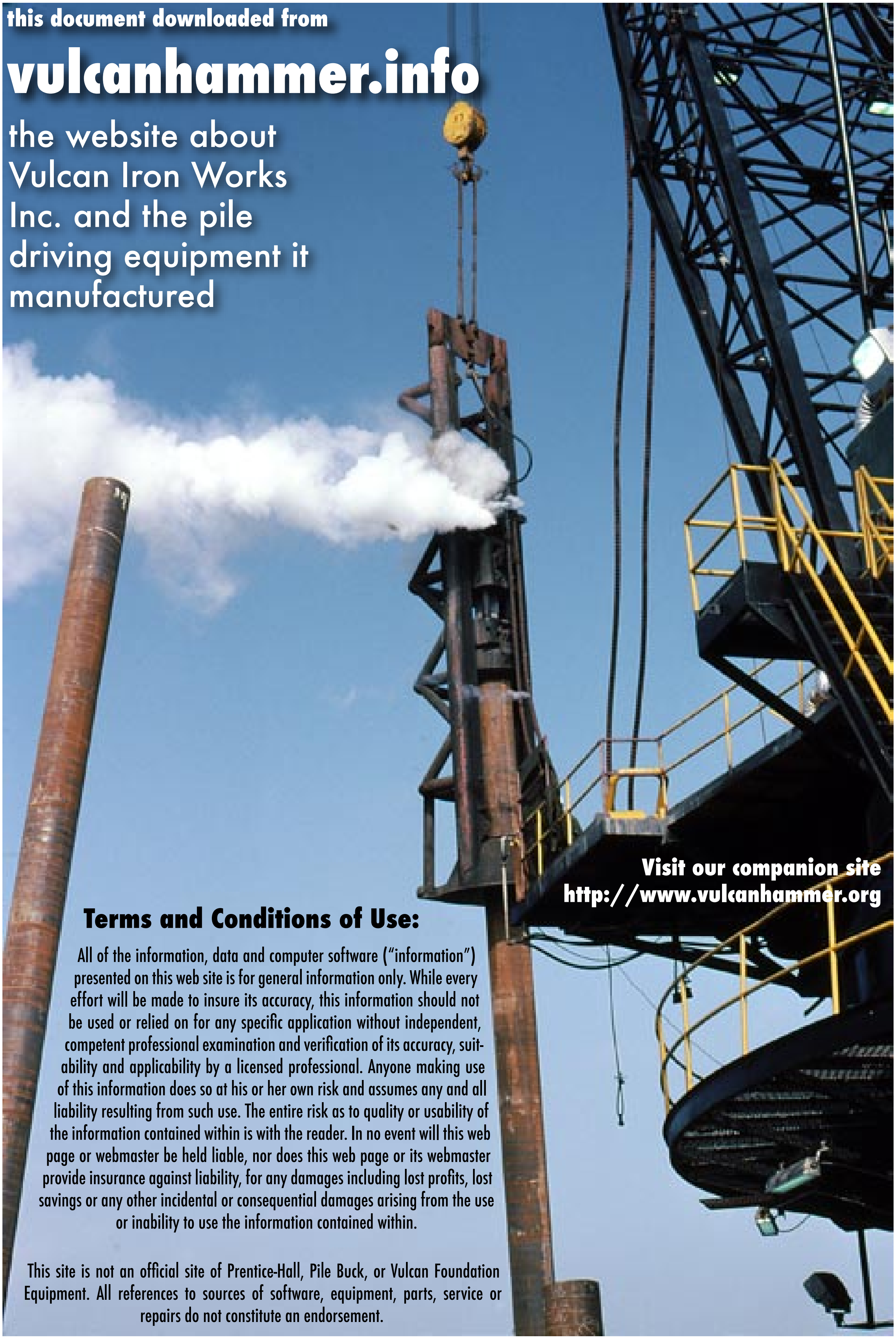

The Wave Equation Page for Piling

Efficiency and Energy Transfer in Pile Driving Systems

One of the most discussed and least understood aspects of pile driving in general and the wave equation in particular is the matter of efficiency and energy transfer. This article will attempt to shed some light on this subject.

What is Efficiency

The word *efficiency* is a term used virtually every day in a myriad of circumstances; thus, it needs to be clearly defined for any specific usage. For the purposes of pile driving systems, let us begin by defining energy efficiency as follows:

Energy Efficiency
The ratio (usually expressed as a percentage) of the actual energy generated or transferred through any point of the system to an ideal energy definition.

This may seen vague and overly general at first, but as we proceed we will discover that we need a broad definition of efficiency as we also need a precise definition of the two quantities that make it up -- the ideal energy definition on the one hand, and the actual energy on the other. But first we need to discuss the whole topic of energy generation and transfer in pile driving equipment.

Energy in Pile Driving Systems

Basic Energy Concepts

Every since the simple ENR formula with its emphasis on the rated striking energy of a pile driving system, the common concept amongst pile drivers and others involved with driven piles has been simply that "Energy drives piles." And it's true that energy is important to drive piles. But how is energy generated?

The formal definition of energy is

$$E = \int F \, ds$$

where
E= Energy
F = force
s = distance

Energy is thus the product of a force moving or moved through a distance. The force can be constant or variable with time and distance. If the force is constant, then the equation reduces to

$$E = F\,s$$

Let us begin by assuming that all the force we are dealing with are in fact constant through the distance chosen. With a single acting hammer, this means the force of gravity acting on the ram mass (the ram weight) moving through its stroke with a value of, say, 1-3 meters. The ram moves through its stroke and impacts the pile top (or intermediate pieces.) This impact generates a force with a higher intensity but through a short distance, say .001-.01 meters. Moving through such a short distance, the force imparts energy and thus moves the pile.

The key to understanding this is to realize that, in both cases, a force is moving through a distance, thus effecting a transfer of energy. In the first phase the force of gravity acts on the ram through its stroke; in the second the impact force moves through the initial compression of the pile top and this effects another transfer of energy. If both of these forces are constant through the distances and the resistance of the pile is simply the resistance of the soil, the latter could be computed by the equation

$$Ru = \frac{Ws\ stroke}{set}$$

where

Ru = Soil or Pile Resistance
Ws = weight of striking parts
stroke = Hammer stroke
set = set of pile

This was the basis for the earliest pile driving formulae; needless to say, however, this is an oversimplification of the system. Nevertheless it illustrates the basic concept behind the use of energy in driving piles and the relationship between that energy, the set of the pile and the resistance of the soil.

The Role of Kinetic Energy

Up to this point we have considered energy in a "static" way. Impact pile driving, however, is anything but a static phenomenon. So how does the energy get from the ram to the pile?

The answer to this question is kinetic energy. As the ram moves through the gravity field, the potential energy from that field is progressively converted to kinetic energy. Without other losses, this conversion is expressed by the equation

$$Er := Ws\ stroke = \frac{1}{2} m\, v^2$$

Upon impact this kinetic energy is converted back into a force which moves through a distance, in this case the movement of the pile.

Thus we can conceive of pile driving as a two-stage process:

1. Conversion of energy from potential energy (due to the gravity field or other downward acting force, such as fluid pressure) to kinetic energy, which is a function of the velocity of the ram.
2. Conversion of the kinetic energy from the ram to the impact force, which then moves the pile.

Energy Losses in Pile Driving Systems

Losses in Pile Hammers

In addition to idealizing the force-time relationships (especially with the pile top force,) all of the above assumes that the ram is free falling through a vacuum with no losses. But pile drivers on earth do not operate in a vacuum; moreover, there are a number of factors that can slow a ram down during its descent, such as

- Friction on the ram guides.
- Back pressure losses in the fluid ports; these can include valving, exhaust or relief ports, fluid hoses from the hammer to its power source, etc.
- Losses due to sealing elements exerting pressure, such as compression packing, piston rings, O-rings and other hydraulic seals.
- Inefficient combustion of fuel in diesel hammers, leading to pre-ignition and other problems.

In addition to this, hammers driving a batter pile are driving at an angle, so they do not fall as far through the gravity field as those driving plumb piles. Their energy is thus reduced by the loss of effective stroke through the gravity field. In any case, we now need to define efficiency as applied to hammers; it is

$$e1 = \frac{En}{Er}$$

where

e1 = hammer efficiency, usually expressed as a percentage
En = Net Striking Energy

It is **important** to understand that the rated striking energy as defined earlier (the product of stroke and ram weight) is only applicable to single-acting hammers, and not always then. The definition of rated striking energy can be rather arbitrary, as we will see below. This obviously will have a significant impact on the efficiency.

Irrespective of how the rated energy is defined, it is essential to know that *the energy imparted to the pile is no greater than the net striking energy*, and in fact will be reduced between the ram and the pile.

Losses Around the Pile Top

Since pile driving is a two stage process, it makes sense that energy losses can take place in both stages. There are many significant energy losses in the transmission of energy into piles; these include

- Hysteresis losses in the cushion material. This includes both hammer and pile cushion.
- Misalignment between the hammer and driving accessory, or between the driving accessory and the pile.
- Poor contact surfaces at the interface points.

We now need to define

Enthru
The energy that actually arrives at the pile top without consideration of rebound from the pile.

The efficiency rating associated with this important quantity is referred to as the *system efficiency* and can be expressed in two ways.

The first (and more common way) is to relate it to the rated striking energy; this is expressed as

$$e2a = \frac{Er}{Enthru}$$

The second is to relate it to the net striking energy of the hammer,

$$e2b = \frac{En}{Enthru}$$

where
e2a, e2b = system efficiencies

The advantage of the second method is that it gives a more meaningful expression to the energy losses taking place between the hammer and the pile top.

We can see that these two efficiencies are different. This is an important distinction that will be discussed in more depth below.

Energy Losses in the Pile and Soil

Once the energy passes through the pile top, in goes into the pile and then the soil. Because most pile monitoring takes place at the top, these are seldom directly measured; however, some important things need to be understood about them.

The pile acts as a transmission line to direct the energy obtained through the pile top down the pile and into the soil. Pile materials, like other engineering materials, have internal dampening and this dampening does dissipate energy; compared with the soil, however, these losses are not that great.

In simple terms, the soil acts against the pile in two ways; as a spring, representing the elastic resistance of the soil, and as a velocity-dependent visco-radiation dampener, which represents the linear dissipation of energy into the soil mass. This takes place wherever the soil and pile interface, be it along the shaft or at the toe of the pile. Additionally the whole object of pile driving is to advance the pile into the soil; this necessitates exceeding the elastic limit of the soil to effect pile penetration into the ground. Once the elastic limit is exceeded, most of the resistance the soil offers represents dissipation of energy into the soil.

In the early stages of driving, the elastic limit of the soil is readily exceeded and virtually all of the energy into the pile top ends up in the soil. As pile resistance increases with increasing penetration, the elastic characteristics of the soil become more important and they return a portion of the energy back to the hammer-pile system. This is referred to as rebound. Conventional definitions of enthru exclude rebound from them, but energy rebounding back to the ram can give a ram an initial upward velocity and thus initial energy. This certainly affects hammer performance, especially with diesel hammers.

A Word About Pile Elastic Compression

No discussion of pile and soil energy phenomena is complete without some mention of elastic compression of the pile top. Semi-infinite pile theory predicts that, when the pile top has an applied force to it, the pile top will compress a certain distance. This is referred to as the elastic compression of the pile. This compression represents the storage of energy both by the compression energy in the material and the kinetic energy of the moving particles in the pile. As the compressed stress wave travels to the toe and back again, it releases energy to the soil depending upon the latter's response. If after one round trip the stress wave has energy left in it, it can either come back into the hammer or be reflected back into the pile or both.

Semi-infinite pile theory also predicts that, depending upon the properties of the hammer system and pile top, that some of the energy from the hammer can be reflected back to the hammer from the pile top without the rest of the pile ever seeing this energy to start with. Thus it would neither be included in Enthru nor be accounted for with the dissipation losses in the hammer-cushion-cap system, as such an energy phenomenon is linear and elastic in nature.

How important these considerations are depends on the pile system. With shorter piles, the stress wave can return before impact is complete; this complicates the picture. Moreover shorter piles tend more to act as a single mass; wave mechanics in general are less important in these cases. With longer piles the absorption of the energy by the pile in elastic compression and its dissipation in the soil are two distinct stages and these considerations are more important.

Energy Losses for Various Types of Hammers

Since we have made a distinction between energy losses in the hammer and energy losses between the hammer and the pile top and those again afterwards, we need first to discuss in detail various types of hammers and how energy losses take place and are accounted for.

Air-Steam Hammers

Single-Acting Hammers

Single-acting air-steam hammers were the first "automatic" (as opposed to drop hammers) hammers to receive a definition of "rated" striking energy, which is of course the weight of the ram times the stroke. As we have said before, this assumes that the ram is falling through a vacuum with no other constraints on it; this is obviously an idealization of the process.

Because of the age of many air steam hammers (hammers in operation for a century or more and not unheard of,) the wide variation in the maintenance and repair of a hammer that can still operate, the technology used in the manufacture of these hammers (which also contributes to their simplicity and reliability,) and other variables, air/steam hammers are subject to wide variations in their efficiency. Usually, however, when attempting to predict the performance of these hammers, the low efficiency generally ascribed to them (67%) can head off surprises during actual driving.

Differential and Double Acting Hammers

These hammers share many of the same characteristics of the single-acting hammers; however, their energy is heavily dependent upon the downward force of the air or steam on the piston during the downstroke. Should this pressure be low for any reason (rebound, problems with the air compressor, etc.), the net energy from the hammer can be significantly lower than expected. This in turn produces low efficiency, even though with deficient pressure the energy going into the hammer from the power source is reduced as well.

Diesel Hammers

Diesel hammers are basically single free piston engines. Usually when engineers think of the efficiency of diesel engines, they think of the thermodynamic efficiency for an Otto or Diesel cycle engine. Such an efficiency, while important, is not of direct concern as far as the mechanical efficiency of the machine. However, the fact that a diesel engine basically operates between the ram and the pile makes diesel hammer interaction with the pile very different from other types of hammers.

Before impact, to effect combustion it is necessary to have the air between ram and anvil compressed. This can consume up to 20% of the kinetic energy of the diesel hammer. It would seem that this energy would be lost to moving the pile; however, this compression pressure can also act on the pile before impact. Moreover in addition to the usual ram impact force the force of the explosion of the fuel also acts on the pile as well as starting the ram on its ascent. If preignition is present, then this too can affect the energy transfer to the pile. Most diesel hammers also rely very heavily on rebound to effect a full stroke.

The upshot of all this is that diesel hammers defy a very simple definition of their energy output. Attempts to do so in the past have not been very successful. Fortunately the wave equation programs available today enable an analysis of diesel hammer performance without having to rely on a single number or rating with efficiency.

As far as efficiency is concerned, removing the combustion considerations, the mechanical efficiency of diesel hammers does not vary much if the hammer is operating. This is because diesel hammers are intolerant of lack of lubrication, and will generally cease to function if this persists for any length of time. This last event can certainly be more serious than low efficiency.

Open Ended (Single Acting)

Single acting diesel hammers are usually rated in the same was as air-steam hammers; however, comparing these ratings directly is uninformative. In addition to the combustion considerations, generally single acting diesel hammers achieve their rated striking energy using a light ram and long stroke; the impact characteristics of this are different than the heavy ram and short stroke of the air-steam and hydraulic impact hammers.

Closed Ended (Double Acting)

Double acting diesel hammers usually have a heavy ram and short stroke; in addition to this, they have a gas spring in the top of the hammer which affords downward assistance to the ram and thus more energy for the stroke. Their combustion characteristics and interaction with the pile pose some unique analysis challenges due to the nature of their fuel injection.

Hydraulic Impact Hammers

Hydraulic impact hammers are the newest form of impact pile driver. One of their main claims is that they are more efficient. This claim must be completely understood in order to objectively analyze these machines.

As is the case with air-steam hammers, hydraulic impact hammers can be either single acting or double acting (or, more accurately, have "downward assistance" for the ram.) However, they are generally equipped with devices to measure the impact velocity and thus give a direct field measurement of the impact energy. Moreover even single-acting hammers can have some downward assistance; in addition to increasing the "efficiency" of the hammer relative to a conventional rating, it serves to make the hydraulic oil flow to the hammer more even.

This has led hydraulic impact manufacturers to either dispense with conventional rating systems or to raise the energy output of the hammer to make for a very high apparent efficiency. This poses no problems as long as the rating systems are understood and the net output estimates for the hammer are accurate.

Energy Losses in the Cushion and Cap System

One of the main sources of confusion with efficiency and energy in driven piles is that the mechanical efficiency of the hammer -- the efficiency, for instance, that is put into the wave equation -- is the same as the system efficiency. As we have seen, this is not the case. There will always be some losses between the hammer and the pile.

Hysteresis Losses in the Cushion Material

Most impact hammer systems use cushion material to do the following:

- Protect the hammer from excessive stresses and loads during driving.
- Protect the pile from similar excessive loads (especially concrete pile, where both hammer and pile cushions are used.)
- Modulate the force-time characteristics of the impact impulse.

However, all cushion materials experience some kind of mechanical hysteresis during compression and rebound, which take place with each blow of the hammer. How much will depend upon the type of material being used, the speed at which it is loaded and the amount which is it compressed.

Most wave equation programs currently use a "coefficient of restitution" concept for accounting for cushion material plasticity. Strictly speaking, this is not applicable to this application, because the cushion material is dynamically loaded, and the "coefficient of restitution" concept of variation between loading and unloading is a static concept. However, generally speaking, the lower the coefficient of restitution, the higher the energy losses are for that cushion material.

As is the case with most energy losses, the energy lost in the plastic deformation of the cushion material generally turns into heat. Cushion material generates a tremendous amount of heat and thus the range of materials that can be used is limited..

Misalignment

Virtually all the theory on which the wave equation as applied to piles is based on is one-dimensional. Implicit in this is that all of the driving system is centered on one axis, namely that of the pile. In real job situations, however, the perfect alignment of the hammer and the pile is nearly impossible, especially when swinging leaders are used. These losses can be significant.

Impedance Mismatching Losses

As we discussed earlier, it is possible for energy that emanates from the hammer to be reflected back from the pile top without even passing into the pile. Such losses can be characterized as impedance mismatching losses. In one respect, these are not really losses; the energy simply is returned to the hammer. But since the enthru is reduced the energy appears as lost.

When Equal Energies are Not Equivalent

One of the common misconceptions about the energy that pile driving equipment imparts to the pile is that, if two hammers put out the same energy, then their effect on the pile is the same. Such is not always the case.

Consider the case of two force-displacement curves whose area under the curve -- and thus the energy represented -- is identical, but whose peak force is different. Even though the energy under the curve is the same, each blow will produce a different result in the pile. This recalls the whole point of impact pile driving, namely using a ram with a weight which is relatively light to the required force to overcome the driving resistance and imparting energy to it so that, by generating a higher force than the resistance upon impact, the pile will move. In general terms, the higher the force, the higher the resistance the hammer can move the pile against. Thus, with the lower peak force, one would expect the pile to move less even though the energy is the same.

This difference can take place for a number of reasons:

- Different relationships between the stroke and the ram weight for a given energy. For a given energy, increasing the ram weight increases the striking momentum or impulse, but may decrease the peak force.
- Softer or harder hammer cushion, or the addition of a pile cushion. Needless to say, the use of a completely cushionless hammer presents a whole new dimension to this situation
- Addition of diesel combustion, which significantly modifies the force-time or displacement characteristics of a hammer.
- Changing the relationship between the impedance of the hammer and the impedance of the pile.

It should be emphasized that a higher peak force is not always desirable. With concrete piles, it is always necessary to control the stresses in the pile; the simplest way to do this is to control the peak force.

We see from this that a single energy number is not sufficient to characterize the performance of a hammer-pile-soil system.

Pointers in Applying Energy and Efficiency Concepts

When analyzing either a new or recently installed foundation, the following should be kept in mind:

- The hammer's efficiency and the system efficiency are not the same, due to intermediate losses between the hammer and the pile. Thus, when "calibrating" a wave equation study or making any specification about the output, the system efficiency is by necessity different from the mechanical efficiency.
- If one compares hammers based on an energy rating, it should be done by comparing the anticipated net energy output of the hammer. Saying that one hammer is more efficient than the other may not be helpful due to differences in the rating systems.
- It is best not to compare energies directly between hammers for final hammer specification purposes. The best course is to run the wave equation analysis for each

hammer on the same pile and to make the selection on this basis. This is especially important when comparing diesel hammers with air/steam and hydraulic ones.

- Avoid at all costs "after the fact" discoveries about insufficient energy or pile penetration. Test pile programs are designed to do this in the beginning.
