

This document downloaded from
vulcanhammer.net vulcanhammer.info
Chet Aero Marine



Don't forget to visit our companion site
<http://www.vulcanhammer.org>

Use subject to the terms and conditions of the respective websites.

[54] **WATER HAMMER PILE DRIVING WITH CONDENSABLE VAPOR RESET**

[75] Inventor: **Serge S. Wisotsky**, Sharon, Mass.

[73] Assignee: **Orb, Inc.**, Marion, Ohio

[22] Filed: **June 30, 1972**

[21] Appl. No.: **267,751**

Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 163,422, July 16, 1971, abandoned.

[52] U.S. Cl. **61/53.5, 173/1, 181/5**

[51] Int. Cl. **E02d 7/28**

[58] Field of Search **61/53.5, 63, 46.5, 53.54; 173/1; 114/206; 181/5**

[56] **References Cited**

UNITED STATES PATENTS

3,646,598	2/1972	Chelminski	61/53.5
3,604,519	9/1971	Chelminski	173/1

Primary Examiner—Jacob Shapiro

Attorney, Agent, or Firm—Pollack, Philpitt & Vande Sande

[57] **ABSTRACT**

Driving long piles with a liquid ram or spear generated in an evacuated tube using a condensable vapor reset. In one embodiment, the pile itself is used as at least a portion of the working chamber for generating water hammer.

8 Claims, 7 Drawing Figures

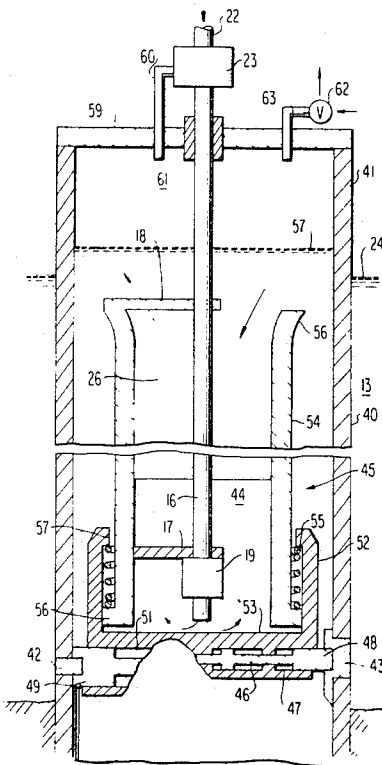


FIG 1

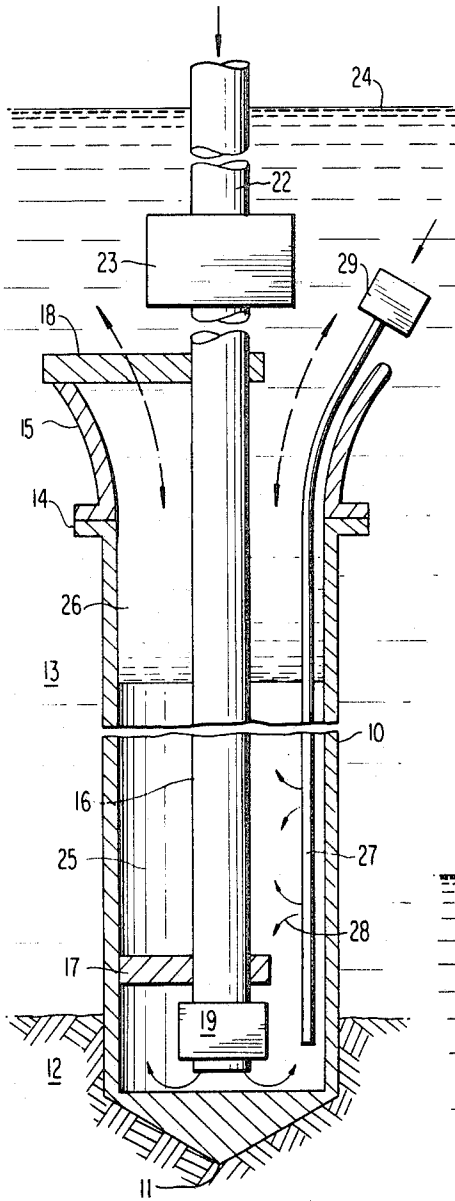


FIG 2

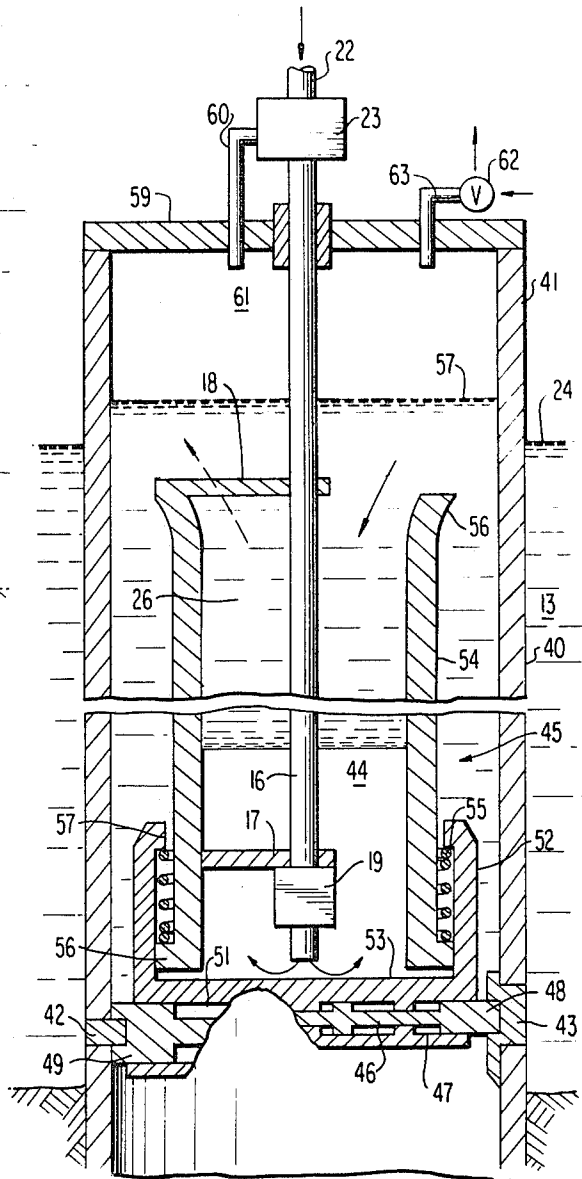


FIG 3

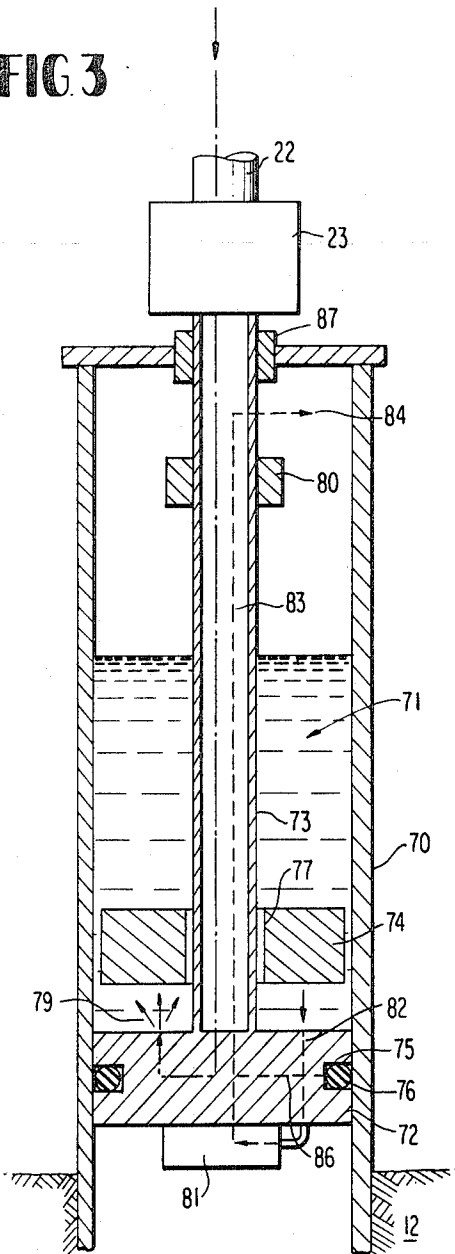


FIG 6

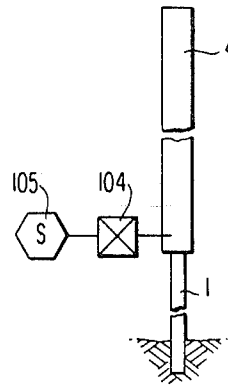


FIG 4

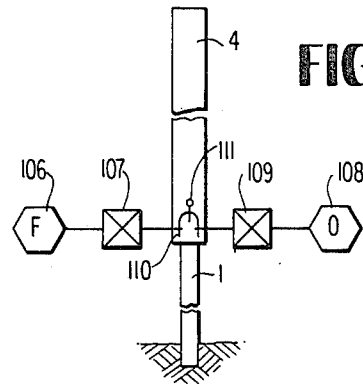


FIG 5

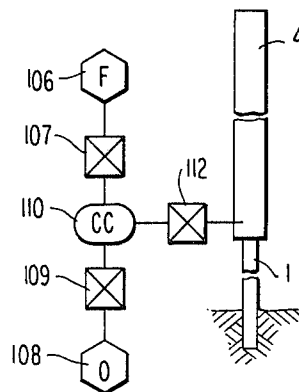
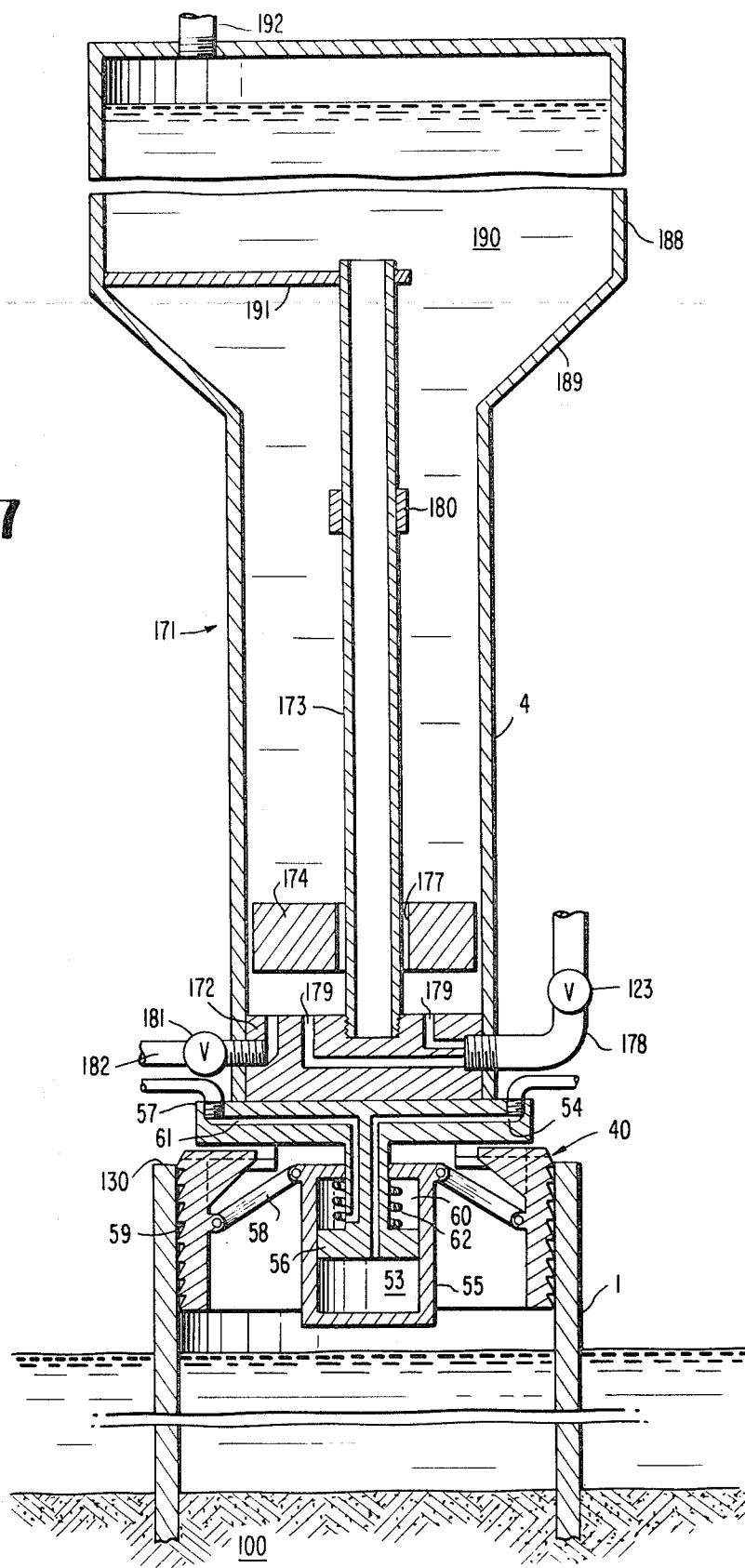


FIG. 7



WATER HAMMER PILE DRIVING WITH CONDENSABLE VAPOR RESET

CROSS-REFERENCE

This is a continuation-in-part of prior copending application Ser. No. 163,422, filed July 16, 1971 and now abandoned, the disclosure of which is hereby incorporated by reference.

BACKGROUND

The kinetic energy output of a pile driver is the product of its driving mass times its velocity at the instant of impact with a pile. The emplacement of piles in the ground by pile driving is accomplished by transmitting the kinetic energy of a hammer or other driving mass to a pile in sufficient quantity to cover nonproductive energy consuming factors such as impact stresses, radiation, reflection and ground quake, and to overcome the friction, elasticity and inertial impedance components of the pile and ground.

Increasingly larger land-based and offshore structures are constructed year after year. Larger structures demand longer and more massive piles for their foundations, more deeply embedded in the ground. This requirement is particularly severe in the case of large offshore installations such as ship terminals, and oil drilling, production and storage facilities. Without suitable foundations, such structures weighing tens of thousands of tons can be readily dislodged and toppled by heavy storms, large vessels bumping, earthquakes, and ice floes, often with catastrophic loss of life, damage to the environment and loss of invested capital. Thus, to provide adequate load-bearing and to prevent pull-out, requirements exist for driving piles hundreds of feet long, several feet in diameter, weighing hundreds of tons, and for continuing the driving to depths of soil penetration where driving resistance is severe.

A complex series of relationships pertaining to pile and soil characteristics, driving environment, economics and materials governs the design of a pile driver. However, generally speaking, the advent of piles of greater mass and conditions productive of more severe driving resistance require drivers of increasing kinetic energy output. In the absence of adequate driving energy, that which is available is consumed largely or completely by the aforementioned nonproductive energy consuming factors, leaving little or no energy to drive the pile. Under such conditions, some help is obtained by palliatives such as drilling a pilot hole, water jetting or grouting into an over-size hole, but these measures normally reduce load-bearing capacity. Thus, as each new generation of more massive piles and more severe driving conditions arises, drivers of greater energy output must be designed.

The kinetic energy output of an existing hammer can be increased by increasing either its mass or its impact velocity. The latter alternative is unattractive for a number of reasons.

First, there is the matter of the efficiency with which the hammer transfers energy to the pile. In a complete inelastic collision between a hammer and pile, the kinetic energy remaining after impact for overcoming the nonproductive factors and driving the pile is in proportion to the ratio of the hammer mass divided by the total mass of hammer plus pile. An increase in pile mass

without a corresponding increase in hammer mass results in a reduction of driving efficiency.

Also, higher hammer velocities are more predisposed to produce high local impact stresses. When the latter exceed the yield point of the pile material, kinetic energy is wasted and efficiency reduced.

For these and other reasons, manufacturers discourage the use of pile driver in which the hammer's mass is less than one-fourth that of the pile, and a mass ratio of one-half is generally recommended for land-based operations.

This presents a dilemma in off-shore pile driving. The largest steam hammer pile drivers currently in use in offshore/marine work are limited, practically, by safety considerations relative to their handling in stormy weather, to weights on the order of 60 tons (hammer mass about 30 tons). Consequently, they usually are inadequate to drive the larger piles due to mass-mismatch.

For instance, with a 200-ton pile, the energy transfer efficiency of a 30 ton hammer would be 100 percent \times $30/(30 + 200)$ or about 13 percent. Moreover, even this relatively small amount of energy transferred to the pile is not altogether effective in driving for other reasons stated below.

The picture is further complicated by the fact that the energy in a pile is effective to penetrate the soil only if there is a proper impedance match between the force-time-displacement characteristics of the driver and corresponding parametric thresholds of the soil. The available alternatives for varying the force-time-displacement characteristics of a steam hammer are limited, and this presents practical problems as the tip and sides of a pile often pass through strata of widely varying characteristics as the pile penetrates the earth.

Thus, under the severest conditions, pile driving is an arduous, time consuming and expensive task which sometimes ends in failure to achieve design load-bearing capacity or depth. Also, the inability to drive large piles to sufficient depths often necessitates driving a larger number of smaller piles, so that as many as eight or 16 piles may be required for the foundation of a single leg of a multi-leg offshore structure.

Bearing in mind the storm-weather safety considerations mentioned above, it is of interest that at least one pile driver manufacturer has proposed for offshore operations a pile driver, nominally rated at almost 500,000 ft. lb., weighing on the order of 230 tons, equivalent to the weight of several locomotives. Lifting this gigantic mass and adequately securing it during storm conditions present major challenges. Nevertheless, the fact that at least some of those active in the art seem ready to accept these formidable challenges suggests the severity of the problems and limitations with which the pile driving art is now struggling.

SUMMARY OF THE INVENTION

The method of the present invention is carried out in (including "on") a pile which has its tip embedded in the ground, including for instance the subsoil of a body of water. An evacuable enclosure with sidewalls and a lower barrier is effectively coupled with the tip of the pile for transmitting driving forces exerted upon said barrier to said tip. The method comprises: at least partially filling said enclosure with water, providing a hydrostatic head in said water bearing upon said barrier;

evacuating said chamber by releasing condensable vapor in (including "into") said chamber under sufficient pressure for displacing water along the longitudinal axis of the chamber away from the barrier and by then rapidly condensing said vapor to liquid to leave said chamber in an evacuated condition; accelerating a mass of water along the axis of the chamber towards said barrier under the influence of the hydrostatic head and which moves substantially independent of said pile; suddenly decelerating said mass against said barrier, thereby converting hydraulic kinetic energy to a water hammer driving pulse for driving said pile into the ground; and repetitively evacuating, accelerating, decelerating and driving as aforesaid. Using this method, it is possible to generate powerful mechanical impulses whose pressure-time characteristics can be tailored over a wide range of values to match corresponding requirements of the pile and soil conditions. Although the invention was developed for and provides special benefits for underwater pile driving, it also has applications in the driving of piles on land. Various other advantages will be discussed along with certain preferred embodiments of the invention illustrated in the accompanying drawings and text.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a sectional view of an evacuated tube water hammer driver with condensable vapor reset in which the evacuable enclosure is defined by the walls of the pile itself.

FIG. 2 is a schematic diagram of a driver similar to that shown in FIG. 1, but wherein the evacuable enclosure is defined by a tube other than the pile itself, which is provided with a coupler for securing the driver within the pile.

FIG. 3 is a sectional view of a free-piston type evacuated tube water hammer driver module with condensable vapor reset.

FIGS. 4-6 are schematic diagrams of the above general type of pile driver which include means for releasing various condensable vapors, including combustion products, into top-mounted separate, evacuable enclosure tubes coupled to the pile.

FIG. 7 is a sectional view of a steam reset free piston driver with water reservoir.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

As shown in FIG. 1, the evacuable chamber walls may be defined by the walls of the pile itself. A closed-end pile 10 has its tip 11 embedded in the sub-soil 12 of the sea or other body of water 13. To the top 14 of the pile is secured a module comprising flared horn 15, steam jet tube 16, spiders 17 and 18, and check valve 19.

The evacuable enclosure is defined by the cylindrical side walls of pile 10 and the inner surface of the closed tip 11 which acts as a barrier. Thus the enclosure is directly coupled to the pile tip through the pile walls and the material of the tip itself. The horn 15 is in open communication with the open top 14 of pile 10, and has upwardly and outwardly flared walls for guiding water smoothly into the pile between evacuations (during power strokes). The pile is normally full of water, with the hydrostatic head bearing on the pile tip or barrier.

A first (upper) three-legged spider 18 (only one of the three equal-angular spaced spider legs being shown) is secured to the top of the horn. In an aperture in the center of this spider is secured the rigid steam jet tube 16. It extends downwardly into the pile's evacuable enclosure along the longitudinal axis thereof, terminating adjacent the pile tip 11, but spaced upwardly therefrom by a short distance to permit the escape of steam from the jet tube 16 into the pile. The second (lower) three-legged spider 17 assists in holding the jet tube in axial alignment.

Jet tube 16 is supplied with steam from any variety of boiler (not shown), including the types commonly used for steam pile driving hammers, via an insulated, large diameter (to control) condensation), flexible hose 22 and control valve 23. Superheated steam is desirable if available. Valve 23 may be at any convenient location along hose 22, either above or below the water surface 24. However, location of valve 23 above the surface, e.g., on the barge (not shown) where the boiler is located is advantageous. When employing a check valve 19 which only permits the passage of fluid out of jet tube 16 and a normally closed control valve 23 above the surface, one can then maintain less than full operating steam pressure in line 22 between evacuations. The amount of steam subject to condensation loss may thereby be reduced.

The apparatus just described can be used, through suitable manual or automatic, programmed opening of valve 23, to evacuate water by blowing into the bottom of the pile a predetermined burst of steam at a pressure greater than that of the ambient water. In the preferred mode of operation, sufficient steam quantity, pressure and superheat are used so that the energy of the resultant steam bubble is expended just before the pile is emptied of water. When the efflux momentum (away from the barrier) supercools the steam and condenses it, the interior of the pile is evacuated.

The ambient hydrostatic pressure then accelerates a mass of water 26 along the pile axis toward the barrier or pile tip. The mass of water substantially fills the available cross-section of the pile and moves substantially independent of the pile. When the water is decelerated, by direct or indirect (e.g., through contacting residual water) contact with the fixed barrier, it is normally at its theoretical bulk modulus, as condensation of the steam leaves the descending water substantially free of added (dissolved gases). Entrained or entrapped gases such as air, if present, would introduce sufficient compliance into the mass of water to very substantially reduce the mechanical impulse which results when the water mass is suddenly decelerated against the barrier. Indeed, one of the advantages of this condensable vapor-method is that for a given size of chamber or pile and a given volumetric displacement of the water it produces a significantly more powerful driving impulse. Repetitive evacuation, acceleration, decelerating and driving by this method can drive very large piles.

For best results, the quantity of steam used should be no more than required to completely evacuate the tube. Otherwise, excess effluent steam mixing with incoming water creates a turbulence which also tends to reduce the resultant mechanical impulse. For most efficient capture of the available driving energy, the operation should be conducted to bring about a smooth and minimally-impeded, e.g., substantially free, flow of water into the mouth of the tube during the power

stroke. For similar reasons, it may be desirable to "streamline" those structural elements, e.g., spiders and check valve, past which the water moves on the power stroke.

When efflux momentum is not sufficient to fully supercool and condense the steam or where it proves difficult to avoid injecting excess steam, condensation may be assisted by injecting cool water 28 into the steam in the evacuated portion 25 of the chamber. This can be done through spray outlets in a water spray tube 27, the control valve 29 of which is normally closed and is opened at a predetermined time after release of the steam into the pile.

FIG. 2 demonstrates the facts that the evacuable chamber walls may be defined by a tube other than the pile itself, and that the apparatus and procedure may be easily tailored to suit a variety of different driving conditions. For example, many off-shore installations use hollow piles 40 whose tops 41 are above the surface 24 of water 13 before and after emplacement. Such piles are usually fabricated in short cylindrical sections which are welded together end to end to form a pile of the desired length. Thus, it will be convenient when joining these sections to provide either internal lugs 42 or grooved rings 43 where the various sections are joined together. These provide a series of locations within the pile for coupling an evacuable chamber to the pile and its tip. This is advantageous when working with open tip piles. When the pile is first stabbed in the ground, the driver may be secured at the lowest available point of attachment in the pile. As the pile is driven deeper and the driver approaches the lengthening plug of soil 12 in the bottom of the pile, the driver may be released from the lowermost attachment lugs or rings and moved to the next higher position.

FIG. 2 shows a driver 45 secured within pile 40 to the topmost available attachment points. In this figure, the driver has a portion of its lower end broken out to permit illustration of two different means for coupling the driver to the pile 40. At the lower right is shown a latch 46 which reciprocates laterally in channel 47 so that its head 48 may be moved into and out of engagement with the corresponding groove provided in grooved ring 43. On the left is shown a laterally reciprocal jaw 49 slidably mounted in a channel 51 and having a groove 50 formed in its outer surface corresponding in size with the lug 42. The jaw 49 and latch 46 may both be reciprocated in their respective channels by a hydraulic or pneumatic cylinder (not shown).

In this embodiment, the driver 45 includes a cylindrical pot 52, having a bottom wall 53. A shock tube 54 is telescoped within the cylindrical walls of pot 52 for limited reciprocal movement along its longitudinal axis. It is biased downwardly by a coil spring 55 engaged by corresponding lugs 57 above, and 56 below, pot 52 and tube 54 respectively. The evacuable enclosure is defined by the cylindrical side walls of shock tube 54 and the bottom wall of the pot 52, which acts as a barrier. The enclosure is coupled to the pile tip indirectly through the portion of the pile embedded in ground 12, and a plurality of either grooved rings 43 and latches 46 or lugs 42 and jaws 49.

The shock tube is in open communication with the interior of the pile above its upwardly and outwardly flared mouth 56. The pile is filled with water to a substantial height above said mouth, and when the pile is being driven in shallow water, the water level 57 in the

pile may be substantially higher than the level 24 of the water outside the pile. The water depths and sizes of components have not been shown to scale in the drawing, it being understood that the greater the depth of water above the shock tube mouth in the pile, and the greater the height to which the shock tube is evacuated, the more driving force will be available.

The FIG. 2 embodiment also includes a steam jet tube 16. It may be supported, positioned, terminated, supplied, controlled and operated the same as the corresponding part of the FIG. 1 embodiment. However, when the pile top 41 has a gas-tight seal 59 thereon, certain useful options may be added.

In such case, an artificial atmosphere or overpressure may be furnished in the space 61 above the liquid level 57 in pile 40. For instance, the valve 23 may be a three-way valve adapted to first supply steam pressure through the bottom of jet tube 16 to evacuate enclosure 44, then switch to a position in which steam is delivered through auxiliary tube 60 into space 61 above liquid level 57, and then close. Also, it is possible to employ a two-way valve which alternately feeds jet tube 16 and auxiliary line 60, another valve upstream in the supply line being used to shut down the driver when desired. The overpressure steam can be condensed by the enlargement of and pressure reduction in space 61 which occurs during the downstroke. Optionally, the overpressure may be provided by an auxiliary air line 63 and two-position valve 62 which exhausts the space 61 as water level 57 rises and admits air under pressure at the time of the driving stroke. When the volume above water surface 57 is very large, it may be necessary to commence building up the overpressure before the downstroke actually starts. In such case, it would be convenient to provide separate valves for the evacuation and pressurization functions. In any event, the various valves and their controls can be electro-hydraulic, -pneumatic, -mechanical, and so forth, monitored by liquid-level pressure, temperature or position sensors; or, they may be hydro-mechanical with the actuation performed by water-level floats. As those skilled in the art can readily supply the necessary water level and pressure controls, and valve actuation means, these will not be described in detail.

The operation of this embodiment is basically similar to that disclosed in FIG. 1. There is a steam evacuation and then a mass 26 of water is accelerated toward the barrier wall 53 under the influence of the hydrostatic head. In this embodiment, however, the hydrostatic head is augmented by the overpressure provided in space 61. When the mass of water decelerates directly or indirectly against barrier 53, they and the pile are able to move downwardly at least partly independently of shock tube 54 due to the spring biased, telescoping arrangement of the latter. Thus, the shock tube mass is at least partially decoupled from the pile. Accordingly, a portion of the driving energy and impulse which would otherwise be used to accelerate the shock tube 54 is saved and applied to the driving of the pile itself. It will be appreciated that the preload provided by spring 55 could also be supplied by mechanical, pneumatic or hydraulic means. When driving an open-end pile it may be necessary to provide means of venting any pressure build-up between the barrier and the soil plug beneath.

In the foregoing embodiments, evacuation is most thorough and efficient when the steam is released in the

form of one or more coherent bubbles. The longer each bubble remains coherent, the more coherent the steam-water interface and the more efficient the evacuation. Under conditions which make difficult the maintenance of a coherent bubble, such as with shock tubes of very large diameter, or a large ratio of shock tube diameter to steam pipe diameter, or with marginal steam pressure or trouble with condensation of steam, or if adulterants, solutes or other conditions adversely affect the surface tension and heat transfer properties of the water and condensable vapor, a free-piston condensable vapor reset driver like that shown in FIG. 3 may be used. The piston assists in maintaining a coherent steam-water interface during the water-evacuation and driving.

In FIG. 3 is a closed tip pile 70 in which is temporarily mounted a driving module 71 comprising a base 72, central column 73, free piston 74 and associated parts. The base 72 is cylindrical, slightly less in diameter than the inside of pile 70, and includes any suitable means for releasably gripping the inside of the pile and maintaining the position of the base during driving. This may be accomplished, for instance, by inflatable gland 76, in peripheral groove 75, which presses outwardly against the pile. Gripping teeth may be provided on the outer surface of the gland. Various other mechanical and hydraulic coupling arrangements may also be employed.

The bottom of the column 73 is secured in the center of the base. Its top may be secured in any desired manner, such as by spiders, leaving the top of the pile open. The column may also be supported by a plate having a gas tight seal 87, for example when it is desired to provide an overpressure as explained with FIG. 2. The column is normally hollow, and is therefore a convenient channel for supply and control cables extending between the top and the base of the module. It also guides the piston 74.

Piston 74 is mounted for vertical or axial reciprocation on column 73 between base 72 and stop 80 secured near the upper end of the column. Both the piston and base are reinforced to withstand the mechanical shock associated with water hammer pressures. The piston has a central aperture 77 of slightly greater diameter than the outside of the column 73, and has an outer diameter slightly less than that of the inner diameter of the pile. Suitable seals may be provided if desired in the clearances between the piston on the one hand and the pile and column on the other. However, when operating with a small pressure differential across the piston, e.g., one atmosphere or less, leakage of water and steam past the piston will be minimal. Thus, it is possible to fabricate the apparatus in such a way as to provide a close but essentially drag free relationship between the piston and the other parts. Also, making the piston neutrally buoyant relative to water may reduce the pressure differential and discourage leakage.

Connected to steam supply hose 22 and control valve 23 is a steam conduit 78 which runs downwardly through column 73 into base 72 and has one or more outlets 79 beneath the piston. When the control valve 23 is opened to emit a burst of steam from the outlets 79 at a pressure greater than the ambient water pressure above the piston, the piston will be forced upwardly in the pile. When piston 74 retains sufficient upward momentum after control valve 23 closes, the re-

sultant further expansion of the space beneath the piston can supercool the steam and condense it, thus evacuating the space beneath the piston. Where, because of insufficient momentum or other reasons, there is not sufficient auto-cooling of the steam, cool water may be sprayed into the space beneath the piston by water conduits and spray nozzles (not shown) fitted into the central column.

In order to keep the evacuable enclosure free of steam condensate, and possibly of cooling water where such is used, the base 72 is fitted with a pump 81 which withdraws water from the top of the base via line 82 and discharges same through a line 83 which passes up through central column 73 to a discharge point 84 above the upward limit of the piston's travel. If desired, part of the effluent from pump 81 may be routed to inflatable gland 76 via a line 86 in order to keep or help keep the gland inflated.

The apparatus of FIG. 3 may be controlled by any suitable manual or automatic system. For instance, the control valve 23 may be automatically opened and closed in response to signals from sensors responsive to the position or velocity of piston 74 and/or monitoring such parameters as pressures, temperatures, water column depth and height. A ring magnet embedded in the piston can be used to actuate corresponding position and velocity probes located in the column 73. Piston-position limit switches and similar operational controls may be provided in the stop 80. Also, the steam valving may be actuated in a manner similar to that used in steam engines or steam pile hammers. The necessary mechanical linkages can, if desired, pass through the column 73.

With the three foregoing embodiments in mind, one can construct portable pile driving apparatus complete with its own water reservoir which would be useful for land-based operations or operations in very shallow water. Such devices could, for instance, be manufactured in accordance with any of FIGS. 1 through 3, in which case the parts described as piles in those figures would be any suitable casing of tubular or other shape having a socket, clamp or other fastening means at its lower end so that it could be secured to a pile or other object which was to be subjected to water hammer pulses for driving and other purposes. Thus, the invention is not limited to apparatus in which the outer casing is a pile.

FIG. 4 discloses a condensable vapor reset driver in which the evacuable tube is defined by a tube 4 other than the pile 1 itself. The tube 4 is coupled, to the pile, for instance, by a coupler (not shown) similar to that in FIG. 3. The controls for the coupler, the steam generator 105 and control valve 104 may be mounted on a surface barge (not shown) and may pass to the pile in any desired manner. In the operation of this embodiment, the steam control valve 104 is open momentarily to meter the proper amount of steam from generator 105 to the interior of the pile. The operation is the same as the FIG. 1 embodiment.

FIG. 5 represents an arrangement similar to FIG. 4, utilizing a two-phase combustible mixture comprising a pressurized fuel such as hydrogen, or a hydrocarbon as kerosene or alcohol, in container 106, a fuel-metering valve 107, a pressurized oxidizer such as oxygen in container 108, and its corresponding metering valve 109. The fuel combustion chamber 110 is located within the water hammer tube 4. The component 111

represents either the external ignition source, such as a spark plug, a proprietary catalyst for the monopropellant type rocket fuels such as hydrogen peroxide or hydrazine. For hypergolic (spontaneous combustion upon mixing) type propellants the igniter 111 may be eliminated. On the other hand, liquid (water)-borne particles of solid type propellants or explosives may be metered via the valve 107, caught in the screened combustion chamber, and fired off by means of the igniter 111. The products of combustion are used to expel the water as previously discussed. These combustion products will be condensable, or at least partly so due to their water vapor content.

Similarly, FIG. 6 also represents the use of so-called rocket fuels wherein the combustion chamber 110 is external to the water hammer tube 4. The combustion products' metering valve 112 controls the water evacuation cycle and also acts as a check valve against the water hammer pressure. The remaining parts are similar to those shown in FIG. 5.

Practically, the principal limitation on the generation of larger values of water hammer within a single pipe may be the circumferential tensile or hoop stress. As will be shown, the generation of water hammer at a 1,000 ft. depth in a two-foot diameter steel pipe requires a wall thickness of 2.34 inches in order to keep the stress down to 69,000 psi. While this is not an excessive working stress for modern alloy steels, it still exceeds structural grade ratings. Since the invention is normally in limited access or restricted environments, a low safety factor can be employed. To avoid the use of excessively massive pipe walls, reinforcement in the form of filament winding or an axial series of external or internal spaced reinforcing rings is recommended. The distributed spring mass configuration of the latter also reduces the transonic velocity of wave propagation along the pipe. Two advantages follow, namely, reduction of hoop stress and increase of impulse duration. The use of pipe wall materials with a lower elastic modulus like aluminum or resinated fiberglass achieves a reduction in water hammer pressure by lowering the transonic velocity. For these to be fully effective under water, additional acoustic pressure release material like cork may be applied at the ambient water interface in order to preclude acoustic loading. Another method of reducing wall stresses, by slowing down the axial velocity, is to use a series of truncated cone baffles arranged in water hammer tube 4 or to spiral the water in the tube by uni-directionally twisted or alternately twisted bundles of smaller diameter tubes or baffles. Thus, the water hammer tube 4 of the preceding embodiments may be provided with a plurality of twisted tubes within the tube 4 and extending axially of at least a portion of the tube which defines the evacuable enclosure to induce helical motion of the water and downward twisting of the pile. Where the tube 4 includes a steam jet pipe or other equipment along its axis, the spiral tubes may be arranged around or above them. Similarly, series of baffles of opposite rotation may be used to slow the water velocity without causing rotation of the tube 4. The longer travel path provided by these various means proportionally creates a longer pulse.

Thus, for a given driving application (assuming a given depth, pile mass and soil conditions) it is possible to tailor the force-time characteristics of the water hammer impulses by a suitable selection of the length

and diameters of the water hammer tube, and the reinforcement and material of construction thereof. Also, one may employ the acoustic pressure release material, baffles and valve opening rate as discussed above. Thus, it will be seen that the method has far more flexibility than is provided by the conventional steam hammer.

In certain cases, especially shallow water applications, the water hammer tube may be at least partially above the surface of the water. Whether the evacuable enclosure is defined by a tube separate from the pile, or by the pipe itself, the water for generating the water hammer pulses may be provided by an upward extension of the pile or the tube, which is filled with water, or by a reservoir located above the hammer tube as shown in FIG. 4.

In FIG. 7 is shown a pile 1 partially embedded in subsoil 100 and having its upper end 130 protruding above the water's surface. A driver 171 is releasably secured in the top of the pile by a coupler 40, the base 57 of which is coupled to the base 172 of the driver. To secure the driver within the pile, high pressure fluid is fed into the lower cylindrical cavity 53 of the pile coupler 40 through port 54. This flow causes the cylinder frame 55 to move downward over the piston 56. The piston shaft is secured to the base 57 that is bolted to the barrier or base of the water hammer tube 4. When the cylinder frame 55 moves downward it creates a toggle action in the multiplicity of links 58. The resultant mechanical advantage varies as the cotangent of the angle between the link and the radial normal. Consequently, hard-tooth shoes 59 slide radially outward in T slot guides in the base 57 and bite into the pile walls. Simultaneously, the fluid in the upper cylindrical cavity 60 is exhausted through port 61. A 4-way electrically controlled valve (not shown) can be used to control the influx and efflux of the pressurized fluid, which may be hydraulic or air. To release the pile coupler, the influx and efflux ports on the piston base are interchanged by control valve action. The compression spring 62 in the upper cylinder 60 retracts the entire mechanism when the air pressure is off.

Extending upwardly from base 172 is an upright, elongated water hammer tube 4. A reservoir 188 is supported by the tube 4 and connected thereto by flared walls 189 to promote smooth flow of water 190 between the tube and reservoir. The reservoir may be pressurized if desired by forcing in gas or vapor through inlet 192. A central column 173 is suitably secured to the base 172 and extends upwardly and coaxially with the water hammer tube 4 and thence at least part way into reservoir 188, where it may be supported by a three-legged spider 191 secured to the reservoir walls, only one leg of which is shown in the drawing.

Piston 174 is mounted for vertical or axial reciprocation on column 173 between base 172 and stop 180 secured toward the upper end of the column. Both the piston and base 172 are reinforced to withstand the mechanical shock associated with water hammer pressures. The piston itself may of course contribute some driving momentum during operation, but normally, during driving, the mass of the piston is less, and usually substantially less than half, the mass of the fluid (water) which is above it or which enters the tube 4 during the down stroke.

The piston has a central aperture 177 of slightly greater diameter than the outside of column 173, and

has an outer diameter slightly less than that of the inner diameter of the water hammer tube 4. Suitable seals may be provided if desired in the clearances between the piston on the one hand and the pile and column on the other. However, when operating with a small pressure differential across the piston, e.g., one atmosphere or less, leakage of water and steam past the piston will be minimal. Thus, it is possible to fabricate the apparatus in a way which provides a close but essentially drag-free relationship between the piston and the other parts. Also, making the piston neutrally buoyant relative to water may reduce the pressure differential and discourage leakage.

Connected to a suitable steam supply (not shown) is a steam conduit 178 with control valve 123. Conduit 178 feeds passages in base 172 terminating in steam outlets 179. When the control valve 123 is opened to emit a burst of steam from the outlets 179 at a pressure greater than the ambient water pressure above piston 174, it will be forced upwardly in tube 4. When the piston retains sufficient upward momentum after control valve 123 closes, the resultant further expansion of the space beneath the piston can super-cool the steam and condense it, thus evacuating the space beneath the piston. Where, because of insufficient momentum or other reasons, there is not sufficient auto-cooling of the steam, cool water may be sprayed into the space beneath the piston by water conduits and spray nozzles (not shown) fitted into the central column and/or base, or into the side walls of tube 4.

In order to keep the evacuable enclosure free of steam condensate, and possibly of cooling water where such is used, the base 172 may be fitted with a drain pipe 182 and valve 181. Valve 181, like steam valve 123, will normally be opened during the raising of piston 174 and closed on the down stroke.

Although water is used as an example, the working fluid is not necessarily limited thereto. In a closed system, any liquid may be used.

Some contemporary offshore foundation designs call for loads up to 2,000 tons from piles 200-600 ft. long, 3-8 ft. in diameter, weighing 100-200 tons, in up to 1000 ft. of water. Without supplementary techniques involving pre-drilling or jetting, such piles are practically undrivable by the steam-air hammer even when spliced to extend to the surface.

The invention provides many advantages. It makes feasible a large increase in driving capability. And this can be done using a smaller mass ratio (driving mass versus pile) than has heretofore been thought advisable in steam hammer operations. That is, larger impulses can be generated using a driving mass which is less than one-fourth that of the pile. This, in turn, makes it possible to drive piles without the use of palliatives such as pilot hole drilling, water jetting and grouting into an oversized hole, which measures can reduce pile load-bearing capacity.

The pressure-time characteristics of the water hammer impulse can be tailored over a wide range of values to match corresponding requirements of the pile and soil. Thus, driving impedance can be better matched to that of the earth than when operating with for instance a steel hammer.

Under the longer impulses which can be generated with a water spear of a length to diameter ratio of 10 or greater, piles move more nearly like a nail, rather than a worm, in which one part moves ahead while

other parts are held back. A greater fraction of the driving energy is usefully expended in overcoming displacement skin friction, to advance the pile, rather than being tied up in the rubber-like ground "quake". Unwanted reflected wave conditions in the pile can be prevented more effectively. The use of a cushion block, as sometimes required with a steel hammer, is unnecessary, thereby eliminating the inelastic collision energy loss associated therewith.

Certain important advantages are associated with the convenient manner in which the invention may be applied under water. With the driver submerged, it may be handled with greater safety and ease during storm conditions. Coupling of the driver to the pile at a point below its top end helps to reduce losses of driving energy attributable to the mechanical compliance of the pile. Submerged operation provides inherent capacity for generating larger pulses as submergence increases, and particularly at depths greater than 200 feet where hydrostatic back pressure aggravates the venting problem of the air operated hammer, where thermal line losses preclude the steam driven hammer and where conventional vibratory driving requires such a relatively large back-mass for preload and such low frequencies that reaction forces necessary for driving become ineffective without excessively large excursions. Handling is facilitated because the driving mass can be drained from the apparatus when it is being transported and lifted above the surface.

Moreover, water hammer operation makes it convenient to twist the pile as it is driven downward, such as by including helical baffles in the water hammer tube which impart a twisting motion thereto. In some cases, especially where the "lead" or helix angle is optimized for the soil conditions, this can improve the pile's load bearing capacity.

In view of the foregoing, it is apparent that the present invention is a broad one, and that many changes may be made in the foregoing embodiments without departing from the spirit of the invention.

What is claimed is:

1. A method of driving a pile having its tip embedded in the ground, an evacuable enclosure with side walls and a lower barrier being effectively coupled with the tip of the pile for transmitting driving forces exerted upon said barrier to said tip, said method comprising: at least partially filling said enclosure with water, providing a hydrostatic head in said water bearing upon said barrier; evacuating said chamber by releasing condensable vapor in said chamber under sufficient pressure for displacing water along the longitudinal axis of the chamber away from the barrier and rapidly condensing said vapor to liquid to leave said chamber in an at least partially evacuated condition; accelerating a mass of water along the axis of the chamber towards said barrier under the influence of the hydrostatic head, said mass of water moving substantially independent of said pile; suddenly decelerating said mass against said barrier, thereby converting hydraulic kinetic energy to a water hammer driving pulse for driving said pile into the ground; and repetitively evacuating, accelerating, decelerating and driving as aforesaid.

2. A method in accordance with claim 1 wherein the tip of said pile is embedded in the subsoil of a body of water.

13

14

3. A method in accordance with claim 2 wherein said evacuable chamber is beneath the surface of said water.

4. A method in accordance with claim 2 wherein driving force is transmitted from said barrier to said pile through a coupling which is located below the top of said pile.

5. A method in accordance with claim 4 wherein the driving force is transmitted through said coupling, said coupling being at a point closer to the sub-soil than to the top of said pile.

6. A method in accordance with claim 1 wherein said

condensable vapor is released beneath a free piston which pushes upward on said water to evacuate said chamber, said piston accelerating downwardly with said mass of water, and said mass of water contacting said barrier indirectly through said piston.

7. Method in accordance with claim 1 wherein said condensable vapor is steam.

8. Method in accordance with claim 1 wherein said condensable vapor is water of combustion in combustion gases used to evacuate said chamber.

* * * * *

15

20

25

30

35

40

45

50

55

60

65

UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,800,548

Dated April 2, 1974

Inventor(s) Serge S. Wisotsky

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

In the drawings, on the title page and in FIG. 2, the reference numeral 50 and leadline should be added for the right-hand vertical line of element 42;

in FIG. 3, the reference numeral 78 and leadline should be added for the dot-dash line running parallel to element 83; and

in FIG. 7, "40" should be changed to --140 --; "53" to --153--; "54" to --154--; "55" to --155 --; "56" to --156--; "57" to --157--; "58" to --158 --; "59" to --159 --; "60" to --160 --; "61" to --161 --; and "62" to --162 --.

In Column 1, line 12, "the prod-" should be deleted and -- a function -- inserted; and

line 13, "uct" should be deleted, "times" should be deleted and -- and -- should be inserted.

In Column 5, line 33, "12" should be deleted and -- (not shown) -- inserted.

In Column 10, line 20, "40" should be -- 140 --, "57" should be -- 157 --;

line 23, "53" should be --153--;

line 24, "40" should be --140--; "54" should be --154--;

line 25, "55" should be --155--; "56" should be --156--;

UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,800,548 Dated October 24, 1974
Inventor(s) Serge S. Wisotsky Page - 2

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

line 26, "57" should be --157--;
line 28, "55" should be --155--;
line 29, "58" should be --158--;
line 32, "59" should be --159--;
line 33, "57" should be --157--;
line 34, "60" should be --160--;
line 35, "61" should be --161--;
line 40, "62" should be --162--; and
line 41, "60" should be --160--.

In the claims, Claim 9 should be added:

9. A method of driving a pile having its tip embedded in the ground, an evacuable enclosure with side walls and a lower barrier being effectively coupled with the tip of the pile for transmitting driving forces exerted upon said barrier to said tip, said method comprising: at least partially filling said enclosure with liquid, providing a hydrostatic head in said liquid bearing upon said barrier; evacuating said chamber by releasing condensable vapor in said chamber under sufficient pressure for displacing liquid along the longitudinal axis of the chamber away from the barrier and rapidly condensing said vapor to condensate to leave said chamber in an at least partially evacuated condition; accelerating a mass of liquid along the axis of the chamber towards said barrier under the influence of the hydrostatic head, said mass of liquid moving substantially independent of said pile; suddenly decelerating said mass against said barrier, thereby converting hydraulic kinetic energy to a liquid hammer driving pulse for driving said pile into the ground; and repetitively evacuating

UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,800,548 Dated October 24, 1974
Inventor(s) Sorge Wisotsky Page - 3

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

accelerating, decelerating and driving as aforesaid.

Signed and sealed this 21st day of January 1975.

(SEAL)
Attest:

McCOY M. GIBSON JR.
Attesting Officer

C. MARSHALL DANN
Commissioner of Patents