Nov. 21, 1967 A. LUBINSKI 3,353,362

PILE DRIVING

Filed Oct. 24, 1965 2 Sheets-Sheet 1

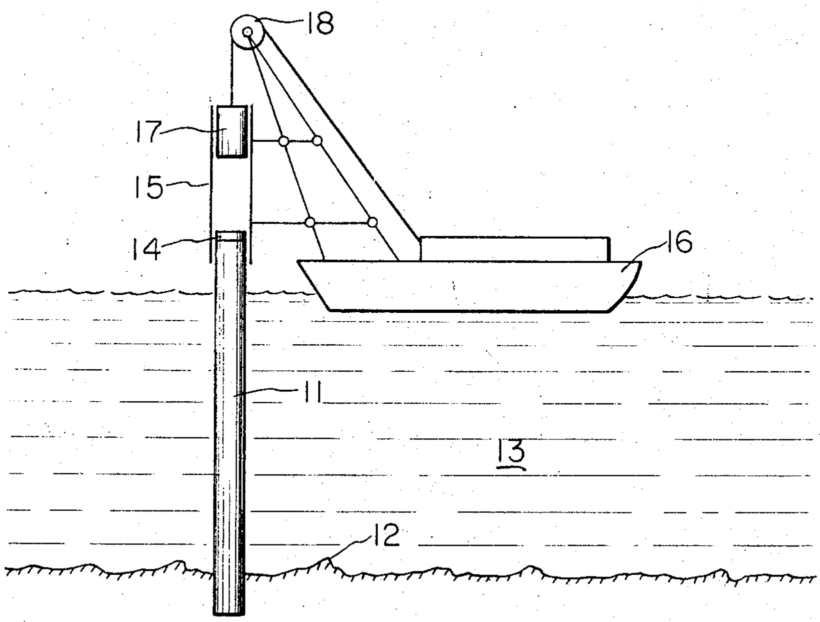

Fig. 1

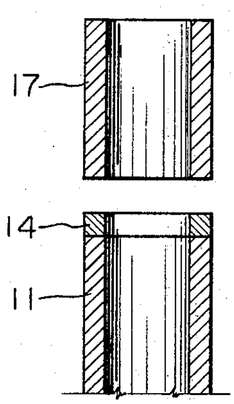

Fig. 2

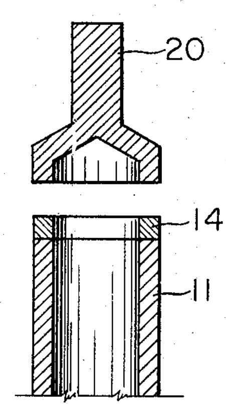

Fig. 3

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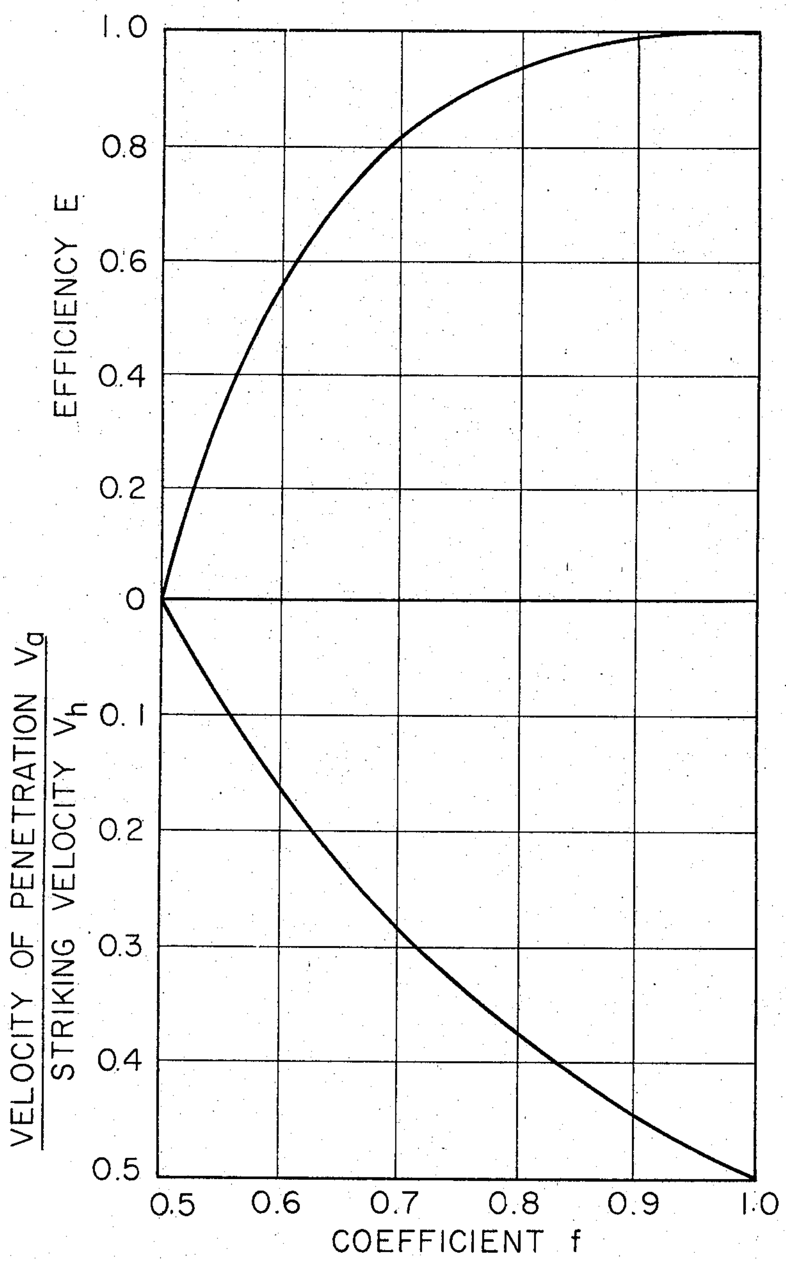

Fig. 4

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United States Patent Office

3,353,362
Patented Nov. 21, 1967

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3,353,362

PILE DRIVING

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Filed Oct. 24, 1965, Ser. No. 504,609
4 Claims. (Cl. 61—53.5)

ABSTRACT OF THE DISCLOSURE

Ordinary pile driving using periodic impact of a hammer on the pile involves considerable rebound, and traveling waves moving up and down the pile, all resulting in the hammer imparting less than peak energy to the pile. In this invention the hammer is modified until its characteristic mechanical impedance essentially matches that of the pile. The velocity of hammer impact is chosen to be at least approximately twice the minimal striking velocity at which any penetration can occur. Under these circumstances, essentially the maximum energy transfer occurs from hammer to pile resulting in minimization of the losses inherent in prior systems.

In the past, the conventional approach to the problem of driving a pile into the earth and particularly into the marine floor has been to use a very large mass which is repeatedly raised above the pile and allowed to fall against it. The impact of the hammer on the pile is supposed to drive it into the earth. However, it has been found that such driving may be quite inefficient, i.e., much of the kinetic energy of the hammer striking the pile is not spent in driving the pile. Simple investigation of the dynamics of the situation indicates from momentum and energy considerations that the velocity acquired by a pile of mass m is $2VM/(M+m)$, M being the mass of the hammer, m that of the pile, and V the striking velocity of the hammer. This is in the absence of dissipation force and hence is a highly over-simplified result. However, from such thinking, the design of drivers for piles has been to make the mass of the driver or hammer as great as possible, and additionally to impart as much kinetic energy as possible to the hammer immediately before impact.

Such a system is usually effective, although there are instances in which 36-inch diameter piles required as many as 2,000 blows per foot, whereas ordinarily with the size of hammer used (of the order of 10 tons, with a striking velocity of the order of 13 feet per second) about 80 blows should drive the pile about a foot.

I have discovered that it is possible to drive piles with considerably less energy and a much higher efficiency than has been previously considered possible. In my system, the hammer used has a characteristic mechanical impedance (described below) about equal to that of the pile, and the striking velocity V_h is selected for maximum efficiency. This is, therefore, a main object of this invention. It is a further object of the invention to provide pile driving apparatus of this type in which losses inherent in prior systems are minimized or eliminated, to permit more rapid and effective driving of the pile.

This invention will be described in connection with the attached drawings which form a part of this specification and are to be read in conjunction therewith. In these drawings, the same reference number in different figures refers to the same or a corresponding part.

FIGURE 1 is a diagrammatic view of a marine pile driving system in accordance with my invention.

FIGURES 2 and 3 are diagrammatic cross-sections of piles and associated hammers designed for optimum effectiveness.

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FIGURE 4 is a graph of velocity ratio and of driving efficiency.

In FIGURE 1, I have shown in very diagrammatical form an elongated pile. "Elongated," as used herein, means that the length is large compared to a transverse dimension, for example by a factor of 10 or more. Such piles are elastic and support the propagation of tensional and compressional waves along a longitudinal axis with small loss within the pile proper. This pile **11** is shown resting at the bottom some distance below the marine floor **12** of a body of water **13**. At the upper end the pile terminates in driving cap **14**. A guide structure **15** supported from a pile barge **16** encloses the upper part of the pile and directs downward movement of the hammer **17** which can be raised on derrick **18** above the cap **14**. Machinery for raising the hammer **17** and permitting it to accelerate downward under the force of gravity to impact on the cap **14** are well known and need no further description. I have found that if the hammer **17** is properly matched in mechanical impedance to the pile **11** and if it is permitted to impinge upon cap **14** with the proper striking velocity V_h, the pile **11** is driven downward into the marine floor at maximum efficiency and in minimum time.

It is to be understood, of course, that only one type of drive mechanism has been shown. It is possible to employ for example a motor which accelerates hammer **17** downward with a force exceeding that of gravity, for example. However, it is to be understood that the type of motion imparted in accordance with my invention to hammer **17** is discontinuous and is not, for example, sinusoidal or the like. Thus, the force imparted to the cap **14** which essentially forms part of the pile **11** is a series of impacts rather than a continuous, though varying, function of time. Specifically, the phenomena taking place in the pile do not involve resonant standing wave patterns. It is also to be understand what while the pile driver shown in FIGURE 1 is of the marine type, essentially the same apparatus can be used in driving piles in marshes or on dry land.

When the hammer has been lifted and then accelerated downward either under the acceleration of gravity or by some source of power, the impact of the hammer on the pile generates a compressional wave in the pile. This traveling wave ultimately arrives at the lower end, generally resulting in driving the pile into the surrounding soil. Some of the energy may not be dissipated in this motion, in which case a reflection occurs and a wave travels upward. A reflection occurs at the upper end of the pile, and the cycle repeats. After several such reflections, the hammer generally rebounds, losing contact with the pile. The kinetic energy of the rebounding hammer is lost, because when the hammer drops and strikes the pile a second time, it usually imparts too little force to cause the pile to penetrate further into the soil. Thus a rebounding hammer is one source of energy loss.

There are in addition other losses of energy. After the pile ceases to penetrate, it is generally subjected to longitudinal vibrations. Compressional and tensional waves travel up and down and are reflected at the pile ends. Each such wave produces motion in the pile which is transmitted to the surrounding medium (partly loosened soil, and in many cases also water) where the energy is progressively dissipated. This residual vibration is detrimental not only in causing a decrease in driving effect, but also in the fact that the vibration loosens the soil and thus decreases the maximum pull-out force to which a pile driven to a certain depth may be subjected as a foundation member.

A third source of lost energy in pile driving is due to the fact that the pile itself may rebound some distance off the maximum bottom position. Thus at the start of the next blow, the pile must first be driven to the bottom of the already existing hole, working against the friction at the wall of the hole, and thus weakening the blow against the bottom of the hole. Such a rebound may result in little penetration occurring at each blow. Put another way, most of the energy imparted by the hammer may be spent in friction during downward motion at the start of the blow and in upward motion due to rebound at the end of this blow.

I have found that it is possible to minimize these losses of energy. The first point of novelty consists in using a hammer the characteristic mechanical impedance of which is equal or nearly equal to that of the pile. In other words, the hammer is mechanically matched to the pile. It should be emphasized that this does not necessarily mean that the mass of the hammer is substantially equal to that of the pile. In fact, a relatively light hammer may be employed at maximum effectiveness, and the light mass of the hammer can result in a greater number of blows being applied per unit of time to again increase the speed of driving the pile. I have also discovered that it is very important to use a particular striking velocity of the hammer, all as described below.

The characteristic impedance of the hammer of the pile (hereafter given the symbol S) is equal to the mass density (weight density divided by acceleration of gravity) multiplied by the velocity of propagation of compressional waves in the hammer multiplied by the cross-sectional area of the solid material. This is given by the equation:

$$S=\frac{\rho c A}{g} \qquad (1)$$

where

ρ=weight density
c=wave velocity
A=cross-sectional area
g=acceleration of gravity

This is for an elongated cylindrical member, and applies whether the member be solid or hollow and regardless of cross-sectional shape. For example, a typical pile consisting of a steel tube 36 inches outer diameter, with 1 inch wall thickness will have a characteristic impedance of 17,400 lb. (in./sec.). In case the pile has a varying cross-sectional area, one preferably uses for A the average cross-sectional area of the solid material.

In FIGURE 2 I have shown a portion of a hollow pile **11** with an appropriate cap **14**, both members having the same characteristic mechanical impedance as defined by Equation 1. As mentioned above, one convenient hammer **17** is simply another section of pile. It is emphasized that the length of the hammer does not in any way affect either of the two critical criteria of performance, either the proper impedance or the striking velocity. What it does affect is the amount of energy stored kinetically in the hammer **17** at instant of impact and hence total amount of drive per stroke.

In FIGURE 3 I have shown the same pile **11** and cap **14**. However, in this case the hammer **20** has been chosen to have a varying outer diameter, though the transverse or cross-sectional area A has been maintained constant. In this case one approximates constant mechanical impedance along the axis of symmerty and can hence observe the impedance matching principle already discussed.

I prefer to have the characteristic impedance of the hammer driving the pile to the matched to that of the pile being driven. This may be, for example, by making the cross-section of the hammer geometrically identical to that of the pile (as in FIGURE 2), the hammer being composed of the same material as that of the pile. However, different materials of different cross-sections may be used, as long as the impedance matching principle is observed. While I prefer to have this match substantially identical, it is possible to vary from this by some margin. I have found that some benefit is gained if the hammer characteristic mechanical impedance is from ⅓ to 3 times the characteristic mechanical impedance of the pile, and that a marked improvement results if this matching is within ±20%, i.e., the characteristic mechanical impedance S of the hammer is from about 80% to about 120% that of the pile.

Furthermore, I wish to employ a certain striking velocity of such a hammer, which results in imparting maximum useful energy to the driving of the pile, and minimum loss.

I have found a simple relationship between the striking velocity of the hammer V_h and the penetration of the pile into the soil. There is a minimum value of V_h for any penetration to occur. This is related to the force F_a with which the pile opposes penetration. The minimum value of V_h is given by:

$$V_h=\frac{F_a}{S} \qquad (2)$$

F_a increases as the pile penetrates deeper into the soil, but is constant during any one blow, as the amount of penetration per blow is very small compared to the cumulative penetration of the pile. If the striking velocity of the hammer V_h is less than that given by Equation 2, traveling waves formed in both the hammer and pile reverberate these members, but cause no pile penetration. In other words, the force imparted to the soil is less than F_a. Accordingly the velocity of the lower end of the pile remains zero. If the striking velocity of the hammer is increased above the minimum value F_a/S, pile penetration takes place, accompanied, of course, by traveling wave phenomena in both hammer and pile. The hammer rebounds with a lower and lower velocity as the value of V_h is increased and becomes equal to zero when the velocity V_h is equal to $2F_a/S$. In this range of velocities there is no residual vibration left in the pile. The pile itself does not rebound (it should be pointed out that unless the characteristic impedance of the hammer matches that of the pile, the pile would rebound and there would be residual vibration left at the pile) in the case of substantial impedance match and if the striking velocity lies within the range of F_a/S and $2F_a/S$. The expression for the rebound velocity V_r of the hammer and the velocity of penetration V_a of the pile into the soil are as follows:

$$V_r=V_h-\frac{2F_a}{S} \qquad (3)$$

$$V_a=V_h-\frac{F_a}{S} \qquad (4)$$

It may be apparent at this point that minimum loss occurs and hence maximum driving effectiveness is achieved when V_h is equal to $2F_A/S$. This can be illustrated another way: Let f be a fraction given by the following expression:

$$f=V_h\frac{S}{2F_A} \qquad (5)$$

Then in the range of V_h considered,

$$0.5<f<1.0 \qquad (6)$$

Substituting for F_a/S from (5) in (3) and (4),

$$V_r=\frac{f-1}{f}V_h \qquad (7)$$

$$V_a=\frac{2f-1}{2f} \qquad (8)$$

If we denote by E the efficiency of the operation, i.e., the ratio of useful energy per blow overcoming the force F_a to the kinetic energy of the hammer, we find (since the only energy lost is that of the kinetic energy of the hammer after rebound):

$$E=1-\frac{V_r^2}{V_h^2} \qquad (9)$$

or, from the substitution for V_r from Equation 7:

$$E=1-\left(\frac{1-f}{f}\right)^2 \qquad (10)$$

A plot of E and of V_a/V_n versus f is shown in FIGURE 4. This shows that for $f=0.5$, $V_a=0$. The pile does not penetrate the soil. The efficiency is zero. As f increases, both the velocity of penetration V_a into the soil and efficiency E increases, as shown on this figure. The curve of efficiency versus f is essentially flat for values of f between 0.8 and 1, that is, for values of V_h between $1.6F_a/S$ and $2F_a/S$. I prefer to operate in this range of striking velocity, hereafter referred to as matched velocity. One easy way of determining such a matched velocity is that essentially the hammer ceases to rebound in this range.

It can be shown that when V_h substantially exceeds $2F_a/S$, the hammer still does not rebound, but that at a later time either the pile itself will rebound, or an appreciable residual vibration will remain in the pile, or both. In all cases these will substantially cancel the apparent advantage of the increased velocity. Accordingly, I contemplate using a maximum striking velocity V_h which does not substantially exceed $2F_a/S$, i.e., a value of about $2.4F_a/S$. In the range from $1.6F_a/S$ to $2.4F_a/S$ the tensions and compressions appearing in succession in the pile are not sufficient to produce either appreciable pile rebound or appreciable residual pile vibration. If one exceeds this value, energy is lost in either or both of these dissipative processes.

The manner of obtaining proper striking velocity V_h of the hammer as it impacts the top of the pile depends, of course, on the accelerating mechanism employed. If the acceleration is simply that due to gravity then as is well known the striking velocity of the hammer is directly proportional to the square root of the height to which it is raised above the pile or pile cap if one is used. This, of course, assumes that the friction in the guides is negligible, which is true in practical cases. Then the striking velocity is given by $\sqrt{2gh}$ where h is the height referred to just above. Of course if other mechanisms are used, suitable determination can be made of the velocity sufficient to observe the reaction of the hammer and top of the pile as the velocity is appropriately varied. One chooses conditions such that the hammer and pile are stationary at the end of each blow.

Of course, as far as possible, I prefer to have both the mechanical characteristic impedance of the hammer match that of the pile and the velocity of penetration V_h be chosen such that the hammer and pile both remain immobile after the first impact has driven the pile into the ground, i.e., with V_h substantially equal to $2F_a/S$.

As the force opposing the penetration of the pile into the soil increases, the greater must be the striking velocity of the matched hammer to achieve optimum efficiency. The greater also becomes the penetration per blow.

It is found that a hammer matched to the pile is usually much lighter than a conventional hammer. Generally the matched hammer is longer but slimmer than the conventional hammer. For example, in the case already considered of a steel tube pile of 36 inch O.D., 1 inch wall thickness with a resistance of the soil F_a equal to 2.5×10^6 pounds, the cross-sectional area of the hammer should be 110 square inches. At a hammer length of 9 feet, one finds the characteristic mechanical impedance to be 17,400 pounds per inch per second; the matched velocity V_h is approximately 24 feet per second. The penetration is substantially 0.0119 foot per blow, i.e., 84 blows per foot of pile penetration. The weight of the hammer is 3,320 pounds and the kinetic energy at instant of impact is 29,500 foot pounds. In contrast, a typical conventional hammer would be the order of 4.5 feet high with a weight of around 10 tons, a cross-section of 1,300 square inches, a striking velocity of 12.7 feet per second, and a kinetic energy at point of impact around 50,000 foot pounds. The characteristic impedance of this hammer (which is greatly mis-matched) is 200,000 pounds per square inch per second. A considerable part of its kinetic energy is wasted and the efficiency is quite low compared to that of the matched hammer. The use of the matched hammer, which is considerably lighter, results in a greater number of blows being applied for the same horsepower employed and a consequent considerable increase in penetration per unit time.

I claim:

1. The method of driving a pile by a periodically impacting hammer in which the characteristic mechanical impedance of said hammer is at least approximately equal to that of said pile striking said hammer and varying the striking velocity of said hammer until there is little rebound of said hammer and little motion of said pile after the initial movement following each impact and thereafter continuing driving said pile.

2. The method of driving a pile by repeated impact of a hammer in which the characteristic mechanical impedance of said hammer lies in the range of ⅓ to 3 times that of said pile and in which the striking force of said hammer lies between about 1.6 and about 2.4 times the minimum force at which pile penetration can occur.

3. A method in accordance with claim 2 in which the ratio of characteristic mechanical impedance of said hammer to that of said pile lies in the range of 0.8 to 1.2.

4. A method in accordance with claim 3 in which the striking force lies between about 1.6 and about 2 times the minimum force at which pile penetration can occur.

References Cited

UNITED STATES PATENTS

3,132,706 5/1964 Ostrowski -------- 61—53.5 X

JACOB SHAPIRO, *Primary Examiner.*