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FLUID-SONIC PILE DRIVING

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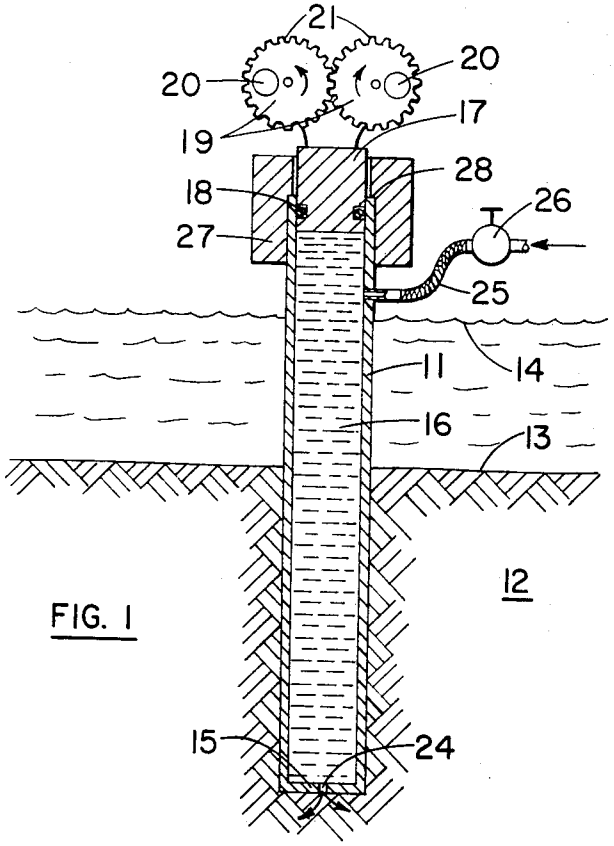



FIG. 1

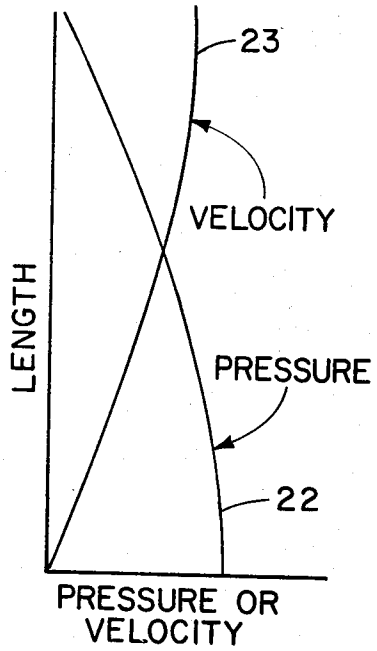



FIG. 2

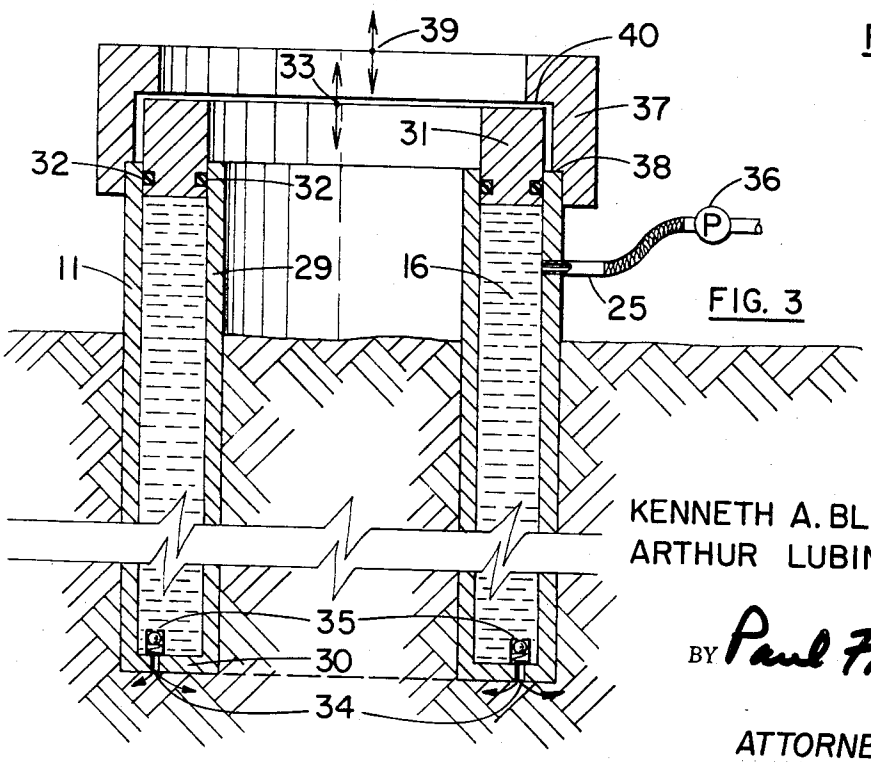



FIG. 3

KENNETH A. BLENKARN
ARTHUR LUBINSKI
INVENTORS

BY Paul F. Hawley

ATTORNEY.

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# FLUID-SONIC PILE DRIVING

Kenneth A. Blenkarn and Arthur Lubinski, Tulsa, Okla., assignors to Pan American Petroleum Corporation, Tulsa, Okla., a corporation of Delaware

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## ABSTRACT OF THE DISCLOSURE

In the present invention a column of liquid (ordinarily water) is confined within the pile and extends substantially to its bottom. Sonic pressure is applied to this column, preferably setting up a standing quarter wave which applies alternating stress hydraulically at the bottom of the pile. This alternating pressure changes the transverse pile dimensions in the region of maximum interest, i.e., near the bottom of the pile. This markedly decreases skin friction and permits easier driving of the pile under any type of axial driving force.

*Background of the invention*

Structures supported on piling must necessarily have a sufficiently strong foundation to furnish support under all expected conditions of stress. This ordinarily requires driving piles (which are usually hollow steel columns) a great distance into the ground. For example in marine piling, to support off-shore platforms in the Gulf of Mexico it is not unusual for piles to be driven to depths exceeding 200 feet below the mud line, i.e., the bottom of the water. The greater the depth of driven piling in the ground, the greater is the resistance to flexure, which again improves the foundation properties of the piling.

However, the deeper the pile is driven the greater is the resistance to the ground to further driving. This may be due to friction along the wall of the pile or to ground bearing resistance. In the last few years a method which has achieved some prominence in pile driving, particularly in marine applications, involves applying a cyclic force to the piling, using a vibrator. This vibrator is rigidly attached to the pile and, for example, may consist of two counter-rotating, eccentrically mounted masses. These are arranged to transmit longitudinal or axial vibration to the pile. The speed at which these are driven to the coupled motor is adjusted to mechanical resonance of the pile. Under these conditions, the applied force induces a pressure which is a maximum at or near the base of the pile, the pressure and the velocity changing in approximately a sinusoidal manner with distance up the pile. Such arrangement is described, among many other places, in U.S. Patent 2,350,212 of A. G. Bodine, Jr. As a result of this mechanical resonance, large longitudinal or axial forces are induced between the pile and the soil which tends to make the pile penetrate into the soil more easily than in the more conventional driving in which impacts are imparted to the pile at much lower equivalent frequencies.

One major difficulty which has occurred with this technique is that when any such mechanically resonating system is frictionally damped, the longitudinal forces transmitted are very considerably decreased. The farther the pile penetrates into the ground, the greater are the frictional effects, particularly in the lowest section. The soil and liquid immediately around the pile in the lower portion have high frictional forces and hence the alternating driving force is quite low. The portion of the pile which is free to resonate is that above the zone of intimate contact of the ground with the pile. In marine cases, this resonating section effectively is that part of the pile above the mud line. Accordingly, the main axial vibratory action



is thus transmitted to the portion of the pile located rather close to the mud line, rather than close to the bottom of the pile where it is most needed. On dry land also, vibratory action is essentially limited to the upper part of the pile, in the loosened soil region. This has been shown experimentally in that it is relatively easy to drive piles by this sonic resonant system for a first, limited region, but becomes progressively more difficult as the depth of pile in intimate contact with the ground increases, especially in such soils as clays which display a strong resistance along the wall of the pile.

*Summary of the invention*

As shown immediately above, a major problem in sonic resonant driving of piles is to overcome frictional effects of the portion of the pile in intimate contact with the ground, i.e., the lowermost portion of the pile. Stated another way, it is necessary to minimize the very appreciable frictional forces in this region due to the presence of the ground, until the pile has been driven to the desired depth. We have found it is possible to overcome this difficulty by providing within the pile a column of a liquid having low damping characteristics. In most cases this liquid is water. The column extends longitudinally through the pile such that it is in contact, and hence in pressure-exchange relationship, with the outer walls of the pile in the region where intimate ground-pile contact exists; namely, in the lowermost portion of the pile. A cyclic stress is applied to the upper part of this liquid column at least approximately at a resonant longitudinal frequency of the column. Since there is little damping in this column, this produces an alternating pressure within the column which is a maximum at the bottom of the column and which varies approximately sinusoidally above this point. Thus, at the bottom of the pile there is maximum alternating pressure and zero velocity, whereas, at points above the bottom, the alternating component of pressure decreases approximately sinusoidally while the velocity increases. We ordinarily prefer to apply alternating flow at the upper end of the column at a frequency which will result in a longitudinal standing wave of a quarter wave length, so that the alternating pressure at the top of the column is very low, while the velocity is the highest. This is accomplished most easily by closing the top of the confined liquid column by a plunger or piston in contact with the water. This piston is actuated by any sort of mechanical vibrator which produces pressure in the liquid of a substantially sinusoidal nature and of a frequency which can be adjusted to make the column resonate, as stated above.

The alternating component of the pressure in the liquid column is, of course, transmitted to the confining walls which in this case means the wall of the pile which is in contact with the ground, at least below the mud line in the marine case. Application of this alternating pressure to the pile causes the transverse dimensions of the pile to dilate. Thus, this alternating pressure produces alternating radial deformation of the pile, which we have found results in considerable decrease of the skin friction between the pile and the contacting ground. This beneficial effect is strongest close to the bottom of the pile, where the soil compaction is the greatest, due to overburden. Accordingly, any downward force applied to the pile will cause it to penetrate the ground much more easily than when this resonating liquid column is not used.

The alternating pressures caused by the resonating liquid column also act on the bottom of the pile and thus transmit an alternating force to the soil immediately below the pile. In numerous cases, this force is sufficient to overcome the bearing resistance of the soil, especially in clays since their bearing capacity is generally small. Bearing capacity in the case of sands is considerably greater and

in this case, the force transmitted to the bottom of the pile and hence to the soil due to the resonating liquid column may be insufficient. In such case, it is necessary to add an additional longitudinal force to the pile to cause it to penetrate. As explained above, such longitudinal force will be much more effective due to the pulsating walls of the pile. This force may be a steady downward force, simply by adding suitable weight to the top of the pile. However, we prefer to apply longitudinal downward force sonically, in accordance with the systems already so used. In this case, an additional longitudinal shaking machine, which may be of the same type employed in resonating the liquid column, is applied at or near the top of the pile, for example by a separate shaking machine. Since the use of the resonating liquid column has greatly decreased the skin friction along the pile wall, the energy dissipated in the system driving the pile is decreased, which increases the mechanical Q of this system and greatly increases the effectiveness of this separate drive.

Sometimes, a pile is jetted during the time that it is being driven. That is to say, liquid is forced into the soil immediately below the pile, of sufficient quantity and velocity so that it considerably decreases the bearing capacity of the ground during driving. This can be very advantageously employed in conjunction with our invention. It is simply necessary to provide a restricted opening at the bottom of the liquid column through the bottom of the pile. Liquid is thus injected into the ground immediately below the pile under both the steady hydraulic head of the liquid column and the superimposed alternating pressure provided by the shaking machine acting on the piston closing the liquid column. This stream of liquid flowing into the ground below the pile is replaced by suitable addition of liquid at the upper portion of the pile so that the driving piston is in contact with the water column during the driving period.

It is not necessary that the entire bottom part of the pile be closed off (except for any jetting orifices provided) in order to achieve the advantages of this system. The pile can be made, for example, with hollow walls and the piston in this case is annular. In this case, the pile appears externally to be a thick-walled annular cylinder. It is in contact with the ground on both the outer and inner surfaces, as well as the bottom.

*Brief description of the drawings*

This invention is illustrated by the accompanying drawings which form a part of the specification. In these drawings the same reference number in several views represents the same or a corresponding part:

FIGURE 1 shows in diagrammatic cross section a single cylindrical pile being driven in accordance with this invention in a marine location.

FIGURE 2 represents in graphical form the pressure and velocity of the alternating components of the stress in the liquid column shown in FIGURE 1.

FIGURE 3 shows a cross section of a second form of the invention applied to a double-walled pile.

*Description of the preferred embodiments*

In FIGURE 1 is shown a cross section of a long tubular pile **11** which is being driven into the ground **12** below the mud line **13** in a marine location. The surface of the water **14** is above this mud line. The tubular pile is fitted with a bottom closure **15** which in this case may be simply a steel disc welded across the otherwise cylindrical opening at the bottom of the pile. The confined space defined by the pile **11**, including its bottom **15**, is filled with a column of liquid **16** (ordinarily water) which extends up to a level near the top of pile **11**. Immediately resting on this liquid column **16** is a plunger or piston **17** which closely fits the inner surface of the pile **11**. Preferably this piston **17** contains one or more seals **18** which may be chevron packing, O-rings (as shown), etc., to effect a substantially fluid-tight seal, preventing the liquid in column **16** from escaping from the system. Mounted on this piston **17** is a vibrator **19**, capable of providing cyclic longitudinal motion to the piston **17**, and hence, to the top of the column of liquid **16**. Such vibrators per se are not novel. The one shown involves two weights **20** eccentrically but symmetrically mounted on a pair of meshed gears **21**, rotated by an engine (not shown). The centrifugal force due to the rotation of the weights **20**, produces a resultant substantially sinusoidal force aligned essentially along the axis of pile **11**, i.e., longitudinally. It is to be understood that any other form of shaking machine which can impart a cyclic longitudinal pressure through piston **17** to the top of column **16** may be employed. The frequency of the cyclic variation in stress should be adjusted so that this liquid column is in resonance longitudinally. In nearly all cases, this frequency will be chosen as the lowest one in which there is quarter wave resonance in the column.

FIGURE 2 shows a plot of the amplitude of the alternating components of pressure (line **22**) and velocity (line **23**) along the liquid column **16** of FIGURE 1. Since there is very little escape of liquid from the column, the velocity is essentially zero at the bottom of pile **11** and the pressure is a maximum. This peak pressure will decrease sinusoidally as the distance **1** from the bottom of the pile increases, and correspondingly, the peak velocity will increase sinusoidally. If the column **16** is resonated at a quarter wave length, the frequency of the cyclic vibration applied to the piston **17** is given by the equation $F=V/4L$ where V is the velocity of compressional waves in the liquid (approximately 5,000 feet/second in water), L is the length of the liquid column **16**, and F is the applied frequency in hertz. The alternating component of pressure exerted against the walls of pile **11** alternately increases and decreases the pile diameter, i.e., dilates the pile. As stated above, since the column of liquid **16** is not subjected to appreciable damping, the pressure applied to dilate the pile walls is substantially independent of the length of pile below the mud line, i.e., below the surface of the ground, regardless of the frictional resistance of the material of which this ground is composed. Accordingly, there is radial deformation of the cylindrical pile wall and decrease in the skin friction between the ground **12** and the pile **11**. The greater the alternating component of pressure in the section of the pile in contact with the ground, the lower will be the frictional resistance of the pile as it is being driven, though this effect is by no means linear.

If jetting of the pile is to be carried out, a relatively small or constricted opening **24** is provided in the bottom closure **15** of the pile. This permits a small stream of the liquid to escape from column **16** through opening **24**, as shown by the arrows in FIGURE 1. This stream of liquid tends to decrease the cohesion of the particles of the ground immediately below the pile and increase the ease of penetration.

To compensate for thhe stream escaping through the bottom of the pile **11**, a makeup stream is provided through a flexible line **25**, controlled by valve **26** and supplied by a pump (not shown).

To increase the speed of penetration beyond that furnished by the vibrator, as discussed above, an additional longitudinal driving force is preferably provided. Probably the simplest arrangement is shown in FIGURE 1, in which a massive cylinder **27** containing an inner abutment **28** is supported by that abutment on top of the pile **11**. Thus its weight contributes extra downward driving force.

The pile is driven to a certain depth and then an additional top section is customarily welded on to provide for additional driving. When the maximum depth has been achieved for the particular pile **11**, as shown in FIGURE 1, weight **27** and the shaking equipment are removed, line **25** is disconnected and blanked off (preferably by welding), and an additional section is longitudinally mounted

on pile **11**, welded to it, the equipment replaced, and driving re-commenced.

FIGURE 3 shows a variation in the form of the pile. It also illustrates driving the pile on land. This same argument can be equally well used in water-covered areas. In this case, the pile **11** is hollow-walled, consisting of an outer cylinder and an inner cylinder **29** which are preferably coaxial. These are connected by an annular closure member **30** welded to both the inner and outer members of the pile. In this case, the liquid column **16** is also annular in shape, extending from the bottom of the pile to a level near its top. Resting on this liquid column **16** and closely fitting the inner and outer members of pile **11** is an annular piston **31** suitably provided with seals **32**. This upper piston is shaken cyclically, longitudinally of the pile axis. The shaking machine in this case is not shown for clarity, but the direction of motion is indicated by the double arrow **33**. In order to provide jetting, orifices **34** are driller in the bottom closure **30**. In this case these are shown provided with check valves **35**. This is simply exemplary of any suitably valving arrangement which can, therefore, govern the amount of liquid used for jetting purposes. This liquid is provided through a flexible line **25** from a pump **36** connected to a source of liquid.

In this case, a different arrangement is shown for applying additional longitudinal driving force to the pile. A collar **37** rests through abutment **38** on the top of pile **11** and is vibrated longitudinally by a shaking machine (not shown). The direction of motion of the vibration is shown by double arrow **39**. This shaking machine may be identical to that used in driving annular piston **31**, and in this case provides an additional alternating force which ordinarily will drive the pile more rapidly than addition of equivalent static force, as shown for example in FIGURE 1.

In some cases, it will be found preferable to drive both the annular piston **33** and the collar **37** by the same vibrating source which can be accomplished simply by increasing the length of column of liquid **16** until abutment **40** rests on piston **31** and abutment **38** makes contact with the top of pile **11** only during a portion of the stroke of a vibrator applied to collar **37**. The advantage of this arrangement is its relative simplicity. Its inconvenience is that the frequency of the system can only be one value and since the speed of compressional waves through the liquid column **16** is not the same as through the pile material **11** (ordinarily, steel), use of a single vibrating machine to drive both the annular piston **31** and the collar **37** will result in maximum effectiveness of the liquid column in radial deformation of the pile in the lower part thereof, but the most effective driving force will not be applied to the pile.

The alternating pressure maximum which takes place at the bottom of the liquid column **16** produces stress in the pile wall which must be maintained within the elastic limit of the material forming this wall. It is simply necessary to compute the hoop stress and determine from this what maximum allowable fluid pressure can be used.

An example will further illustrate some of the quantities taken into account in this arrangement for pile driving. Assume a pile made of steel, approximately 30 inches in diameter with a wall thickness of 1 inch, the arrangement being as shown in FIGURE 1. Assume a length of water column of 150 feet. For this pile a convenient allowable fluid pressure is 100 p.s.i. For a quarter wave resonant condition, the resonant frequency is approximately 8 hertz. To achieve the necessary pressure at the bottom, an amplitude of 0.38 inch is applied sinusoidally to the piston, that is, the total piston stroke is twice this figure, or 0.76 inch. The peak force on the piston is 5.2 pounds and the corresponding average power expended in this sinusoidal motion of the piston is 0.0075 horse power. The peak velocity or flow of the liquid at the top of the column is approximately 1.6 ft./sec. It is seen that a relatively insignificant amount of power is used in this shaking machine to minimize frictional effects on walls of the pile and improving its driving characteristics.



A pressure sensor at the bottom of the pile in the water column **16** is desirable, its leads being taken out near the top of the pile so that it can be used to note the alternating component of hydraulic pressure being applied. This helps the driving crew to notice conditions in time to prevent a pressure buildup exceeding the elastic limit of the pile material. Since such arrangement appears obvious, it has not been illustrated in the drawings. Such a sensor can, if desired, be used to control the amplitude, or the frequency, or both, of the shaking machine used at the top of the column to apply this alternating pressure.

It should be emphasized that any type of driving source can be employed with this invention. Those illustrated are but two out of the several immediately available. For example, if desired, the arrangement shown in co-pending patent application Ser. No. 504,609 Lubinski offers another means for driving, as does the conventional impacting source known for many years.

It is apparent that variations from the forms of apparatus and the precise steps of the methods given will be apparent to those skilled in this art. The essential novelty still lies in the incorporation in the pile of a liquid column driven substantially under resonant conditions to change cyclically the pile dimensions and minimize skin friction of the ground to the pile during driving, substantially as provided by the appended claims.

We claim:

**1.** A method of driving a pile comprising the steps of
confining a column of liquid within said pile extending substantially to the bottom thereof, said column being in pressure-exchange relation with the outer walls of the pile below its contact with the ground,
applying cyclic flow to the upper part of said liquid column at least approximately at a resonant longitudinal frequency of said column to produce cyclic dilation of said pile below said contact with the ground, and
applying force axially to said pile.

**2.** A method in accordance with claim **1** in which said flow is substantially sinusoidal and of such a frequency that the alternating pressure at the bottom of said column is essentially greater than the pressure at any point above said bottom.

**3.** A method in accordance with claim **2** in which said force includes both a downward component and a cyclic component, and in which said column is at least approximately in quarter wave resonance.

**4.** A method in accordance with claim **3** in which said cyclic component of said force is at least approximately at the same frequency as the frequency of said sinusoidal stress.

**5.** A method in accordance with claim **2** including hydraulic jetting of the ground immediately below said pile.

**6.** Apparatus useful in pile driving comprising
a pile confining a liquid column extending substantially to the bottom of said pile, at least the lower portion of said column being confined by the outer wall of said pile,
a vertically movable piston on top of said column and in contact therewith,
means for applying cyclic force to said piston at least approximately at substantially a quarter-wave resonant longitudinal frequency of said column to produce radial deformation of said pile below the earth's surface, and
separate means for applying axial force to said pile.

**7.** Apparatus in accordance with claim **6** in which said pile is hollow with a closure at the bottom and is filled with said liquid.

**8.** Apparatus in accordance with claim **6** in which said

pile has hollow walls defining an annular volume closed at the bottom and filled with said liquid.

**9**. Apparatus in accordance with claim **6** in which said column is in liquid communication with the ground immediately below said pile through a constricted opening in the bottom of said pile, whereby jetting action occurs at said bottom of said pile, and in which means are provided for adding liquid to said column to maintain its height as said jetting action takes place.

**10**. Apparatus in accordance with claim **6** in which said means for applying axial force provides both a downward component and a cyclic component.



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JACOB SHAPIRO, *Primary Examiner.*