PILE DRIVING METHOD AND APPARATUS

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ABSTRACT
Driving of piles into submerged lands with a steadily applied force of sufficient magnitude to appreciably deflect the sub-soil, with or without superimposed driving pulses.

37 Claims, 8 Drawing Figures
PILE DRIVING METHOD AND APPARATUS
CROSS-REFERENCE
This is a continuation-in-part of an abandoned prior copending application Ser. No. 163,422, filed July 16, 1971, the disclosure of which is hereby incorporated by reference.

BACKGROUND
Mammoth structures of 15,000 to 40,000 tons air weight are currently planned for offshore installations such as ship terminals, oil drilling, production, and storage. Although engineering problems are severe, no doubt, larger and heavier ones will appear in the future.

Heavy storms, large vessel-bumping, earthquakes, ice floes and the like will readily dislodge and topple structures weighing tens of thousands of tons unless they have suitable foundations. Anchoring problems are particularly acute in deep water and where the structures extend above the surface. Under such conditions, large structures, and particularly tall ones, exert tremendous pullout forces on their foundations. Failure of the anchoring system means catastrophic failure, causing death or injury to personnel on duty on the structure, widespread extermination of marine life by oil released when oil drilling, production, or storage structures are damaged, and loss of stupendous amounts of invested capital.

The most prevalent foundation method is to drive piles into the sea bottom through or adjacent the lower portion of the structure and secure the structure to them. Usually the most severe requirement is that the piles will not pull out during storm conditions. Consequently, they must penetrate deep into the sea floor, and the driving process must of necessity continue well beyond the point at which the resistance to driving becomes severe.

Experience has shown that contemporary steam-hammer and vibratory pile-driving techniques alone are unable to fully emplace those piles of, for instance, 200 tons air weight which are used for the larger offshore structures. Thus, although powerful steam hammers have developed, the largest of which are so relatively heavy that they become difficult to handle under storm conditions, they are still inadequate to drive many offshore piles efficiently.

In the inelastic collision process between a hammer and pile, the efficiency of energy transfer from the striking mass (hammer) to the driven mass (pile) varies as the ratio of the striking mass to the total of these two masses. For this reason, land-based pile-driving practice recommends for most economical results that the striking mass (approximately one-half of the typical hammer's total weight) should equal that of the pile. This results in a driving efficiency of about 50%. Specifically "not advised" is the use of a driving mass having a ram weight less than one-fourth of the pile. Notwithstanding, the largest contemporary hammers used in offshore/marine work are limited, practically, by storm-weather handling requirements, to weights on the order of about 60 tons (striking mass 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 striking mass would be 100% × 30/(30+200) or only 13%. However, to make matters worse, even this relatively small amount of energy transferred to the pile is not altogether effective in driving due to mechanical compliance in the pile and ground plus mechanical losses in the hammer and pile-coupling themselves. Although such palliative measures as pre-drilling, jetting and grouting may assist in pile emplacement, they have a deleterious effect on pile pull-out resistance. Thus, a need remains for major improvement in techniques for driving large piles into the sea floor.

SUMMARY OF THE INVENTION
In accordance with the invention a pile, suitably braced to control its direction of penetration, is pushed or pulled downwardly into the sea floor with a steadily applied force sufficiently large to appreciably deflect the sub-soil beneath the lower end or tip of the pile. Repetitive driving pulses superimposed upon the steadily applied force in combination, provide the force necessary to drive the pile. A more efficient application of the available driving energy may thus be attained. This in turn makes possible deeper pile penetration, better anchoring, and reduction of the hazards discussed above.

It should be understood that the forces employed herein are significantly greater than the incidental pre-load provided by the weight of the hammer and pile in conventional steam hammer pile driving. Also, the force referred to herein is one which could unacceptably damp or clamp the vibrator in some methods which depend on vibrations to drive piles. For instance, steadily applied forces of the order of 200,000 pounds and preferably 500,000 pounds or more are contemplated.

Driving piles in accordance with the invention reduces "idle" energy storage and permits deeper driving than has heretofore been economically feasible, or at least technically possible, with conventional impact hammers or vibratory methods. When the pile penetrates the ground under the action of such a driving force, a portion of the kinetic energy imparted to the pile is converted into non-productive potential energy in the reversible elastic deformation of the soil and the pile. Such deformation is referred to as "ground quake". The steadily-applied large forces employed in this invention maintain the sub-soil beneath the pile tip in a deformed and pre-stressed condition, thereby reducing the unavailable energy stored in ground quake; and, this is true whether driving is accomplished with the steady force alone or in combination with superimposed repetitive driving pulses. Also, when using superimposed impulses generated by deceleration of a downward moving mass, one can apply the deflected force in such a manner as to reduce the driven mass, thereby improving the efficiency with which driving energy is transmitted to the pile. These and other advantages will become apparent from the description of certain preferred embodiments of the invention, described below.

BRIEF DESCRIPTION OF THE DRAWINGS
In the drawings, wherein like reference numerals refer to like parts and sectional views are taken along the indicated section lines:

FIG. 1 is a schematic diagram of a pile being driven into the sea floor wherein the force is provided by a combination of barge-mounted winches, with cables which are threaded through pulleys anchored to the sea
floor by a pile or suction-anchor and which extend upwardly to attach points on the pile.

FIG. 2 is a schematic diagram of a pile being driven through the foot of an offshore oil exploration structure wherein the load is provided by a combination of a hydraulic cylinder at the top of the structure and chain threaded from the cylinder through pulleys at the foot of the structure and extending upwardly to attach points on the pile.

FIG. 3 is a schematic diagram of a pile being driven into the sea floor, wherein the force is provided by a floating object, e.g., barge, having pile gripping means and fluid-actuated cylinders and pistons adapted to transfer at least a portion of the barge's weight from the water to the pile.

FIG. 4 is a schematic diagram of temporary anchoring means useful in anchoring pulleys, winches, barges and the like in conjunction with driving piles in accordance with the invention.

FIGS. 5–7 are sectional views, partly broken out, of an impulsive device.

FIG. 8 is a schematic diagram showing the driving of a pile using a force transmitted by cable from pulleys or remote control winches mounted on the temporary anchoring means of FIG. 4 and in which the driving device of FIGS. 5–7 is used to superimpose driving pulses upon the force provided by the cables.

In the embodiment of FIG. 1, there is a pile 10 having its tip 11 embedded in the sub-soil 12 of a body of water 13. Releasably positioned on the pile is clamp 14, which may be a mechanical scroll, hydraulically pneumatically operated chuck controlled by cable 33 from sub-sea power console 34 and raised by its own winch 35 via line 36 from barge 31. To the clamp 14 are attached the upper pulleys 15 and 16 of the two sets of block and tackle 17 and 18 arranged to pull downwardly on the pile. The blocks and tackle include cables 19 and 20 extending downwardly from upper pulleys 15 and 16 to lower pulleys 21 and 22. The latter may be anchored in any desired manner such as for example to a suction anchor 23 more fully disclosed in FIG. 4 or by a clamp 24 to a pile 25 which has previously been embedded in sub-soil 12.

Two sets of block and tackle are shown, but any desired number may be used. The block and tackle sets may be used with various auxiliary arrangements of anchors, cables, templates, guides, and/or other means for bracing the pile 10 and controlling its direction of penetration into sub-soil 12. Such auxiliary arrangements will readily be supplied by those skilled in the art, and are therefore not shown in the drawing. When such auxiliaries are omitted altogether, it may be found desirable to use three, four or more sets of block and tackle. When the latter perform both pulling and bracing functions, they may, if desired, be arranged on radii of the pile's longitudinal axis which are perpendicular thereto and have approximately equal angular spacing relative to one another; and the lower pulleys 21 and 22 will be situated at radial distances from the pile that are approximately both for pulling the pile vertically and holding it at the desired driving angle, as shown in FIG. 1. When one or more block and tackle sets are used solely for downward pulling, the lower pulleys 21 and 22 may be set quite close to the pile 10.

The number and positions of the block and tackle sets, the number of sheaves in the blocks and the tensile rating of the cables will also be selected in reference to the force which is to be applied. The force is one which will deform the subsoil in excess of the "ground quake" as defined by R. D. Chellis, *Pile Foundations*, McGraw Hill, 1961, or E. A. L. Smith "Pile-Driving Analysis by the Wave Equation", J. Soil Mechanics and Foundations Div., Proc. A. S. C. E., AUG. 1960.

On a barge 31 floating upon the surface 32 of water 13 above pile 10 are winches 29 and 30. Portions 27 and 28 of cables 19 and 20 extend downwardly from the winches through the water and through the pile means 21 and 22, these pulley means being situated at fixed points defined by anchor 23 and pile 25. By operation of the winches, cable portions 27 and 28 are drawn upwardly, drawing the upper (15, 16) and lower (21, 22) pulley means together, thereby pulling the pile 10 upwardly into the soil. The downward force advantage exerted by the block and tackle combination 15, 17, 19, 21 over the tension in line 27 is, theoretically, the number of strands between the blocks 15 and 21, consequently the load on the surface vessel 31 is reduced by this mechanical advantage ratio.

In the embodiment of FIG. 2 is illustrated the emplacement of an offshore oil drilling or production structure which is fabricated onshore, set in place on the bottom of the sea and secured in place by driving piles at the foot of the structure. The structure 40 includes a base 41, resting on the sub-soil 12. From base 41 extend upwardly generally upright supports 42 and 43 which pass upwardly through the water 13 to a platform 44 above the surface 32. The structure is braced by vertically-spaced horizontal members 45, 46 and 47, extending between the upright members 42 and 43. Various diagonal supports 48 also serve to brace the structure.

In FIG. 2 may be seen a previously emplaced pile 25 which has been driven through an aperture 49 in base 41 into sub-soil 12. A collar 50 tightly secured around the upper end of pile 25 against the upper surface of base 41 secures the structure to the pile.

Through another aperture 51 through the other side of base 41, a pile 10 is being driven. To a clamp 14 is attached a chain 52. The latter extends downwardly from clamp 14 along the side of the pile 10 to a pulley 53 secured to base 41. From this pulley the chain extends generally horizontally to a second pulley 54 also secured to base 41 near the center of the structure. From pulley 54, the chain extends upwardly through water 13 and through an aperture 55 in platform 44. After passing through releasable gripping jaw 56, the chain passes to a wind-up drum 57. Jaw 56 is attached to the piston rod of hydraulic cylinder 59 supported on platform 44 by legs 58 above aperture 55. Operation of the cylinder upwardly exerts an upward pull on the chain as it passes from the winch to pulley 54 and a downward pull on pile 10 at collar 14. When pile 10 has been driven into the sub-soil to the desired point, it may also be secured by a collar like the collar 50 on pile 25.

It should be appreciated that in the preceding two embodiments, the means chosen for anchoring the pulleys may be freely varied. The lower pulleys may be secured to any fixed point or member having the requisite holding power. Any desired combination and number of pulleys may be employed. Also the chain or cable may be drawn upwardly by any means. However, when the cable or chain is drawn upwardly by a fluid actuated piston and cylinder combination mounted on a
barge, platform or elsewhere, and the piston and cylinder combination are provided with releasable means for coupling it to the chain or cable, long lengths of chain or cable may be pulled in increments of length corresponding to the stroke of the piston. Also, the suction anchor 23 may be used to hold down the structure 40 by means of block and tackle 15, 17, 19, 21 and a clamp 14.

FIG. 3 discloses application of the force as a downward push on the pipe. The drawing shows the pile 10 already partially emplaced with its tip 11 embedded in subsoil 12. The remainder of pile 10 extends upwardly through water 13, breaking through the water’s surface 32 in a slot or well 60 provided in a floating barge 61. The barge is held in place radially and vertically relative to the pile by anchor lines 62, 63, anchors 64, 65, and other anchors and lines as required.

In order to conserve space in the drawing the water depth, anchor lines 62, 63 and pile 10 are fore-shortened. In order that the slot or well 60 and means for pushing downwardly on the pile may be better seen, a portion of the barge around the slot or well 60 has been broken out in the drawing. Within the broken out portion of the drawing is a releasable clamping collar 66 which may be squeezed together or released by operation of a fluid actuated cylinder and piston combination 67. A plurality of pile-pushing cylinder and piston combinations 68, 69 are secured to clamping collar 66 at spaced points around the pile 10. The opposite ends of cylinder 68, 69, are supported by generally upright frameworks 70 and 71 erected upon the upper surface of the barge.

In this embodiment, the required soil-deforming force is applied by releasing clamping collar 66, retracting cylinders 68, 69, gripping the pile with clamping collar 66 by energizing cylinder 67 and actuating cylinders 68 and 69 to extend them. In this manner, a portion of the weight of barge 61 is transferred to pile 10. If desired, water may be pumped into the barge to increase the force exerted on the pile, or fixed ballast may be used.

After pile tip 11 has been pushed some distance further into sub-soil 12, cylinders 68 and 69 may be retracted, gripping collar 67 being released so that it can again grip the pile, this time at a position somewhat closer to the top of the pile. The operation may be carried out repetitively until the pile has penetrated the sub-soil to the desired extent.

It should be noted that if impulsive or vibratory forces are superimposed upon the static force by means of a hammer or vibrator, the barge mass can be decoupled from the pile during downward motion of the latter, if efflux from the cylinder on the low-pressure side of the piston is not impeded.

FIG. 4 discloses one example of an anchoring means suitable for use in the same manner as anchor 23 of FIG. 1. This suction anchor includes a base 80 having a peripheral, downwardly extending rim 81 adapted to penetrate the sub-soil 12. Within and secured to rim 81 is a guide screen 82 which is spaced downwardly from the underside of base 80 to provide a suction chamber 83. A differential pressure pump 84 is also mounted in base 80 with its suction port within chamber 83. In order to reduce the opportunities for hydraulic short-circuiting from the pump outlet around the outside of rim 81 and back into suction chamber 83, an elasto-meric pressure skirt is secured around the periphery of base 80 extending generally horizontally and outwardly from the base in all directions. When pump 84 is energized, a portion of the ambient hydrostatic head is employed to provide firm anchoring to the subsoil 12.

An analysis of the operation of hydrostatic anchors reveals that they are subject to two fundamental failure mechanisms. One limit is imposed by the soil’s hydraulic punch-through stress, that is, resistance to hydraulic wash-outs or short-circuits resulting from the combination of pressure gradient and associated percolation-leakage flow produced by the differential pressure pump 84. The second limitation is the tensile pull-out strength of the soil clumped around the base at some isobaric fraction of the differential pressure across the base. Both of these limits may be extended by employing an evacuated well point, similar to that disclosed in U.S. Pat. No. 2,895,301, Casagrande et al., July 21, 1959. A well point may for instance be a pipe having porous walls or having screened perforations throughout its length and with gravel packing inside. Use of a sub-surface well point decreases the differential pressure gradient by increasing the percolation leakage path so as to result in an overall increase in the hydraulic punch-through resistance of the soil. At the same time, a larger clamp of soil tends to break out with the anchor upon failure, thus adding the weight and shear resistance of that mass of soil to the anchor’s pull-out force.

The preferred embodiment of the suction anchor used with the invention includes means for driving and retrieving such well points. A generally upright guide and support member 85 is secured to the base 80. Any type of suitable driver 86 is mounted on guide member 85 in a manner permitting vertical sliding movement of the driver relative to the guide member. This driver may for example be an electro-hydraulic servo vibrator or hydraulic hammer type driver. On the top of guide member 85 is an apertured cap plate 89 in which are mounted upper pulleys 87 and 88. Lower pulleys 90 and 91 are mounted at the lower end of vertical guide 85. These pulleys together with wire 92 and remote controlled bi-directional winch 93 cooperate to pull upwardly or downwardly upon driver 86 as required.

The well point 98 is secured to the driver 86, and passes through the base 80 and screen 82 via a packing box 95 provided with scraper rings or an impermeable boot. A flexible hose 96 is interconnected between the interior of the well point and a suction tap on pump 84 provides a means for generating a differential pressure between the hydrostatic head in the sub-soil and the interior of the well point at the lower end of the well point.

The suction anchor is connected with a vessel or other floating object at the surface by a cable 99 connected to the upper end of the vertical guide and support member 85. In or along cable 99 run various electric power, and control cables which disperse from junction box 100. Cable 101 operates pump 84. Cable 102 operates driver 86. Cable 103 operates the bi-directional winch 93. Hydraulic or pneumatic power and controls may of course be substituted.

In normal operation, the anchor is sent to the bottom with the well point 98 retracted. When the suction anchor has reached the bottom, pump 84 is energized to hold the anchor firmly in place. With the bi-directional winch 93 and wire 92 exerting a pulldown on driver 86, the driver is energized to force well point 98 into sub-
soil 12 until its downward motion is arrested by collar 97. Evacuation of the well point via flexible hose 96, combined with the differential pressure generated across the screen 82 extends the differential gradient influence of the suction anchor deep into the ground as indicated by the isobaric lines 104 in FIG. 1. Thus a very large anchoring force is provided. It should be understood also that each suction anchor may be provided with a plurality of well points, the driver being indexable to drive or withdraw the well points in sequence.

This anchor may be used for example as a fixed point for the attachment of a lower pulley of a block and tackle set as shown in FIG. 1, the pulley being secured for instance to the base 86 of the suction anchor. The anchor may also be used for anchoring a barge, such as the barge 61 of FIG. 3, or for any other desired purpose. When it is desired to move or remove the anchor, the winch 93 is energized to provide an up-pull on driver 86 while the latter is operated to assist in withdrawing well point 94 from the subsoil. Pump 84 is deenergized. Then, the anchor may be hauled to the surface or moved to a different location with the aid of cable 99.

The steadily applied force may constitute the sole force employed to drive a pile as illustrated in FIGS. 1 through 3. However, the use of a steadily applied force of the requisite magnitude substantially enhances the operating efficiency of pile drivers of the type which depend upon repetitive decelerations of a driving mass for their operation. Typical of such drivers are steam driven hammers and more preferably water-hammer drivers. In general, the latter are devices in the form of a long tube, coupled to the pile and having means to quickly stop a flow of liquid in the tube. The input energy is in the form of fluid flow in the tube. When the flow is suddenly stopped, its momentum creates high-powered mechanical impulse and hydraulic pressure waves of relatively high magnitude which propagate at speeds approaching that of sound in the fluid. In effect, the action is that of a fluid spear or ram.

Water hammer drivers can be fabricated in a wide variety of configurations, one illustrative example of which is shown in FIGS. 5 and 7 hereof. FIG. 5 represents a configuration of a pile 10 driven underwater into the ground 12 by a top-mounted hammer. The pile 10 is securely fastened to the hammer 123 by a coupling means 122. This coupling 122 may take the form of simply bolted flanges or a more sophisticated mechanical clamping arrangement similar to the scroll or pneumatically-operated machine tool lathe chucks which are well-known and will not be described further. The pile hammer 123 in the present case includes hammer tube 124, made of flanged sections of heavy-walled tubing bolted together and contains a shock-mounted electric motor 125 - hydraulic pump 126 combination at its bottom. The pump 126 evacuates the water out of the hammer tube 124 through a center-mounted pipe 127 discharging vertically out its top. The pump 126 axially supports the discharge pipe 127 or, in other configurations, vice versa. On the topmost section of the water hammer tube 124 is mounted the fast-opening water control valve 128, and its pneumatically operated actuator 129. When open, valve 128 freely admits water from the surrounding body of water through the valve body and its inlet 132 into hammer tube 124. A wire rope sling 130 supports the entire assembly from the surface and also conveys the power and control harness 133 thereto.

The design of the water control valve 128 may be such that rapid opening thereof is aided by the force generated by the ambient hydrostatic head acting on the valve. In order to prevent the inrushing water from exerting any drag forces on the pump 126 and motor 125 assembly, the liquid level is controlled to prevent the draw-down of water to the pump level. The casings of the pump, motor and discharge pipe should be made strong enough to withstand the resulting water hammer pressure. When required, the motor-pump-discharge pipe assembly can be made free-floating and mechanically shock-isolated axially from the water hammer tube by a lower compression spring (not shown) which supports the static air weight of the motor-pump-pipe assembly and an upper compression spring (not shown) which helps the gravity return of the pump assembly to its normal mid-position. A hydraulic type shock absorber (not shown) can be used to provide viscous damping to reduce oscillations. Further shock resistance can be provided by making the motor-pump critical components neutrally buoyant in their respective liquid by means of low density construction materials and high density liquids incorporated in their respective frames. Motor conductors and control cables pass from the surface to the motor 125 and valve 128 through the water-tight power and control harness 133.

When the pile is of sufficient length and diameter, and also to facilitate the handling of long assemblies, the hammer tube 124 may be located internally within the pile as shown in FIG. 6, using any internal coupling, such as that (142) shown in FIG. 7. This permits incremental upward repositioning of the hammer as the pile 10 is driven into the bottom 12. It also permits coupling of the driver to the pile at a position which is closer to the subsoil 12 than the top of the pile, giving an improved driving action. Concentricity alignment rings 152 may be secured to each water hammer tube flange joint as shown in FIG. 6.

To secure the hammer within the pile high pressure fluid is fed into the lower cylindrical cavity 153 of the pile coupler through port 154, FIG. 7. This flow causes the cylinder frame 155 to move downward over the piston 156. The piston shaft is secured to the base 157 that is bolted to the bottom flange 148 of the water hammer tube 124. When the cylinder frame 155 moves downward it creates a toggle action in the multiplicity of links 158. The resultant mechanical advantage varies as the cotangent of the angle between the link and the radial normal. Consequently, hard-tooth shoes 159 slide radially outward in T slot guides in the base 157 and bite into the pile walls. Simultaneously, the fluid in the upper cylindrical cavity 160 is exhausted through port 161. 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 interchangeable by control valve action. The compression spring 162 in the upper cylinder 160 retracts the entire mechanism when the air pressure is off. This pile coupler also can be used in the end-drive configuration of FIG. 5.

When the wall of the pile 10 is of sufficient internal collapse pressure strength then it itself can assume the function of the water hammer tube 124 in FIG. 6. The
FIG. 6 assembly would be modified so that the pile coupler of FIG. 7, configured to include a pressure-sealed driving flange, would be located between tube 124 and control valve 128.

Any other design of water-hammer driver may be used in the present invention. Included are those in which evacuation of the water is accomplished by a piston moving in the tube 124 or by condensable vapors injected into or generated within the tube. In such cases, a valve is not essential to start the flow of liquid in the hammer tube. Alternatively, the water hammer driver may be of the type in which the hammer tube remains flooded throughout its operating cycle, a fast-acting valve closing periodically to momentarily stop a flow of liquid in the tube. When operating with flooded tube drivers, the fast acting valve may be "tuned" or its closure may be controlled for instance by a feed-back circuit to provide resonant operation. In either case, means such as baffles or pressure release means may be provided in the tube to control the intensity of the water hammer pulses and/or to provide rotational movement. Thus, operation of the water-hammer may be tailored as desired to match the characteristics of the pile, sub-soil and other driving conditions.

The operating cycle of the illustrated hammer includes a relatively slow-water evacuation phase and a relatively fast power stroke. The evacuation period, depending upon the water-tube volume and pumping rate, ends upon the actuation of a liquid level switch (not shown) in tube 124 which controls opening of the water control valve 128. However, since the power period may be of the order of one second or less, the electric motor 125 driving the water-evacuating pump need not be shut down and restarted for each hammer cycle. Of course, the elevation of the liquid level switch may be compensated for the water level draw-down during the driving period.

FIG. 8 illustrates the driving of a pile using a combination of a steadily applied force sufficient to appreciably deflect the subsoil and superimposed water hammer driving pulses. In the drawing, the pile 10 is already partially embedded in the sub-soil 12 of a body of water 13. The driver 123 of FIG. 5 is secured to the top of pile 10 by coupler 122. To a clamp 14 are attached cables 19 and 20 extending downwardly to a lower pulley 21 and suction anchor 23 on left side and to a remote controlled winch 180 and suction anchor 181 on the right. These suction anchors are both provided with well points 94 as in the FIG. 4 anchor embodiment.

On a barge 31 floating upon the surface 32 of water 13 above pile 10 is a winch 29. Portion 27 of cable 19 extends downwardly from the winch through the water and through the pulley 21. That pulley and the winch 180 are situated at fixed points defined by suction anchors 23 and 181. By operation of the winches, cable portion 27 is drawn upwardly while cable 20 and the remainder of cable 19 are drawn downwardly. Simultaneously, driving pulses are generated in the water hammer driver 123. Thus, the pile 10 is pulled and impulsively driven downwardly into the soil.

Cables 19 and 20 may, if desired, be attached to clamp 14 through springs 182 and 183. Normally, the winches are operated to keep the cables tight and free from slack, or at least to take up before the next driving pulse — any slack that becomes available during downward movements of the pile. Springs are perhaps more useful when using chains than with cables, as wire rope cables ordinarily have enough elasticity to remain taut if the take-up of the winch momentarily lags behind the downward progress of the pile. Virtually any vibratory or impulsive driver may be used with a steadily applied soil deflecting force applied with any suitable means. For instance the driver may be situated above or below the water surface, atop, within or alongside the pile, or with the pile itself constituting part of the driver, while applying the soil deflecting force in any of the various ways illustrated herein. However, the best mode of practising the invention is to apply the soil deflecting force with a wire-rope block and tackle and to apply impulsive force with a water hammer. If the water is reasonably deep, e.g., more than 200 feet deep, it is considered best to employ a submerged water hammer able to draw upon the hydrostatic head, and, insofar as possible, to couple the water hammer to the pile at a point which is closer to the sub-soil than to the top of the pile.

It is to be understood that the steadily applied force referred to herein is in addition to the weight of the pile itself, and is much greater than the preloads which would be considered appropriate in vibratory driving practice. Thus, when vibrations are superimposed on the steady soil-deforming force, said steady force will be at least 200% of the peak force generated by the vibration and will deform the soil to at least about half, more preferably to about 80% and most preferably to about the equivalent of full ground quake. Full ground quake is generally considered to be about 0.1 inch.

Because of the steadily applied force, at least a significant portion of the reversible elastic deformation of the soil is eliminated as a factor in the operation of the driver. It is no longer necessary for the driver to repetitively supply the energy required for the elastic deformation of the piles and soil which, in spite of its reversible character, cannot be utilized and therefore is wasted. Consequently, a greater portion of the power of the driver is therefore available for driving than would be available in the absence of the soil-deforming force. Moreover, when the force is applied by chain or wire rope cables, rather than a static deadweight, the application of such force does not result in a large increase in the driven mass, e.g., the weight added can be less than one-fourth of the force applied. Accordingly, as can be seen from a reconsideration of the prior discussion of driving efficiency, the use of chain or cables to provide the requisite force increases the driven mass only slightly, thereby providing a much higher energy transfer efficiency than would be obtained if the force were provided by a deadweight coupled to the pile. Additional benefits may be obtained when the driver is a water hammer type, as such hammers offer the longer driving impulse and greater driving power at a lower overall weight. This in turn favorably affects driving efficiency. Moreover, since the driving mass of such drivers is water which can be conveniently drained from the apparatus during handling (as opposed to the metal hammer which cannot) and be removed from the conventional steam hammer every time it is lifted (by a crane) water hammers offer the possibility of both improved handling during storm conditions and higher driving power.

The driver, including a water hammer driver, may be secured to the pile above the surface of the water when the pile is sufficiently tall and if the water hammer driver includes a water reservoir which is preferably
pressurized. However, significant advantages are obtained with the evacuated tube water-hammer driver if such is situated below the surface of the water. Then it may draw water from the surrounding body of water, thereby using to advantage the potential energy available from the hydrostatic head. The deeper the operation, the greater the amount of potential energy available. Furthermore when the pile's design length is less than the water depth, extra, otherwise unnecessary, length need not be provided for driving purposes.

Although the invention has been referred to as including the use of a "water" hammer, liquids of densities heavier and lighter than water like carbon tetrachloride or mercury may be used in the hammer tube to achieve proportionally greater or lesser mechanical impulses.

Accordingly, it is apparent that the invention is a broad one and that many changes can be made without departing from the scope of the invention.

What is claimed is:

1. A method of driving piles into soil with a vibratory or impulsive driving means adapted to subject the pile to repetitive vibrations or pulses for driving same, the improvement which comprises: subjecting the pile to a steadily applied, downwardly directed force which is at least 200% of the peak force generated by any such vibration, which substantially exceeds the incidental preload provided by the driving means and pile, and which is of sufficient magnitude to appreciably deflect the subsoil in which the pile is embedded for maintaining said soil in a deformed and prestressed condition, and driving the pile by superimposing said vibrations or pulses upon said steadily applied force, thereby reducing the amount of available driving energy which would otherwise be lost in the reversible elastic deformation of the soil and pile.

2. A method in accordance with claim 1 wherein the force is at least 200,000 pounds.

3. A method in accordance with claim 1 wherein weight added by the means applying the force is less than one-fourth of the steadily applied force.

4. A claim in accordance with claim 1 wherein said deflection is at least about 0.05 inch.

5. A method in accordance with claim 1 wherein said force is applied by pulling downwardly on a portion of the pile.

6. A method in accordance with claim 5 wherein said downward pull is applied by means attached to at least one fixed point beneath the surface of a body of water.

7. A method in accordance with claim 6 wherein said fixed point is a member anchored to the bottom of said body of water by suction.

8. A method in accordance with claim 6 wherein said fixed point is a previously emplaced pile.

9. A method in accordance with claim 6 wherein said fixed point is a portion of an off-shore structure which is to be anchored in place at least in part by said pile.

10. A method in accordance with claim 6 wherein the means for applying said force includes a chain or cable attached to said pile and extending downwardly through the water block and tackle pulley means to said fixed point and then upwardly to pulling means for exerting an upward pull on said chain or cable.

11. A method in accordance with claim 10 wherein said pulling means is a winch.

12. A method in accordance with claim 10 wherein said pulling means is a cylinder and a fluid-actuated piston.

13. A method in accordance with claim 10 wherein said pulling means is located above the surface of the water.

14. A method in accordance with claim 13 wherein said pulling means is mounted on a floating object.

15. A method in accordance with claim 13 wherein said pulling means is mounted on a portion of an offshore structure which is to be anchored in place at least in part by said pile.

16. A method in accordance with claim 1 wherein said force is applied by means pushing downwardly on a portion of the pile.

17. A method in accordance with claim 16 wherein the pushing means is attached to a floating object.

18. A method in accordance with claim 17 wherein the pushing means is secured to said floating object at least partly above the surface of the water.

19. A method in accordance with claim 16 wherein the pushing means includes a cylinder and fluid-actuated piston interconnected with means for releasably gripping said pile.

20. A method in accordance with claim 1 wherein said force is applied by a plurality of pushing and/or pulling means.

21. A method in accordance with claim 20 wherein said pushing and/or pulling means assist in bracing the pile to control its direction or penetration into the subsoil.

22. A method in accordance with claim 21 wherein said pushing and/or pulling means are the sole means for bracing the pile during at least a portion of the driving of said pile.

23. A method in accordance with claim 21 wherein the pile is braced and its direction of penetration into the subsoil is controlled at least in part by apportioning the force among said pushing and/or pulling means.

24. A method in accordance with claim 1 wherein said force is at least 500,000 pounds.

25. A method in accordance with claim 1 wherein said force is sufficient to produce a deflection of about 0.1 inch in the subsoil.

26. A method in accordance with claim 1 wherein said driving means is an impulsive driving means and said pulses are liquid hammer driving pulses.

27. A method in accordance with claim 1 wherein said force is applied by pulling downwardly on a portion of the pile.

28. A method in accordance with claim 27 wherein the means for applying said force includes at least one chain or cable interconnected with said pile and extending downwardly, said chain or cable being pulled downwardly.

29. A method in accordance with claim 27 wherein the means for applying said force includes a chain or cable attached to said pile and extending downwardly through the water by block and tackle pulley means to said fixed point and then upwardly to pulling means for exerting an upward pull on said chain or cable.

30. Apparatus including a pile which is embedded in but not yet fully emplaced in the subsoil of a body of water, force applying means including at least one chain or cable connected to said pile above the subsoil and extending downwardly from the point of attachment for subjecting the pile to a steadily applied down-
wardly directed force of at least 200,000 pounds, exclusive of the weight of the pile itself, the weight of said force applying means being less than one-fourth the magnitude of said force.

31. Apparatus in accordance with claim 30 wherein said pile is coupled to an impulsive or vibratory pile driving means, said force-applying means including a floating object and a means for transferring at least a portion of the weight of said object from the water to said pile and means for decoupling the mass of said object from said impulsive or vibratory pile driving means.

32. A method in accordance with claim 26 wherein said liquid hammer driving pulses are generated with water from a body of water in which the pile is at least partly submerged.

33. In a method of driving piles into soil with vibratory or impulsive driving means adapted to subject the pile to repetitive vibrations or pulses for driving same, the improvement which comprises subjecting the pile to a steadily applied, downwardly directed force which is at least 200% of the peak force generated by any such vibration, which substantially exceeds the incidental preload provided by the driving means and pile, and which is of sufficient magnitude to deflect the subsoil in which the pile is embedded to at least about half the equivalent of full ground quake for deforming and prestressing said soil, and driving the pile by superimposing said vibrations or pulses upon said steadily applied force, thereby reducing the amount of driving energy which would otherwise be lost in the reversible elastic deformation of the soil and pile.

34. In a method of driving piles into soil with vibratory or impulsive driving means adapted to subject the pile to repetitive vibrations or pulses for driving the same, the improvement which comprises: pulling downwardly on a portion of said pile to apply thereto a steadily applied, downwardly directed force which is at least 200% of the peak force generated by any such vibration, which substantially exceeds the incidental preload provided by the driving means and pile, and which is of sufficient magnitude to appreciably deflect the subsoil in which the pile is embedded for maintaining said soil in a deformed and prestressed condition, and driving the pile by superimposing said vibrations or pulses upon said steadily applied force, thereby reducing the amount of driving energy which would otherwise be lost in the reversible elastic deformation of the soil and pile.

35. A method in accordance with claim 34 wherein the means for applying said force includes at least one chain or cable interconnected with said pile and extending downwardly, said chain or cable being pulled downwardly.

36. In a method of driving piles into the floor of a body of water with an impulsive driving means adapted to subject the pile to repetitive pulses for driving same, the improvement which comprises: subjecting the pile to a steadily applied downwardly directed force which substantially exceeds the incidental preload provided by the driving means and pile, which is of sufficient magnitude to appreciably deflect the subsoil in which the pile is embedded for maintaining said soil in a deformed and prestressed condition, and which is applied by means having a weight of less than one-fourth the force applied, and driving the pile by superimposing liquid hammer-driving pulses upon said steadily applied force, thereby reducing the amount of driving energy which would otherwise be lost in the reversible elastic deformation of the soil and pile.

37. In a method of driving piles into the floor of a body of water with impulsive driving means adapted to subject the pile to repetitive pulses for driving same, the improvement which comprises: pulling downwardly on a portion of the pile with chain or cable for applying a downwardly directed force which substantially exceeds the incidental preload provided by the driving means and pile, and which is of sufficient magnitude to deflect the subsoil in which the pile is embedded to at least about half the equivalent of full ground quake for deforming and prestressing said soil, and driving the pile by superimposing water hammer driving pulses upon the force applied by said chain or cable, said water hammer pulses being generated with water from said body of water, and thereby reducing the amount of driving energy which would otherwise be lost in the reversible elastic deformation of the soil and pile.

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