prior to impact. The ram then falls against a very strongly increasing pressure which reduces ram velocity plus kinetic energy. Note however, that some energy already gets transferred to pile and soil during the pre-compression phase.

Pre-compression is only possible if the pile can offer a resistance that matches the compression forces. For this reason, the hammer will not run if the soil resistance is very small.

In diesel hammers, energy losses are typically caused by:

- pre-compression,
- friction between ram and cylinder,
- impact and inertia losses of the impact block,
- low stroke,
- pre-ignition, and
- misalignment.

Considering pre-compression a design loss that can be calculated, the remaining losses are typically less than 20% of the potential energy. The appendix contains a numerical example for the calculation of pre-compression energy.

Ram weights range from 2 kN to 200 kN, rated energies from 0.4 to 600 kJ. The hammer efficiency typically averages 0.8. Transferred energies have medians of 31 % on steel piles and 25 % on concrete piles (Figs. 6-7).

Hydraulic drop hammers

Hydraulically powering hammers has become attractive with the development of powerful hydraulic pumps and other accessories. A direct conversion of air/steam hammers to hydraulic hammers proved unsuccessful, because of the problem of preadmission for incorrect valve settings.

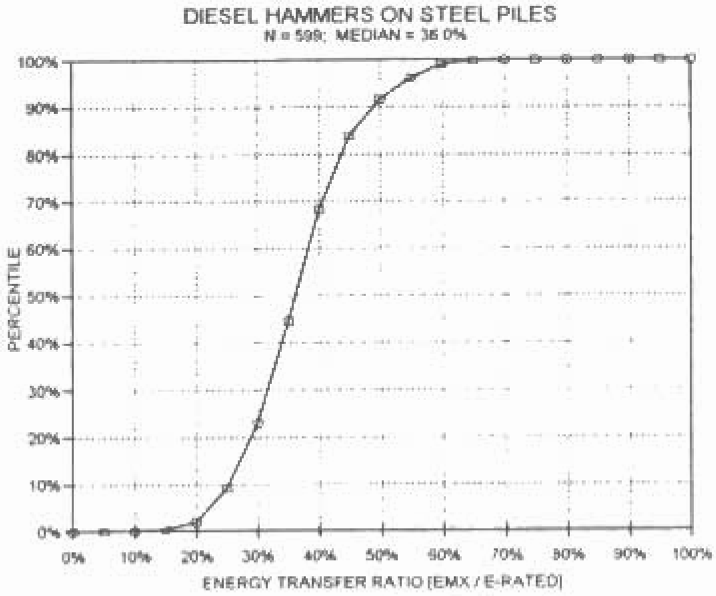


Figure 6. Transferred energies of diesel hammers on steel piles at the end of driving

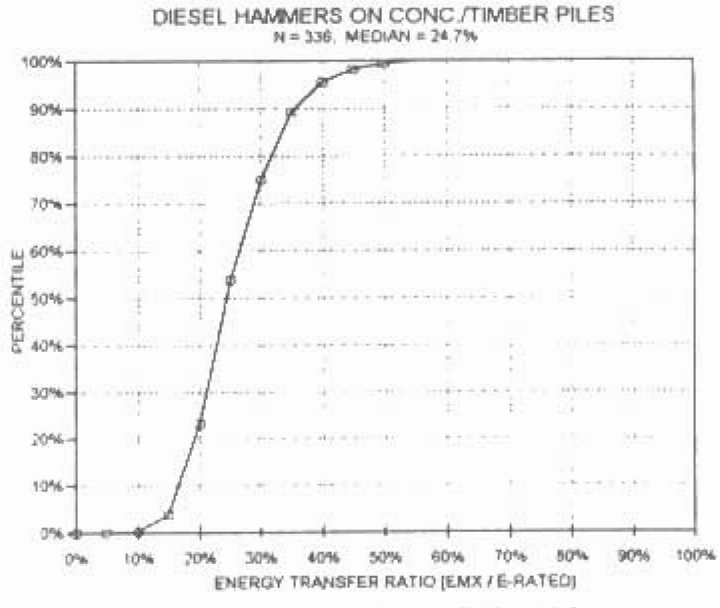


Figure 7. Transferred energies of diesel hammers on concrete piles at the end of driving .

The first successful hydraulic hammers were simply drop hammers: a jack would pick up the ram and then retract quicker than the falling ram. Since these hammers were at first built with low drop heights, energy losses were extremely small. Examples are the Banut, ICE, Junttan, Menck MHF series, Uddcomb and other hammers. Ram weights are as high as 150 kN and rated energies reach 200 kJ.

Energy losses are caused by:

- guide friction, and
- misalignment.

whereby guide friction is often insignificant due to the short strokes.

Self-monitored hydraulic hammers

The IHC and Menck MHU hammers are built differently, however they share features which make them very similar. A piston rod and piston are connected to the ram. The piston is pushed up by hydraulic power and downwards from its upper side by active pressure. Electronics sense the impact velocity and count hammer blows. A computer outputs energy and blow numbers.

The energy that is used to control pile driving with this hammer is the kinetic energy contained in the ram just before impact. This energy is adjustable by continuous variation of stroke and/or downward pressure. The hammer's rated energy is therefore a net maximum value, after most losses. Hammer efficiency for this type of hammer is therefore defined differently from others: it only covers losses occurring during the impact. The energy necessary to accomplish the ram impact velocity is inconsequential and therefore not monitored. It is not surprising that the hammer efficiency is usually set to 95%. This covers such relatively insignificant losses as

- measurement errors of impact velocity, and
- misalignment.

This hammer type, being remote controlled, completely enclosed and having an external power source supply that can be supplied through hoses, can also be employed under water. This explains why the manufacturers removed the need for cushioning by perfect machining of the impact surfaces. Frequently used in offshore applications, ram weights of these hammers reach 1500 kN.

Other hydraulic hammers

There are a variety of other hydraulic hammers available today. For example, BSP makes hammers that are operated either with or without active downward pressure. They may or may not include a monitoring equipment. The variety of hammers in this category preclude general statements of energy losses and recommended efficiencies. Indeed, Figure 8 shows that the combination of all hydraulic hammers tested by the author's firm generate an efficiency diagram with two distinctly different groups of performance: a lower area around 55% and a higher one with an 85% mean. Additional data is needed to produce a clearer classification of these hammers.

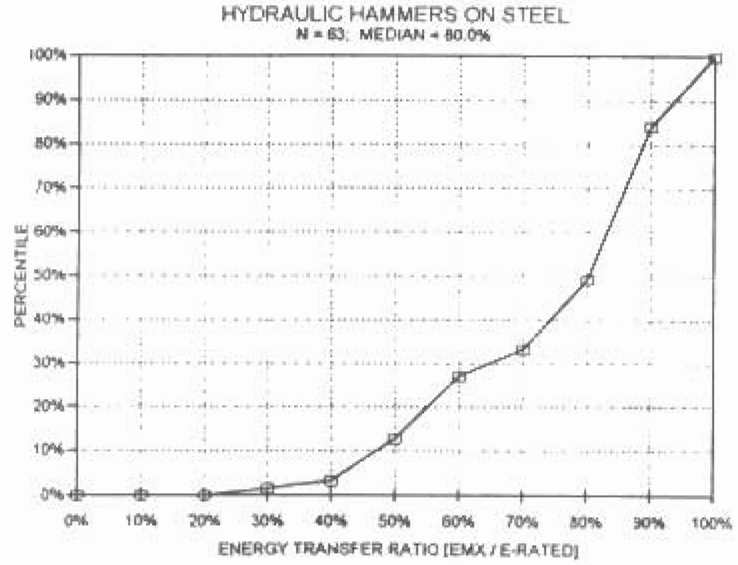


Figure 8. Transfer efficiencies for a variety of hydraulic hammers on steel piles.

5 DRIVING SYSTEMS

Driving systems are defined as the accessories necessary to transfer the impact forces safely to the pile top. They include a cushion for the protection of the hammer, a helmet with adaptor inserts and a cushion to protect concrete piles.

Hammer cushions

With a few exceptions, hammer impact is usually cushioned by a relatively resilient material. The reason is the need of protecting the ram from excessive fatigue stresses. Often man made materials are used and they require little exchange as long as the cushion is protected by a well fitting steel striker plate and is sandwiched between aluminum sheets for heat extraction. If they are made of a stiff material (softwood is not acceptable as a hammer cushion), hammer cushions store and dissipate relatively little energy.

Driving systems without hammer cushions

Certain hammer manufacturers have decided that it is unnecessary to protect the hammer against high pile stresses. Indeed, diesel hammers whose rams strike the impact block directly and which have been in existence for decades without damage to ram or impact block have proven that well fitting impact surfaces generate tolerable stresses. These hammer manufacturers therefore devised a cushionless driving system which features a well fitting and machined impact surface for the ram such that high contact stresses are avoided. This idea was first incorporated in the IHC hydraulic hammers.

Pile cushions

Pile cushions are only necessary for concrete piles where they serve two purposes. First they must reduce the likelihood of stress concentrations at points of steel-concrete contact. Second, they are often designed to reduce the peak stress in the pile by spreading the impact forces over time. Historically, when hammers had limited drop heights of less than 1 m, only the reduction of contact stresses was important and straw was often successfully and economically employed. Today, hammers with high strokes and/or high efficiencies also require that the second condition be satisfied and that requires a cushion block with low stiffness. Plywood fulfills both purposes quite well, however, it only lasts for about 1500 hammer blows. This limit can be a problem when driving for an extended time period with a follower under water where a cushion exchange is not possible. Using thick cushion blocks to lower the impact force by spreading it over time leads to a rather wasteful use of plywood. A combination of thin plywood sandwiching a somewhat more resilient material can then be more economical. Hamortex, a man-made material consisting of rolled-up, aluminum coated paper has been successfully employed for this purpose.

Pile cushions are also made of a variety of other materials. For example, in Latin America sisal and hemp rope have been successfully used though with greater energy losses than plywood.

Helmets

Helmets must align hammer and pile and securely spread the impact forces over the pile top. Depending on the type of pile, they must be fitted with inserts that match the pile profile. Helmets also accommodate the hammer cushion. It is important that the hammer only allows for a small lateral tolerance (e.g. 25 mm) on the pile top for good hammer pile alignment.

6 PILE GUIDES

Guiding of the pile is an important part of the pile driving equipment. Historically, dedicated systems with a stiff leg and a skid have fulfilled this role and these systems are still used for some very large projects. However, these systems are not very easy to move and therefore reduce productivity.

Swinging leads

A very simple system is the swinging lead which can be cable supported from a multi-purpose crane and which is stabbed in the ground for a second point of support. Obviously, such a system is relatively flexible, a feature that sometimes protects piles from breakage when the pile encounters an obstruction and wants to move laterally.

Fixed leads

Fixed leads are supported at the boom tip of the crane with a hinge and near their bottom by a brace. Normally, this brace can be extended or contracted hydraulically to set the batter. Fixed leads are probably the most common support system and many dedicated lead-hammer systems that use a dedicated carrier also achieve mobility and control with such a lead type. Often these systems can adapt to a compound batter.

Freeriding leads

Over water, piles are often driven through a template which assures the correct location and direction of the pile. In such a case leads are merely aligning the hammer with the pile. These "caison-type" or freeriding leads are supported at their top by the crane. A disadvantage is for battered piles that the transverse component of hammer and lead weight has to be supported by the pile, thereby introducing potentially high bending stresses in the pile which are superimposed to the dynamic stresses from pile driving.

7 UNDERWATER PILE DRIVING

Under water pile driving in water depths of 1000 m or more can be done, however, only after a number of formidable problems are solved. For example, hammers and piles have to be run through the same guiding system. The hammer outside diameter therefore should not be greater than the pile diameter. In fact, it is sometimes necessary that a pipe extension is added to the hammer top for additional guiding once the pile has been driven below the lowest guide.

Supplying high hydraulic pressures at high rates of volume through long hoses pose another challenge. One solution would be a remote hydraulic power inside the guiding system of the hammer. That means that the power pack also has to fit through the guides and that electric power is supplied over a long distance.

Ambient pressures are, of course, very high in a 1000+ m depth environment. This means that the air surrounding the moving ram becomes quite viscous and care has to be taken that air passages are large enough so as not to impede the ram movement. Of course, the hammers' sensors will be able to indicate the actual kinetic energy.

Finally, driving against a water column inside the pile would dissipate valuable energy. Thus, excess water must be allowed to escape through holes in the pile near its top and an air cushion should be maintained beneath the helmet.

8 VIBRATORY HAMMERS

An impact hammer generates a short duration force/velocity pulse in the driven pile. Between hammer blows the pile and soil are practically at rest for a time (typically 1 second) that is large compared to the impact event itself (typically 20 to 50 ms). The impact hammer therefore generates a complete cycle of loading and unloading during the short impact event.

First built in the Soviet Union in the mid 20th century, vibratory hammers became the installation device of choice for non-bearing piles, because of their superior speed of pile installation in many soil types.

Vibratory hammers consist of pairs of rotors with eccentric weights attached. Always two rotors are synchronized such that their horizontal centrifugal force components cancel while their vertical ones add. The vibratory machine therefore obtains an up and down sine motion with a frequency equal to the speed of rotation. Obviously, the maximum vertical force is the same in upwards and downwards direction with a downward bias given by the weight of the machine itself and the pile. If the eccentric moment of all rotors in the machine is M_E and the frequency, f, then the downward maximum dynamic force is

$$F_F = (2 \pi f)^2 M_E \qquad (6)$$

Originally, vibratory hammers had a relatively low frequency of less than 20 Hz (1200 RPM), were electrically powered, and of moderate size. Today these standard machines are powered with hydraulic aggregates reaching 600 kW (800 HP) with centrifugal forces of up to 4000 kN (800 kips) and frequencies typically up to 30 Hz. Larger outputs may be achieved with two machines running in tandem.

Resonant pile drivers

The vibratory pile driver's dream has always been to achieve even better penetration rates with a machine that would generate resonance in the hammer-pile system. Resonance would generate forces much larger than the centrifugal force of the hammer. Such a high frequency machine has been built, used, improved and retried, generally with the result that pile driving indeed became very quick, however, the machine would suffer and frequently break down. The Boudine pile driver is equipped with two diesel engines driving the eccenters directly at the pile top. It is capable of frequencies up to 80 Hz which would generate resonance in a pile of 15 to 30 m length, depending on the relative weights of pile and machine and on the resistance magnitude and distribution.

Variable moment hammers

An interesting aspect of vibratory pile driving is the response of pile and soil to various frequencies. Typically, for somewhere above 3 and below 10 Hz a resonance between pile and soil occurs which generates strong soil motions. Nearby buildings can sustain damage due to these vibrations. When shutting the machine off, the standard vibratory hammer again generates these lower damaging frequencies. In addition, while higher frequencies tend to densify the soil, low resonant frequencies may actually cause a loosening of denser materials. It is therefore highly desirable to make a hammer that does not cause a low frequency resonance and since no motor can suddenly run at a high speed the only solution is to increase the eccentric moment after the desirable hammer speed has been reached. Such variable moment machines are now being produced in Europe. They are also effectively used for soil densification (Massarsch 1992).

9 INSTALLATION AIDS

It is often not wise to force a pile through harder layers into softer materials or to give the pile a much higher strength than necessary merely for driveability. Instead it may be possible to use installation aids such as jetting or drilling. However, such installation aids must be used wisely. They may actually cause harm to pile and soil if not properly executed.

Predrilling

In the United States one can often see a pile driving hammer with a continuous auger attached on its lead next to the hammer. Usually a hole that is only 80 percent of the pile size is drilled through the potentially difficult overburden. It is important that the hole is not drilled too deep. Strongly reducing shaft resistance on a long pile and then driving against a high end bearing may actually cause damaging pile stresses and make the pile harder to drive.

Jetting

Either on the side of a pile, or sometimes through a center tube of a concrete pile, water may be used to loosen and remove soil from around the pile tip. In softer soils large cavities may accidentally be opened up and that would, of course, detrimentally affect the bearing behavior of the soil.

Spudding

Prior to driving large concrete displacement piles (e.g. a 900 mm square) a hole can be driven with a spud which is typically a steel section of the same size as the concrete pile. The spud may be so heavy that it can be repeatedly lifted and dropped to form a hole in which the concrete pile is then inserted. The concrete pile only needs enough hammer blows to seat it into soil undisturbed by the spud.

External friction reducers

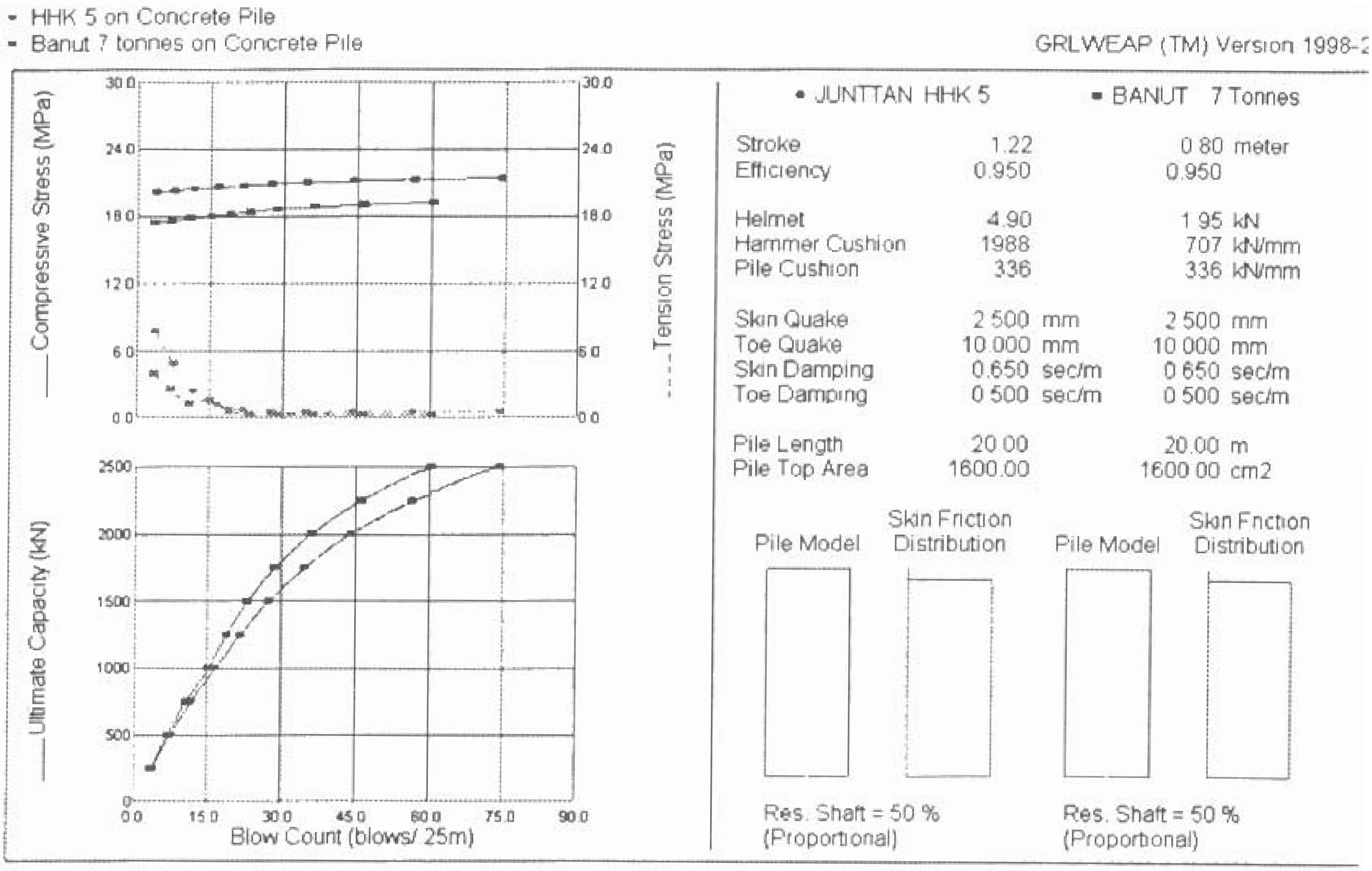
For pipe piles that have to penetrate competent soils for deep penetrations it is advantageous to attach shallow rings to the outer pile circumference. These rings reduce the friction temporarily during pile driving by creating a heavily disturbed zone in the area above. Design details such as size of and distance between the rings are either proprietary or non-existent.

Internal friction reducers

For pipe piles, a so-called internal driving shoe, i.e. a section of pipe with increased wall thickness but identical outside diameter is attached to the pile bottom. Above this section the soil penetrating into the pipe during pile driving experiences reduced lateral confinement and therefore reduced friction.

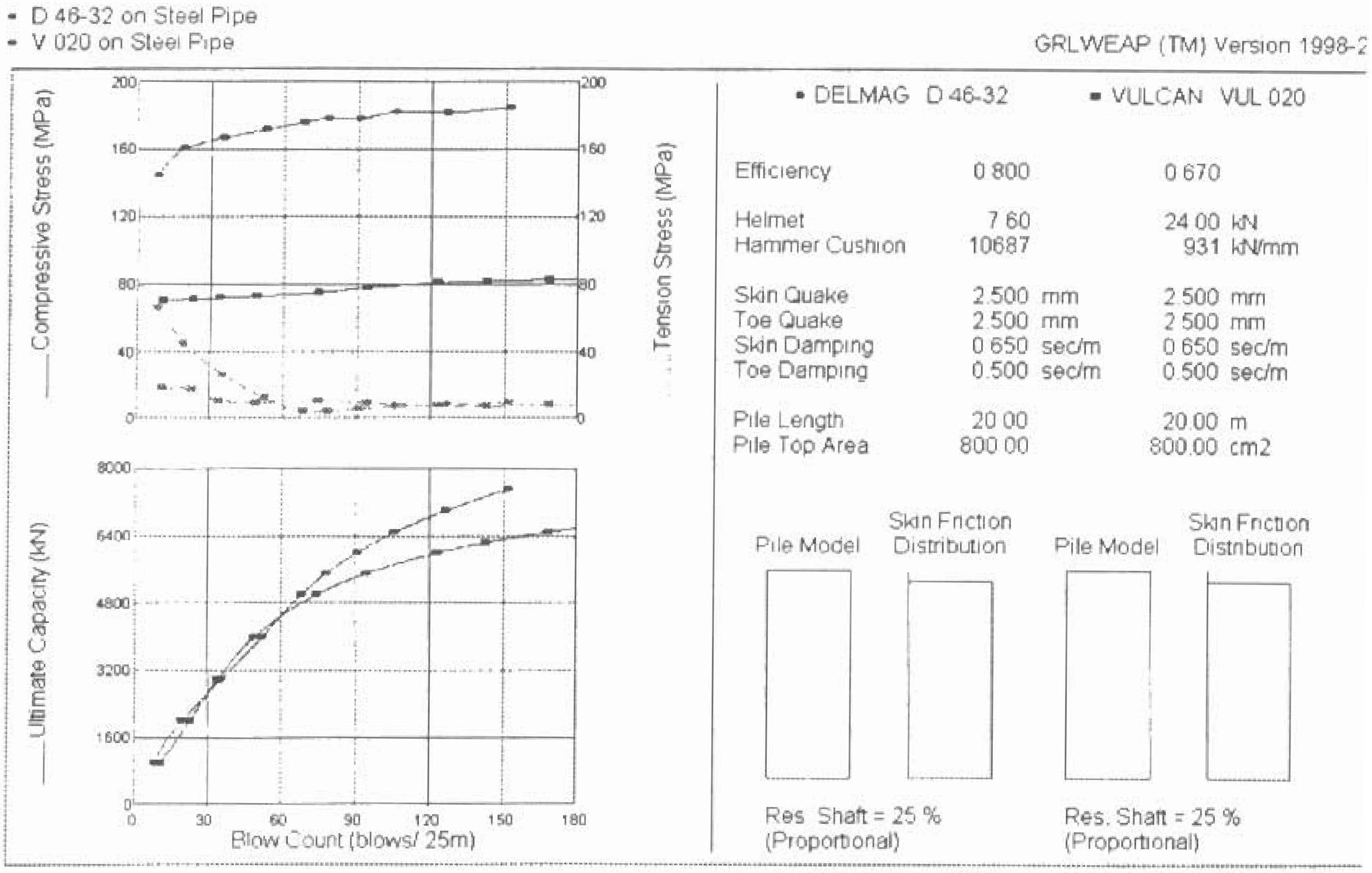
Electric potential

For offshore steel pipes that have to be driven into clay, an electric current can produce a temporary



	• JUNTTAN HHK 5	▪ BANUT 7 Tonnes
Stroke	1.22	0.80 meter
Efficiency	0.950	0.950
Helmet	4.90	1.95 kN
Hammer Cushion	1988	707 kN/mm
Pile Cushion	336	336 kN/mm
Skin Quake	2.500 mm	2.500 mm
Toe Quake	10.000 mm	10.000 mm
Skin Damping	0.650 sec/m	0.650 sec/m
Toe Damping	0.500 sec/m	0.500 sec/m
Pile Length	20.00	20.00 m
Pile Top Area	1600.00	1600.00 cm2

Figure 9. Bearing graphs for two different hydraulic hammers on the same pile.



	• DELMAG D 46-32	▪ VULCAN VUL 020
Efficiency	0.800	0.670
Helmet	7.60	24.00 kN
Hammer Cushion	10687	931 kN/mm
Skin Quake	2.500 mm	2.500 mm
Toe Quake	2.500 mm	2.500 mm
Skin Damping	0.650 sec/m	0.650 sec/m
Toe Damping	0.500 sec/m	0.500 sec/m
Pile Length	20.00	20.00 m
Pile Top Area	800.00	800.00 cm2

Figure 10. Comparison of a diesel (D 46-32) with an air steam hammer (V 020).

reduction of the strength of the clay. This can dramatically reduce the installation time and effort. However, this system apparently has not been proven economical or safe enough for general applications.

Steam for permafrost

Pile driving in permafrost poses special problems. The frozen ground behaves under hammer impact like a soft rock. Resonant vibratory pile driving is a actually a possible solution only limited by the lack of reliable machines. For regular pile driving steam injection thaws the permafrost temporarily and therefore allows the pile to penetrate under normal hammer impacts.

10 EQUIPMENT SELECTION

Selecting the proper equipment for pile installation can make and break a project's technical and economic success. An underpowered equipment may cause excessive numbers of hammer blows and pile fatigue and installation may not even be possible. Selecting very powerful equipment also may cause damage and/or require unnecessary capital expense.

While many "rules of thumb" have been tried and dynamic formulas been used to estimate the hammer size for a particular job, the wave equation, (e.g. using GRLWEAP [GRL 1999]), is still the most reliable tool to size hammer and driving system for reasonable blow counts and safe stresses. Very briefly for friction piles, blow counts should be less than 80 blows for .25 m, for end bearing piles where hard driving is expected to be of a relatively short duration, this criterion can be relaxed to 200 blows for .25 m. According to Hannigan et al, 1996, compressive concrete stresses should be less than 85% of the concrete strength (after any subtracting prestress). Tensile concrete stresses should amount to less than 70% of the equivalent yield strength of regular reinforcement or prestress plus 50% of the concrete tensile strength. For steel piles, stresses should be less than 90% of yield.

A comparative analysis was made as a demonstration of the value of the basic wave equation output, the bearing graph. As shown in Figure 8, a 20 m long concrete pile, 400x400 mm square was analyzed under two somewhat different hydraulic drop hammers. One of these hammers, the Junttan HHK 5, has a ram mass of 5 Mg and a maximum fall height of 1.22 m (maximum rated energy 60 kJ). The other hammer, the Banut 7 tonnes, operates at a stroke of at most 0.8 m and therefore has a rated energy of 55 kJ.

Figure 9 shows that the heavier hammer, even though it has a lower energy, requires approximately 20% less blow count to accomplish the same bearing capacity. The compressive and tensile stresses were considerably lower. Obviously, the lower stresses are a result of the lower impact velocity of the heavier hammer. The somewhat surprising result of lower blow counts for the lower hammer energy is caused by a relatively large quake (10 mm) at the pile toe where 50% of the total resistance were assumed to act. This large quake means that the toe resistance has a high flexibility which can best be overcome with a force pulse in the pile that extended over a long time. The heavier ram does this better than the lighter one with the stroke.

While heavy rams do rather well in relatively easy driving, high impact stresses help to overcome a higher soil resistance in hard driving. An example of a diesel hammer with 4.6 Mg ram and an air/steam hammer with 9 Mg ram is shown in Figure 10. Obviously the lighter hammer is performing better in hard driving. This is not too surprising if rated energies are compared which are 153 and 81 kJ, respectively. In other words, the heavier hammer is rated with a much smaller stroke (.9 m) than the diesel (3.4 m). Obviously, an air/steam hammer with a heavier ram and a higher stroke for comparable energy ratings would make the air/steam hammer perform better than the diesel.

CONCLUSIONS

Equipment for driven pile installations has undergone slow changes. Depending on where in the world piles are being installed, equipment may range from a simple winch driven drop hammer to a sophisticated computer controlled hydraulic hammer. The hammers and piles may be guided by an old skid rig or a dedicated fixed lead system.

Depending on the type of hammer and driving system, great variations of the system efficiency must be expected. These efficiencies can be accurately assessed in the field using a Pile Driving Analyzer which calculates the so called transfer energy from pile top force and velocity measurements.

Predictions of pile blow counts, stresses or capacities should be based on a wave equation analysis which incorporates realistic models for hammer, driving system, piles and soils. These predictions should be verified by measurements.

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APPENDIX

Energy considerations

This appendix summarizes the various forms of energy in hammer, driving system and pile. It is hoped that this description will help to explain these concepts to the practitioner.

Energy is a measure of the amount of work that can be done: push a mass over a rough surface, lift a weight, compress a volume of gas, accelerate a mass to a certain speed, compress a spring, etc. Mathematically energy is defined as the product of force and distance over which the force acts. For example, the weight of a ram, W_R, suspended a distance h above a reference datum, has the ability to do work equal to its potential energy

$$E_P = W_R\, h \qquad (A1)$$

Since energy is "indestructible" (in the worst case it is converted to heat, sound or other forms of energy) after falling through a vertical distance h, the ram now contains a kinetic energy E_K while its potential energy has become zero.

$$E_K = ½\, v_i^2\, W_R / g = E_P = W_R\, h \qquad (A2)$$

where g is the gravitational acceleration. Therefore

$$v_i = \sqrt{\ }(2gh) \qquad (A3)$$

This is the ram impact velocity in the absence of any friction or other losses. The work that a friction force R would be doing while the ram is falling is

$$E_F = R\, h \qquad (A4)$$

practically reducing the available energy from W_R h to $(W_R - R)h$. Let us assume that the friction force is a certain percentage, μ, of W_R, then we can write the reduced potential energy as

$$E_{PR} = (W_R - R)h = (W_R - \mu W_R)h =$$
$$= \eta W_R \qquad (A5)$$

Where $\eta = (1 - \mu)$ is the so-called efficiency of the hammer while μ indicates the fraction of the energy that has been converted to heat rather than speed. Of course, the impact velocity of the ram is now

$$v_i = \sqrt{\ }(2gh\eta) \qquad (A6)$$

In addition to friction, other losses also occur during the descent of a hammer. For example, a diesel hammer compresses air which requires the following energy:

$$E_D = \int (p\, dV)$$
$$= A \int (\, p_{IN}\, [V_{IN} / V]^{exp})ds$$
$$= [A\, p_{IN} / (exp - 1)]\, [V_{IN}/A + h_C]^{exp}\, \Lambda \qquad (A7)$$

with

$$\Lambda = 1 / [V_{IN}/A]^{(exp - 1)} - 1 / [h_C + V_C/A]^{(exp - 1)} \qquad (A8)$$

In this formula, V_{IN} is the initial volume of air that is present in the diesel hammer chamber when compression starts, A is the inside area of the cylinder, p_{IN} is the initial pressure (atmospheric), s is the distance that the ram has traveled after the compression started, V is the associated volume, h_C is the compressive stroke, and exp is the exponent of adiabatic compression, typically 1.4 for clean air. The chamber volume, V_C , i.e. the volume left over during impact is the product of compressive stroke h_C and area A equal the initial volume. The compression ratio is therefore V_{IN} / V_C. Note that the atmospheric pressure also does positive work on the top surface of the ram. This energy is merely the product of atmospheric pressure times ram top area times compressive stroke.

As an example, let us use a few realistic numbers representing a typical diesel hammer with 2 Mg ram mass. Assume h_C = 394 mm, V_C = 2,584,240 mm^3, A = 80000 mm^2, exp = 1.35, atmospheric pressure of 100 kPa. Then V_{IN} = 2,584,240 + (394)(80,000) = 34.1 10^6 and the compression ratio is 13.2.

Entering these numbers in the above equation and considering the work of the atmospheric pressure yields a pre-compression energy of 11.4 kJ.

If this hammer has indeed a ram weight of 20 kN and if its maximum stroke is 3 m, then it would be rated with 60 kJ. The pre-compression loss is therefore 19% of the rated energy.

Energy in the driving system

During impact the ram also compresses one or two cushions. If the spring constant of the cushion is k and the maximum compression x and the maximum force F = k x, then the energy stored in the cushion is

$$E_C = \tfrac{1}{2} F x \qquad (A9)$$

Let us compare a 20 mm thick plywood cushion and a 200 mm thick plywood cushion with cross sectional area 0.1 m and normal plywood modulus (200 MPa). The corresponding cushion stiffness values are k = (0.1)(200) / 20 = 1000 kN/mm and 100 kN/mm, respectively. A mass falling onto these springs and producing a force of 1000 kN in the pile underneath will produce the following respective cushion compression values

x = 1000/k = 1 and 10 mm

and therefore store energies of

$$E_C = \tfrac{1}{2}\, 1000\,(1) \text{ or } \tfrac{1}{2}\, 1000\,(10) = 0.5 \text{ or } 5 \text{ kJ} \quad (A10)$$

(Actually, the force underneath the softer cushion is probably lower than the force under the thinner and stiffer cushion; this would make the effect demonstrated here a little less extreme.) For a concrete pile and cushion of this size it would be reasonable to assume that the hammer rated energy ranges between 20 and 60 kJ. The thick cushion therefore stores a considerable amount of energy during the compression phase. The thinner cushion, on the other hand generates rather insignificant energy losses. Assuming a coefficient of restitution of 0.5, which is reasonable for a plywood cushion, half of the compression energy would be converted into heat. The other half is returned to the ram during its upward movement.

Hammer cushions are subjected to higher forces than pile cushions because the helmet's high weight causes high inertia forces. The helmet acceleration is maybe 1,000 g and the helmet weight of our pile with 0.1 m^2 area may be 10 kN. The inertia force is then 10,000 kN. The stiffness of this cushion [assuming a thickness of 100 mm and a modulus (wood with grain parallel to load) of 15,000 MPa] is 0.1(15,000,000)/100 = 15,000 kN/mm. The compression x is therefore 0.67 mm and the energy stored is 3.3 kJ of which one half may be converted to heat (if it is a wooden block).

Let us now calculate how much energy it takes to accelerate the helmet to its highest velocity which is approximately equal to the maximum velocity that we see at the pile top and which may reach 3 m/s. Again assuming a helmet weight of 10 kN or a mass of roughly 1 Mg yields a helmet kinetic energy of

$$E_{HK} = \tfrac{1}{2}\, m\, v_i^2 = \tfrac{1}{2}\, 1(3)^2 = 4.5 \text{ kJ} \qquad (A11)$$

It may be assumed that this kinetic energy is still doing useful work on the pile after the helmet has started to slow down.

In summary, our hammer may have a rated energy of 60 kJ. If it is a diesel hammer it stores in the compressed gases roughly 10 kJ. The hammer cushion stores approximately 3.3 kJ, the helmet 4.5 kJ, the pile cushion between 0.5 and 5 kJ. For a single acting air/ steam hammer we would expect an energy loss of 33% of 60 kJ or 20 kJ due to friction, misalignment, pre-admission etc. For a diesel hammer we would normally expect additional losses (friction, misalignment) of 20% of (60 - 10) = 10 kJ. For the diesel hammer there would also be kinetic energy temporarily stored in the impact block. Its magnitude may be comparable to the energy stored in the helmet when it moves. However, most of this kinetic energy is probably transferred to the pile at a time when it still can do useful work on the pile and soil. The energy transferred to a concrete pile may therefore be approximately 30 kJ for a single acting air/steam hammer and 25 kJ for a diesel hammer. For steel piles which have no pile cushion the transferred energy would be about 5 kJ higher. The transfer efficiencies would then be 0.5 and 0.45 for the single acting hammers on steel and concrete piles; for diesel hammers these numbers would be 0.45 and 0.4. These results are in reasonable agreement with the measured transfer efficiency shown in Figures 2 through 7.

Energy losses are generally lower for hammers with low impact velocity, obviously because inertia and cushion forces would be lower and thus the associated cushion strain energy and mass kinetic energy losses. However, experience, measurements and wave equation analyses all indicate that high velocity hammers do rather well when driving gets hard.