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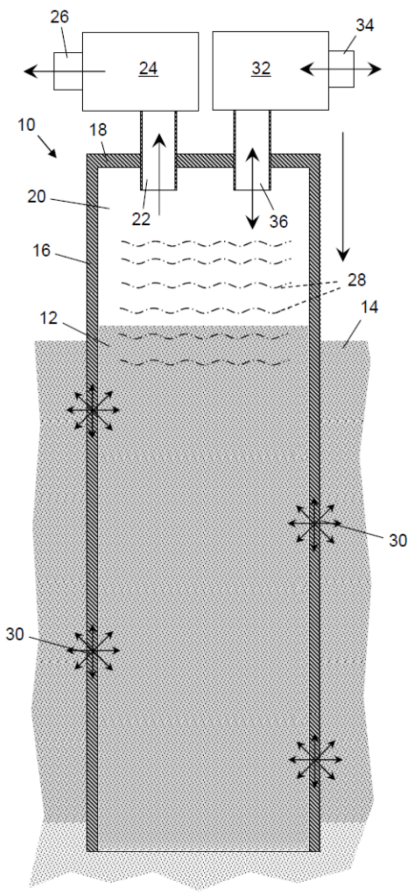
(57)	Abstract	

An underwater pile foundation comprises a pump in fluid communication with an internal chamber of the pile to pump water out of or into the chamber. This reduces or increases the pressure of water in the chamber relative to ambient pressure of water outside the chamber during installation or removal of the pile. While that pumping phase is ongoing, and potentially before or after that pumping phase, a pressure variator in fluid communication with the chamber imparts oscillations in the pressure of the water in the chamber. The resulting pressure waves in water within the chamber reduce resistance to movement of the pile relative to soil in which the pile is embedded



Installation and removal of subsea foundations

This invention relates to subsea foundations that are designed to be embedded into seabed soil, for example suction foundations. The invention particularly addresses the challenges of improving penetration of such foundations into the seabed on installation or easing their removal from the seabed on decommissioning.

Suction piles - also known in the art as suction anchors, suction cans, suction caissons or suction buckets - are commonly used in the renewable energy industry and in the oil and gas industry to anchor large marine installations to the seabed. To do so, they are designed to engage soft seabed soil that typically comprises marine sediments such as sand or soft clay.

A suction pile is usually fabricated from steel and typically comprises a deep cylindrical skirt defining an open-bottomed hollow straight tube. The skirt may be several metres in length, for example ten metres. A bottom portion of the skirt engages the seabed soil by friction or cohesion upon being embedded axially into the soil. The top of the skirt is closed by a top plate. A suction chamber is defined between the top plate, the skirt and the seabed soil trapped within the embedded skirt.

Installation of a suction pile involves firstly allowing the pile to self-penetrate under its own weight into the seabed and secondly, after a short period of settlement, pumping water out of the resulting suction chamber to create a pressure differential. For this purpose, the top plate is penetrated by a suction vent or port through which water can be pumped out of the suction chamber. The resulting underpressure in the suction chamber promotes engagement of the suction pile with the soil.

Specifically, when a suction pile is landed on the seabed in an upright orientation, the skirt embeds partially into the seabed soil under the self-weight and momentum of the pile. Self-penetration of the pile ends when resistance to downward sliding movement of the skirt relative to the soil balances the weight of the pile. The soil within the embedded skirt closes the bottom of the pile to create the suction chamber.

When seawater is subsequently pumped out of the suction chamber, underpressure in the chamber draws the top plate toward the seabed as the chamber contracts under external hydrostatic pressure. This forces the skirt to sink further into the soil, hence effecting fuller engagement of the suction pile with the soil to increase load-bearing capacity. Thus, suction overcomes the resistance of friction or cohesion to force the skirt deeper into the seabed, hence enabling the pile to resist forces that will be applied after installation by equipment subsequently anchored to or supported on the pile.

Once embedded into the seabed soil, a suction pile can serve as an anchor or as a support for various types of subsea or surface equipment. For example, suction piles may be used to sustain tensile loads when mooring or tethering a platform, a surface vessel or a buoy. Suction piles are also commonly used to sustain compressive loads when supporting the weight of a structure such as a manifold or a wind turbine.

US 2002/0122696 typifies a pumping operation performed by an ROV docked to a subsea suction pile. However, pumping takes time that is precious in offshore operations, bearing in mind the high operational cost of support vessels and often limited weather windows. Thus, larger pumps may be used or additional pumps may be used in combination, as disclosed in KR 101178789.

WO 2005/087393 exemplifies how vibrations can be used to assist drilling. Analogously, mechanically vibrating a suction pile to ease its installation is also known. For example, CN 104652502 discloses coupling a vibrating top plate to the top of a suction pile so that vibrations are applied after suction. Conversely, mechanical vibrations are proposed in KR 20150105085 to excite a resonant response in a suction pile for easing removal of the pile as water is pumped into the suction chamber of the pile.

In EP 1881113, suction is combined with dredging inside a pile whereas CN 110670620 teaches the addition of ballast weight to improve penetration of a pile. In other prior art documents, features are added to the bottom rim of the skirt to ease penetration of a pile. For example, the bottom rim of the skirt can comprise teeth as disclosed in the suction pile of KR 101199348, the better to cut into the soil.

In the tubular pile of CN 103088820, conventional hammers drive the pile downwardly aided by oscillating water jets projected from nozzles in a bottom rim of the skirt, which loosens the soil to ease penetration. There is no teaching to vary the water pressure. Also, the pile of CN 103088820 is for installation on land and does not employ suction.

Similarly, in the subsea suction pile of WO 2007/115573, an attachment along the bottom rim of the skirt comprises chambers with nozzles through which pressure and/or flow of a fluid medium can be controlled individually to reduce the shear strength of the soil adjacent to the rim and/or the skirt. This allows the speed of penetration and the inclination of the pile to be controlled. There is a suggestion in WO 2007/115573 that the flow or pressure of fluid in the chambers could be pulsed but any such fluctuations would only affect the bottom of the skirt, buried in the soil, and not the volume of water in the chamber within the pile, especially above the soil surrounded by the skirt of the pile.

WO 95/20075 takes the alternative approach of providing an external low-pressure reservoir on top of the pile to aid penetration by reducing fluid pressure within the pile in a sudden, shockwise manner. The suddenness of the pressure drop within the pile mitigates water inflow through the bottom of the pile. Hydrostatic overpressure exerted on the top of the pile therefore drives the pile downwardly, applying a shock load in a manner akin to a mechanical piledriver.

Specifically, WO 95/20075 proposes that water is pumped out of the reservoir and into the surrounding sea over a period of time, apparently of several seconds or minutes, to create a low-pressure volume outside the pile. Then, a valve is opened rapidly to effect fluid communication between the reservoir and the interior of the pile, which causes water to rush upwardly from within the pile and into the reservoir to equalise pressure. The valve can then be closed and water can be pumped out of the reservoir again to prime the system for another pile driving cycle. The pumping and release operation can be repeated as often as necessary to drive the pile to the required depth with successive sudden reductions of internal pressure.

By emulating the action of a piledriver, WO 95/20075 suffers from various drawbacks. For example, the suction pile must be made robust enough to withstand repeated shock loadings. Also, installation becomes a stepwise, intermittent process in which penetration steps are separated by lengthy pumping intervals to prime the system for the next step. As no suction is applied to the interior of the pile during the pumping intervals, penetration is interrupted during those intervals. It is also unhelpful that the momentum of the upwardly-rushing water acts against the downward impulse of transient hydrostatic overpressure.

Against this background, the invention resides in a method of reducing resistance to movement of a pile relative to soil during installation or removal of the pile underwater. The method comprises: pumping water out of or into an internal chamber of the pile to reduce or to increase a level of pressure of water in the chamber relative to ambient pressure of water outside the chamber; and while that pumping is ongoing, imparting additional oscillations in the pressure of the water in the chamber.

The oscillations may be employed to vibrate a wall of the pile in contact with the soil and/or to drive oscillatory vertical movement of the pile relative to the soil, for example by cyclically expanding and contracting the chamber in response to the oscillations. The oscillations may also be employed to drive pressure waves through the water in the chamber, for example downwardly within the chamber, to impact against soil in the chamber.

The oscillations may be imparted by oscillating flow passing through a pump that pumps the water or preferably by a pressure variator that is distinct from such a pump. Fluid communication with the chamber may be effected through a common port shared by the pump and the pressure variator, with the pump and the pressure variator being arranged in series or in parallel. A fluctuating output of the pressure variator may be directed into the pump as a motive fluid to drive oscillatory flow in the pump

Fluid communication with the chamber could instead be effected through separate ports, at least one of those ports communicating with the pump and at least one other of those ports communicating with the pressure variator.

The pressure variator and the pump may be disposed outside the chamber or the pressure variator may be enclosed within the chamber. There may be fluid communication between the pressure variator and the water outside the chamber.

When installing the pile, pressure within the chamber may be maintained continuously below the ambient pressure of the water outside the chamber. Alternatively, the oscillations can generate a series of pressure pulses within the chamber, each pulse being above the ambient pressure of the water outside the chamber and the pulses being separated by a period in which pressure within the chamber is below that ambient pressure.

The oscillations may, for example, have a frequency of from 5Hz to 50Hz. They may follow a waveform in which pressure varies continuously or with step-change transitions. Any of the following parameters may be varied during installation or removal of the pile, namely: frequency of the oscillations; amplitude of the oscillations;

and/or an average level of water pressure in the chamber about which the water pressure oscillates. Any of those parameters could increase in accordance with depth of penetration of the pile into the soil.

Correspondingly, the inventive concept also embraces an underwater pile that comprises: a pump in fluid communication with an internal chamber of the pile to pump water out of or into the chamber during installation or removal of the pile, thus reducing or increasing a level of pressure of water in the chamber relative to ambient pressure of water outside the chamber; and a pressure variator in fluid communication with the chamber for imparting oscillations in the pressure of the water in the chamber.

The pump could, for example, be a jet pump, in which case an outlet of the pressure variator could communicate with a motive fluid inlet of the pump.

The pump and the pressure variator may be in fluid communication with the chamber through at least one port. The or each port may open downwardly into the chamber in opposition to soil that closes a lower end of the chamber.

The pressure variator could be a positive-displacement pump, for example comprising a piston or other reciprocating element that is movable to draw water from the chamber and to expel water into the chamber in alternation.

In summary, the invention exploits the influence of cycled internal pressure on resistance to installation or retrieval of a suction pile. The principle is to apply continuous suction and, in addition, an oscillating pressure. For example, it is possible for pressure variator such as an auxiliary pump to apply a pressure pulse to create a short overpressure in the suction pile. The pressure pulse may be applied while water is still being pumped out or while pumping out is briefly interrupted.

Implementations of the invention may require at least two different vents or ports in the top plate of the pile but a single port could potentially be used instead. Two or more pumps could be used, at least one pump to apply continuous suction and at least one other pump to apply oscillating pressure. Alternatively, if powerful enough, one pump could be used both to pump out water and to create an oscillating pressure within the suction pile. The or each pump, or at least a pump effecting oscillation of pressure, could be carried by an ROV.

The invention provides a beneficial alternative to vibro-hammers and pin piling and reduces installation risks for suction piles to be embedded in sand, which is particularly relevant for wind turbine foundations. An additional advantage in sandy soils is partial liquefaction around and beneath the skirt of the pile, so that the pile sinks more easily. The invention can also be used with benefit when decommissioning a foundation and when installing a foundation in clay soils.

Embodiments of the invention implement a method to penetrate underwater foundations into soft soils, the method comprising: providing a foundation such as a suction foundation; performing a first phase of penetration under self-weight; and performing a second phase of penetration by suction, wherein in addition, during this second phase, vibrations are generated inside the inner volume of the foundation. Vibrations may, for example, be generated as water pressure pulses with a frequency of vibration in a range of from 5Hz to 50Hz.

Embodiments of the invention also provide a suction pumping system for installing a subsea foundation such as a suction foundation, the system comprising a main suction pump and a pressure-varying means, or a pressure variator, for varying pressure of water inside the foundation continuously, cyclically or intermittently. The pressure variator may be active simultaneously with the main suction pump and may, for example, be a second pump, or a piston, and can be combined with the main suction pump in series or in parallel. The second pump may be in fluid communication with an outlet of the main suction pump and may be in fluid communication with an inner volume of the suction foundation.

In another approach, the main suction pump may be a jet pump in which the flowrate and/or pressure of a driving fluid can be varied, for example by supplying the driving fluid from a variable pump. The second pump and/or the main suction pump may be controlled to deliver water pressure pulses or oscillating suction with a frequency in the range of 5Hz to 50Hz.

Thus, an underwater foundation of the invention comprises a pump in fluid communication with an internal chamber of the foundation to pump water out of or into the chamber. This reduces or increases the pressure of water in the chamber relative to ambient pressure of water outside the chamber during installation or removal of the foundation. While that pumping phase is ongoing, and potentially before or after that pumping phase, a pressure variator in fluid communication with the chamber imparts oscillations in the pressure of the water in the chamber. The resulting pressure waves or other perturbations of water within the chamber reduce resistance to movement of the foundation relative to soil in which the foundation is embedded.

In order that the invention may be more readily understood, reference will now be made, by way of example, to the accompanying drawings in which:

Figures 1 to 7 are schematic sectional side views of suction piles comprising various pumping arrangements of the invention;

Figures 8a to 8d are a sequence of schematic representations of a piston-based pressure variator for use in the invention;

Figures 9 to 12 are graphs of pressure within a suction chamber of a suction pile during installation or removal of the pile in accordance with the invention, plotted against time; and

Figures 13 and 14 are graphs of pressure within a suction chamber of a suction pile during installation or removal of the pile in accordance with the invention, plotted against depth of penetration of the pile into seabed soil.

Figures 1 to 7 show various suction piles 10 equipped with pumping arrangements of the invention. The piles 10 are shown during installation in a suction phase after initially being partially embedded by momentum and self-weight into the soil 12 of the seabed 14.

Each suction pile 10 comprises a tubular skirt 16 whose upper end is closed by a top plate 18, defining a suction chamber 20 in the space within the skirt 16 between the top plate 18 and the soil 12 surrounded by the skirt 16. Water occupies the suction chamber 20 and fills pores between particles or grains of the soil 12 within the skirt 16, in fluid communication with the suction chamber 20.

As is conventional, a wall of each suction pile 10 is penetrated by at least one suction port 22 through which water is pumped out of the suction chamber 20 during the suction phase of installation. For this purpose, the suction port 22 communicates with a suction pump 24 whose outlet 26 exhausts water into the surrounding sea. Typically, valves will close the suction port 22 when the suction phase is complete and will remain closed thereafter while the pile 10 remains in service but such valves have been omitted from the drawings for simplicity.

Conveniently, the suction port 22 is located in the top plate 18 of the suction pile 10, as shown in these examples, although that location is not essential. The suction pump 24 could be mounted permanently on a suction pile 10 or could be coupled to the pile 10 temporarily during the suction phase only, for example if hosted by an ROV.

In accordance with the invention, the pumping arrangements of Figures 1 to 7 are all capable of generating pressure fluctuations, pulses or oscillations that disturb, stir or agitate the body of water within the suction chamber 20. Those oscillations are expressed in the drawings as pressure waves 28 radiating downwardly toward the soil 12 within the skirt 16, although pressure waves 28 or other perturbations could propagate in various directions within the water in the suction chamber 20.

Oscillation of fluid pressure within the suction chamber 20 tends to expand and contract the suction chamber 20 cyclically, hence generating up-and-down oscillation of the skirt 16. The pressure waves 28 also impact against the surrounding skirt 16, hence giving rise to vibrations 30 in the wall of the skirt 16 as shown in Figure 1. Oscillation or vibration of the skirt 16 reduces the effect of friction or cohesion of the soil 12 against both the inner and outer sides of the skirt 16, hence reducing resistance to downward movement of the suction pile 10.

It will also be noted that in view of its saturated, fluid consistency, the pressure waves 28 penetrate into and propagate through the soil 12 within the skirt 16 to some extent. This may disturb, agitate and liquefy or fluidise that soil 12, easing downward movement of the suction pile 10 that is driven primarily by the suction pump 24 evacuating water from the suction chamber 20.

The principle of the invention could also be applied to retrieval of a suction pile 10, in which case the suction pump 24 could be reversed to pump water into the suction chamber 20 through the suction port 22 as the pile 10 is lifted out of engagement with the seabed 14. Again, pressure waves 28 generated in the water within the suction chamber 20 oscillate and vibrate the skirt 16 and may disturb the soil 12 within the skirt 16, with the benefit of reducing resistance to upward movement of the pile 10.

In the variants of Figures 1 to 5, pressure fluctuations within the suction chamber 20 are generated by an auxiliary pump 32 serving as a pressure variator. In each of those examples, the auxiliary pump 32 is in fluid communication with ambient water through an external port 34 that enables the auxiliary pump 32 to expel and/or draw in water in successive pumping and/or suction phases of cyclical operation. However, it is not essential for a pressure variator such as an auxiliary pump 32 to communicate directly with ambient water, as some variants will make clear.

Figure 1 shows an arrangement in which the suction pump 24 and the auxiliary pump 32 communicate separately with the suction chamber 20 on parallel fluid paths. The suction pump 24 communicates with the suction chamber 20 through the aforementioned suction port 22 whereas the auxiliary pump 32 communicates with the suction chamber 20 through an auxiliary port 36.

In Figure 2, the suction pump 24 and the auxiliary pump 32 communicate with the suction chamber 20 on a common fluid path extending through the suction port 22. The common fluid path is defined by a manifold 38 that branches outwardly from the suction port 22 to communicate with the suction pump 24 and the auxiliary pump 32.

Figure 3 shows that the auxiliary pump 32 need not necessarily communicate directly with the suction chamber 20 but could instead drive, or otherwise influence, the flow of water through the suction pump 24 to create pressure fluctuations within the suction chamber 20. In this example, the suction pump 24 is a jet pump and the auxiliary pump 32 draws in and exhausts ambient water, as a motive fluid, into a motive fluid nozzle 40 aligned with a diffuser throat 42 of the jet pump. The resulting pressure drop in the diffuser throat 42 draws water from the suction chamber 20 through the suction port 22 and into the suction pump 24.

Fluctuations in the flow rate of the water injected by the auxiliary pump 32 through the motive fluid nozzle 40 generate corresponding fluctuations in the flow rate of water through the suction pump 24. Those fluctuations, in turn, create pressure fluctuations in the suction chamber 20.

In Figures 4 and 5, the suction pump 24 and the auxiliary pump 32 are in series in a fluid path extending from the suction port 22 to the ambient water. In Figure 4, the auxiliary pump 32 is upstream of the suction pump 24, hence being between the suction pump 24 and the suction port 22. Conversely, in Figure 5, the suction pump 24 is upstream of the auxiliary pump 32, hence being between the auxiliary pump 32 and the suction port 22. Thus, in Figure 4, the auxiliary pump 32 communicates with the suction chamber 20 directly whereas in Figure 5, the auxiliary pump 32 communicates with the suction chamber 20 via the suction pump 24.

The suction pump 24 may be primarily responsible for evacuating water from the suction chamber 20 during the suction phase, hence having a greater aggregate outflow than the auxiliary pump 32. However, the auxiliary pump 32 may also contribute to evacuating water from the suction chamber 20.

Figure 6 shows that a secondary pressure variator such as an auxiliary pump 32 can be omitted if the suction pump 24 itself is configured to operate cyclically, hence imparting the desired pressure fluctuations to the suction chamber 20 via the suction port 22. Thus, the suction pump 24 itself could serve as a pressure variator.

Figure 7 shows that a pressure variator such as an auxiliary pump 32 need not communicate directly with the ambient water. Indeed, the auxiliary pump 32 could be placed within the suction chamber 20 as shown, with an outlet port 44 in direct fluid communication with the suction chamber 20. In this example, the outlet port 44 of the auxiliary pump 32 faces downwardly to project pressure waves 28 toward the seabed soil 12 within the skirt 16 of the suction pile 10. The auxiliary pump 32 may use the outlet port 44 both to draw water in from the suction chamber 20 and to pump water out into the suction chamber 20. Alternatively, the auxiliary pump 32 could draw water in from the suction chamber 20 through an inlet port, not shown, before exhausting the water through the outlet port 44.

Figures 8a to 8d exemplify a positive-displacement auxiliary pump 32 that could be used in the variant of Figure 7, and potentially also in other variants of the invention. In this example, a reciprocating element such as a piston 46 driven via a crankshaft 48 draws in water from the suction chamber 20 through the outlet port 44 in a suction stroke shown in Figures 8a and 8b. The piston 46 then expels water through the outlet port 44 in a compression stroke shown in Figures 8c and 8d, before another suction stroke begins.

The graphs of Figures 9 to 12 plot the pressure of water in the suction chamber 20 on the vertical axis against time on the horizontal axis. They illustrate how a suction pump 24 and a pressure variator such as an auxiliary pump 32 can be used in combination to generate rapid oscillations in the pressure of water in the suction chamber 20 while the suction phase is ongoing. Pressure applied by the suction pump 24 and pressure applied by the auxiliary pump 32 are aggregated to result in the overall pressure 50 applied to water in the suction chamber 20.

In each of these simple examples, the output of the suction pump 24 is nominally constant whereas the output of the auxiliary pump 32 varies cyclically or is reversed periodically. With reference to Figure 6, however, it should be noted that an auxiliary pump 32 is optional and that the output of a suction pump 24 could be varied cyclically, or even reversed periodically, to serve as a pressure variator.

In Figure 9, the flow through the auxiliary pump 32 fluctuates continuously, in this example sinuously, while continuing to apply negative pressure to the suction chamber 20. The suction pump 24 also applies negative pressure, hence suction, to the suction chamber 20. The result is that overall pressure 50 oscillates continuously while remaining negative as suction is applied to the suction chamber 20 throughout.

In Figure 10, the flow through the auxiliary pump 32 again fluctuates continuously but in this case alternates between positive and negative pressure. The amplitude of the waveform relating to the auxiliary pump 32 is greater relative to the corresponding waveform in Figure 9 and relative to the plot of pressure applied by the suction pump 24 in Figure 10. This causes the overall pressure 50 to enter the positive pressure domain briefly during each cycle. Consequently, the auxiliary pump 32 generates brief pulses of positive pressure that, transiently, reverse suction to drive a pressure wave 28 into the suction chamber 20. However, the negative pressure domain, hence suction, predominates so that water continues to be evacuated from the suction chamber 20 over time.

Figure 11 shows that the frequency or wavelength of fluctuating overall pressure 50 can be varied over time. Here, this variation is driven by varying the frequency of oscillation of pressure applied to the suction chamber 20 by the auxiliary pump 32. The frequency could, for example, increase with increasing penetration of the suction pile 10 into the seabed 14.

Figure 12 shows that pressure need not necessarily fluctuate constantly or smoothly. In this example, pressure applied to the suction chamber 20 by the auxiliary pump 32, and hence also the overall pressure 50, oscillates with an angular, near-square waveform. That waveform comprises periods of constant pressure 52 alternating with sudden transitions 54. The sudden transitions 54 lend a step-change character to the waveform, increasing the intensity of the pressure waves 28 within the suction chamber 20 and enhancing their shockwave effect.

Finally, the graphs of Figures 13 and 14 plot the pressure of water in the suction chamber 20 on the vertical axis against depth of penetration of the suction pile 10 on the horizontal axis. These graphs show that pressure in the suction chamber 20, and fluctuation of that pressure, may vary in accordance with the extent to which the skirt 16 is buried in the seabed soil 12.

In Figure 13, negative pressure of water in the suction chamber 20, hence suction, is increased with increasing penetration of the suction pile 10. In this example, the increased suction is due to increasing suction applied by the suction pump 24. Pressure applied to the suction chamber 20 by the auxiliary pump 32 oscillates but in this instance the amplitude of that oscillation remains constant with increasing penetration of the pile 10. The overall negative pressure 50 applied to the suction chamber 20 therefore follows an increasing but constantly fluctuating profile as the skirt 16 of the pile 10 is buried deeper in the seabed soil 12. More generally, the flow rate at which water is pumped out of or into the suction chamber 20 during installation or removal of the pile may be varied to change the average pressure over time.

Figure 14 shows that the amplitude of fluctuating pressure applied by the auxiliary pump 32 can increase with increasing penetration of the suction pile 10. The overall negative pressure 50 applied to the suction chamber 20 therefore follows an increasingly fluctuating profile as the skirt 16 of the suction pile 10 is buried deeper in the seabed soil 12. Nevertheless, the average of the overall negative pressure 50 remains substantially constant with increasing penetration.

Many variations are possible within the inventive concept. For example, the approaches shown in Figures 13 and 14 could be combined, so that the overall negative pressure 50 applied to the suction chamber 20 follows not only an increasing profile but also an increasingly fluctuating profile with increasing penetration of the suction pile 10.

As noted previously, the inventive concept could also be applied to withdrawal or removal of a foundation pile from the seabed. In that case, it will be understood that the operation of a pump to evacuate water from the foundation could be reversed to pump water into the foundation, hence operating mainly or wholly in the positive pressure domain. It would also be possible to apply fluctuating fluid pressure within a foundation to reduce resistance to movement without necessarily applying negative or positive pressure on average over time. For example, fluctuating fluid pressure could be applied before or after a pumping phase. or in addition to or instead of a pumping phase.

Claims

1. A method of reducing resistance to movement of a pile (10) relative to soil (12) during installation or removal of the pile (10) underwater, the method comprising:

pumping water out of or into an internal chamber (20) of the pile (10) to reduce or to increase a level of pressure of water in the chamber (20) relative to ambient pressure of water outside the chamber (20); and

while that pumping is ongoing, imparting additional oscillations in the pressure of the water in the chamber (20),

characterised in that the additional oscillations in the pressure of the water in the chamber (20) are imparted via a pressure variator pump (32).

2. The method of Claim 1, comprising employing the oscillations to vibrate a wall of the pile (10) in contact with the soil (12).

3. The method of Claim 1 or Claim 2, comprising employing the oscillations to drive oscillatory vertical movement of the pile (10) relative to the soil (12).

4. The method of Claim 3, comprising driving the oscillatory vertical movement by cyclically expanding and contracting the chamber (20) in response to the oscillations.

5. The method of any preceding claim, comprising employing the oscillations to drive pressure waves through the water in the chamber (20) to impact against soil (12) in the chamber (20).

6. The method of Claim 5, comprising directing the pressure waves downwardly within the chamber (20).

7. The method of any preceding claim, wherein the pressure variator pump (32) imparting the oscillations is distinct from a pump (24) that pumps the water.

8. The method of Claim 7, comprising effecting fluid communication with the chamber (20) through a common port (22) shared by the pump (24) and the pressure variator pump (32).

9. The method of Claim 8, comprising effecting fluid communication with the chamber (20) through the pump (24) and the pressure variator pump (32) in series.

10. The method of Claim 8, comprising effecting fluid communication with the chamber (20) through the pump (24) and the pressure variator pump (32) in parallel.

11. The method of Claim 8, comprising directing a fluctuating output of the pressure variator pump (32) into the pump (24) as a motive fluid to drive oscillatory flow in the pump (24).

12. The method of Claim 7, comprising effecting fluid communication with the chamber (20) through separate ports, at least one of those ports (22) communicating with the pump (24) and at least one other of those ports (44) communicating with the pressure variator pump (32).

13. The method of any of Claims 7 to 12, wherein the pressure variator pump (32) and the pump (24) are disposed outside the chamber (20).

14. The method of any of Claims 7 to 13, comprising effecting fluid communication between the pressure variator pump (32) and the water outside the chamber (20).

15. The method of any of Claims 7 to 13, comprising enclosing the pressure variator pump (32) within the chamber (20).

16. The method of any of Claims 1 to 6, wherein the pressure variator pump (32) pumps the water to reduce or to increase the level of pressure of water in the chamber (20) and the method comprises imparting the oscillations by oscillating flow passing through the pressure variator pump (32).

17. The method of any preceding claim, performed when installing the pile (10), comprising maintaining pressure within the chamber (20) continuously below the ambient pressure of the water outside the chamber (20).

18. The method of any of Claims 1 to 16, performed when installing the pile (10), comprising employing the oscillations to generate a series of pressure pulses within the chamber (20), each pulse being above the ambient pressure of the water outside the

chamber (20) and the pulses being separated by a period in which pressure within the chamber (20) is below that ambient pressure.

19. The method of any preceding claim, comprising imparting the oscillations with a frequency of from 5Hz to 50Hz.

20. The method of any preceding claim, wherein the oscillations follow a waveform in which pressure varies continuously.

21. The method of any preceding claim, wherein the oscillations follow a waveform with step-change transitions.

22. The method of any preceding claim, comprising varying any of the following parameters during installation or removal of the pile (10): frequency of the oscillations; amplitude of the oscillations; and/or an average level of water pressure in the chamber (20) about which the water pressure oscillates.

23. The method of Claim 22, comprising increasing any of said parameters in accordance with depth of penetration of the pile (10) into the soil (12).

24. An underwater pile (10), comprising:

a pump (24) in fluid communication with an internal chamber (20) of the pile (10) to pump water out of or into the chamber (20) during installation or removal of the pile (10), thus reducing or increasing a level of pressure of water in the chamber (20) relative to ambient pressure of water outside the chamber (20); characterised in that the underwater pile comprises:

a pressure variator pump (32) in fluid communication with the chamber (20) for imparting oscillations in the pressure of the water in the chamber (20).

25. The pile (10) of Claim 24, wherein the pump (24) and the pressure variator pump (32) are in fluid communication with the chamber (20) through a common port (22).

26. The pile (10) of Claim 25, wherein the pump (24) and the pressure variator pump (32) are disposed in series.

27. The pile (10) of Claim 25, wherein the pump (24) and the pressure variator pump (32) are disposed in parallel.

28. The pile (10) of Claim 25, wherein the pump (24) is a jet pump and an outlet of the pressure variator pump (32) communicates with a motive fluid inlet of the pump (24).

29. The pile (10) of Claim 24, wherein the pump (24) and the pressure variator pump (32) are in fluid communication with the chamber (20) through respective separate ports (22, 44).

30. The pile (10) of Claim 25 or Claim 29, wherein the or each port (22, 44) opens downwardly into the chamber (20) in opposition to soil (12) that closes a lower end of the chamber (20).

31. The pile (10) of any of Claims 24 to 30, wherein the pressure variator pump (32) and the pump (24) are disposed outside the chamber (20).

32. The pile (10) of any of Claims 24 to 31, wherein the pressure variator pump (32) is in fluid communication with the water outside the chamber (20).

33. The pile (10) of any of Claims 24 to 31, wherein the pressure variator pump (32) is enclosed within the chamber.

34. The pile (10) of any of Claims 24 to 33, wherein the pressure variator pump (32) is a positive-displacement pump.

35. The pile (10) of Claim 34, wherein the pressure variator pump (32) comprises a reciprocating element (46) that is movable to draw water from the chamber (20) and to expel water into the chamber (20) in alternation.

P A T E N T K R A V

1. Fremgangsmåte for å redusere motstand mot bevegelse av en påle (10) i forhold til jord (12) under installasjon eller fjerning av pålen (10) under vann, idet fremgangsmåten omfatter:

å pumpe vann ut av eller inn i et indre kammer (20) i pålen (10) for å redusere eller øke et nivå av vanntrykk i kammeret (20) i forhold til omgivelsesvanntrykket utenfor kammeret (20); og

mens pumpingen pågår, tilføre ytterligere oscillasjoner i vanntrykket i kammeret (20),

karakterisert ved at de ytterligere oscillasjonene i vanntrykket i kammeret (20) overføres via en trykkvariatorpumpe (32).

2. Fremgangsmåte ifølge krav 1, omfattende å bruke oscillasjonene til å vibrere en vegg av pålen (10) i kontakt med jorda (12).

3. Fremgangsmåte ifølge krav 1 eller krav 2, omfattende bruk av oscillasjonene for å drive oscillerende vertikal bevegelse av pålen (10) i forhold til jorda (12).

4. Fremgangsmåten ifølge krav 3, omfattende å drive den oscillerende vertikale bevegelsen ved syklisk ekspansjon og sammentrekning av kammeret (20) som respons på oscillasjonene.

5. Fremgangsmåten ifølge hvilket som helst av de foregående krav, omfattende bruk av oscillasjonene for å drive trykkbølger gjennom vannet i kammeret (20) for å støte mot jord (12) i kammeret (20).

6. Fremgangsmåten ifølge krav 5, omfattende å rette trykkbølgene nedover inne i kammeret (20).

7. Fremgangsmåten ifølge hvilket som helst av de foregående krav, hvori trykkvariatorpumpen (32) som tilveiebringer oscillasjonene er ulik pumpen (24) som pumper vannet.

8. Fremgangsmåten ifølge krav 7, omfattende å iverksette fluidkommunikasjon med kammeret (20) gjennom en felles port (22) som deles av pumpen (24) og trykkvariatorpumpen (32).

9. Fremgangsmåten ifølge krav 8, omfattende å iverksette fluidkommunikasjon med kammeret (20) gjennom pumpen (24) og trykkvariatorpumpen (32) i serie.

10. Fremgangsmåten ifølge krav 8, omfattende å iverksette fluidkommunikasjon med kammeret (20) gjennom pumpen (24) og trykkvariatorpumpen (32) parallelt.

11. Fremgangsmåten ifølge krav 8, omfattende å rette en fluktuerende utslag fra trykkvariatorpumpen (32) inn i pumpen (24) som et drivfluid for å drive oscillerende strømning i pumpen (24).

12. Fremgangsmåten ifølge krav 7, omfattende å iverksette fluidkommunikasjon med kammeret (20) gjennom separate porter, hvor minst én av disse portene (22) kommuniserer med pumpen (24) og minst én annen av disse portene (44) kommuniserer med trykkvariatorpumpen (32).

13. Fremgangsmåten ifølge hvilket som helst av kravene 7 til 12, hvori trykkvariatorpumpen (32) og pumpen (24) er plassert utenfor kammeret (20).

14. Fremgangsmåten ifølge hvilket som helst av kravene 7 til 13, omfattende å iverksette fluidkommunikasjon mellom trykkvariatorpumpen (32) og vannet utenfor kammeret (20).

15. Fremgangsmåten ifølge hvilket som helst av kravene 7 til 13, omfattende å plassere trykkvariatorpumpen (32) i kammeret (20).

16. Fremgangsmåten ifølge hvilket som helst av kravene 1 til 6, hvori trykkvariatorpumpen (32) pumper vannet for å redusere eller øke vanntrykket i kammeret (20) og hvor fremgangsmåten omfatter å overføre oscillasjonene ved oscillerende strømning som passerer gjennom trykkvariatorpumpen (32).

17. Fremgangsmåten ifølge hvilket som helst av de foregående krav, utført ved installasjon av pålen (10), omfattende å opprettholde trykket i kammeret (20) kontinuerlig i nivå under omgivelsesvanntrykket utenfor kammeret (20).

18. Fremgangsmåten ifølge et hvilket som helst av kravene 1 til 16, utført ved installasjon av pålen (10), omfattende bruk av oscillasjonene til å generere en serie trykkpulser inne i kammeret (20), hvor hver puls er over omgivelsestrykket til vannet utenfor kammeret (20) og pulsene er atskilt med en periode hvor trykket i kammeret (20) er et nivå under det omgivende trykket.

19. Fremgangsmåten ifølge hvilket som helst av de foregående krav, omfattende å tilveiebringe oscillasjonene med en frekvens på fra 5 Hz til 50 Hz.

20. Fremgangsmåten ifølge hvilket som helst av de foregående krav, hvori oscillasjonene følger en bølgeform der trykket varierer kontinuerlig.

21. Fremgangsmåten ifølge hvilket som helst av de foregående krav, hvori oscillasjonene følger en bølgeform med trinnvise overganger.

22. Fremgangsmåten ifølge hvilket som helst av de foregående krav, omfattende å variere hvilken som helst av følgende parametere under installasjon eller fjerning av pålen (10): frekvensen av oscillasjonene, amplitude av oscillasjonene, og/eller et gjennomsnittlig nivå av vanntrykk i kammeret (20) som vanntrykket oscillerer rundt.

23. Fremgangsmåten ifølge krav 22, omfattende å øke hvilken som helst av parameterne i samsvar med penetreringsdybden til pålen (10) i jorden (12).

24. Undervannspåle (10), omfattende:

en pumpe (24) i fluidkommunikasjon med et indre kammer (20) i pålen (10) for å pumpe vann ut av eller inn i kammeret (20) under installasjon eller fjerning av pålen (10), og dermed redusere eller øke et nivå av vanntrykket i kammeret (20) i forhold til omgivelsestrykket til vann utenfor kammeret (20); karakterisert ved at undervannspålen omfatter:

en trykkvariatorpumpe (32) i fluidkommunikasjon med kammeret (20) for å tilføre oscillasjoner i vanntrykket i kammeret (20).

25. Pålen (10) ifølge krav 24, hvori pumpen (24) og trykkvariatorpumpen (32) er i fluidkommunikasjon med kammeret (20) gjennom en felles port (22).

26. Pålen (10) ifølge krav 25, hvori pumpen (24) og trykkvariatorpumpen (32) er anordnet i serie.

27. Pålen (10) ifølge krav 25, hvori pumpen (24) og trykkvariatorpumpen (32) er anordnet parallelt.

28. Pålen (10) ifølge krav 25, hvori pumpen (24) er en jetpumpe og et utløp fra trykkvariatorpumpen (32) kommuniserer med et drivfluidinnløp inn til pumpen (24).

29. Pålen (10) ifølge krav 24, hvori pumpen (24) og trykkvariatorpumpen (32) er i fluidkommunikasjon med kammeret (20) gjennom respektive separate porter (22, 44).

30. Pålen (10) ifølge krav 25 eller krav 29, hvori porten eller hver port (22, 44) åpner nedover inn i kammeret (20) i motsetning til jord (12) som lukker en nedre ende av kammeret (20).

31. Pålen (10) ifølge et hvilket som helst av kravene 24 til 30, hvori trykkvariatorpumpen (32) og pumpen (24) er plassert utenfor kammeret (20).

32. Pålen (10) ifølge hvilket som helst av kravene 24 til 31, hvori trykkvariatorpumpen (32) er i fluidkommunikasjon med vannet utenfor kammeret (20).

33. Pålen (10) ifølge hvilket som helst av kravene 24 til 31, hvori trykkvariatorpumpen (32) er innelukket i kammeret.

34. Pålen (10) ifølge hvilket som helst av kravene 24 til 33, hvori trykkvariatorpumpen (32) er en positiv fortrengningspumpe.

35. Pålen (10) ifølge krav 34, hvori trykkvariatorpumpen (32) omfatter et resiprositetselement (46) som er bevegelig for å trekke vann fra kammeret (20) og for å drive ut vann inn i kammeret (20) vekselvis.

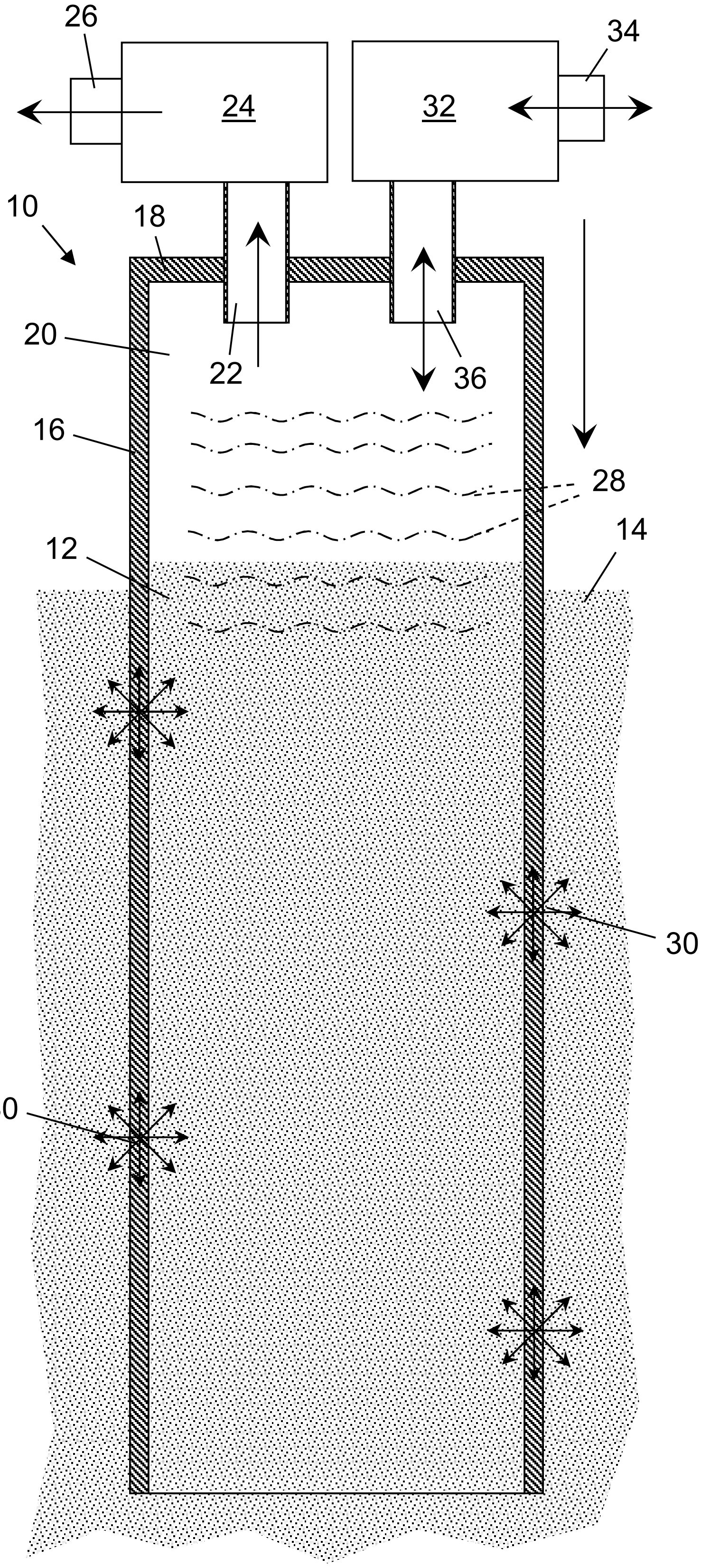


Figure 1

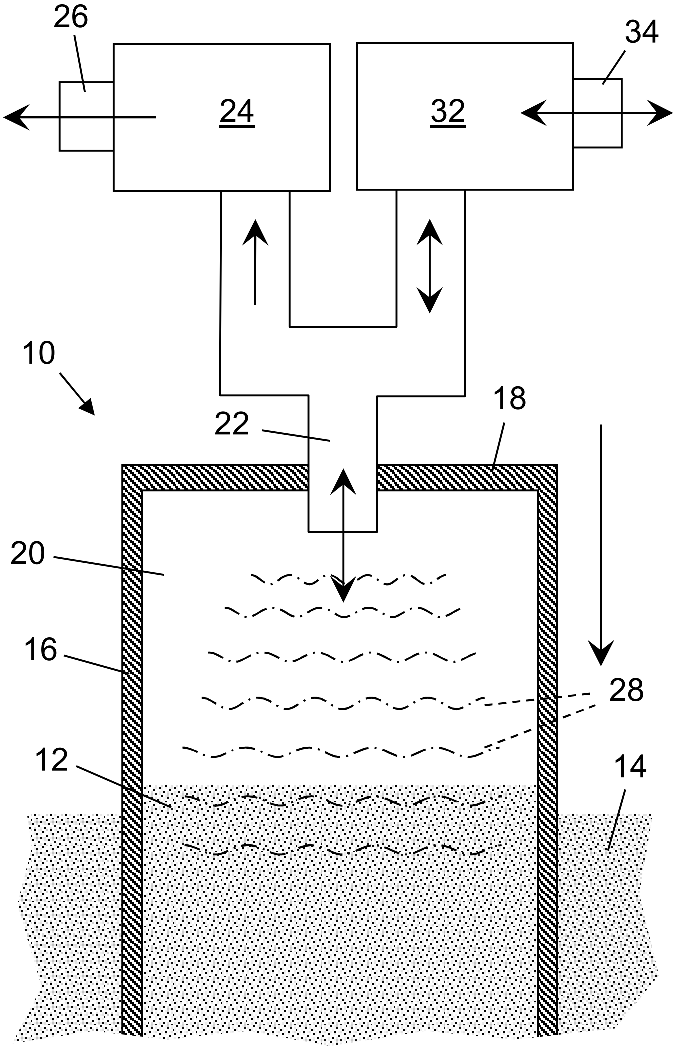


Figure 2

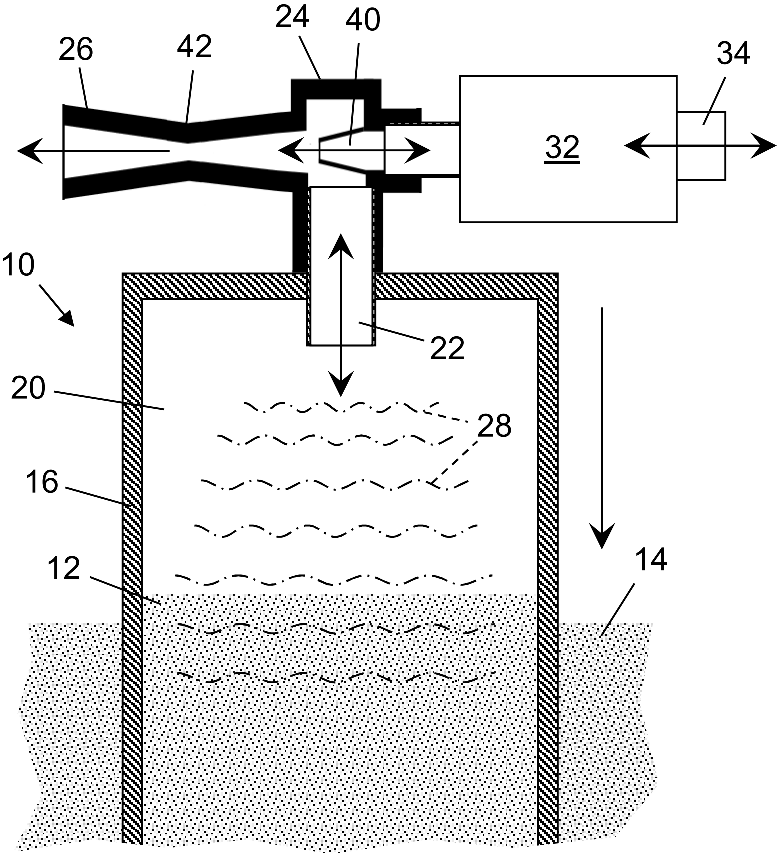


Figure 3

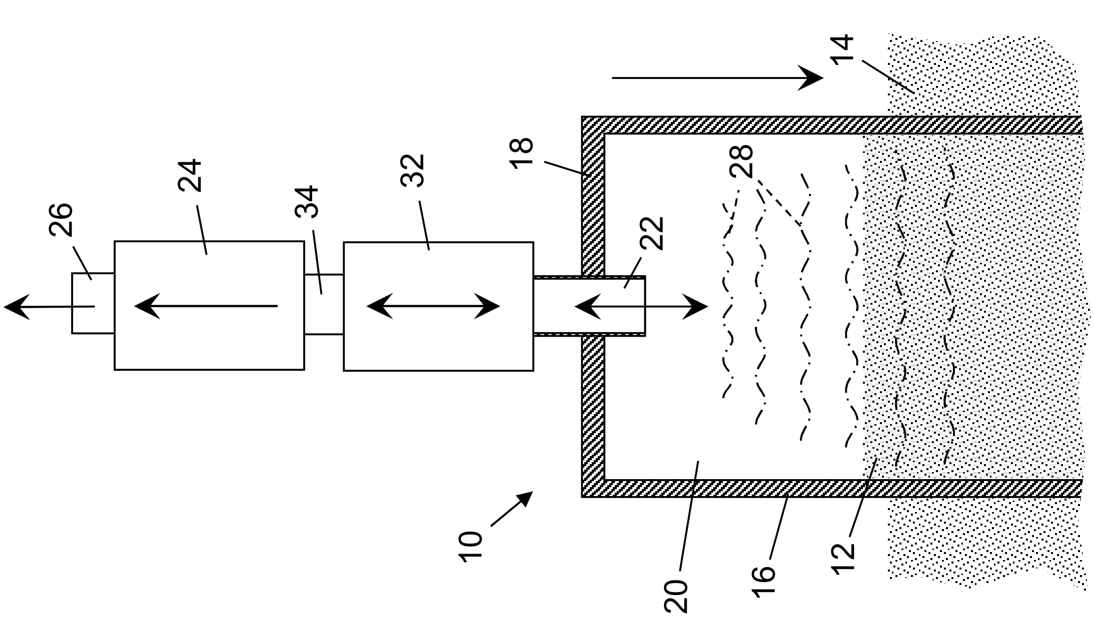


Figure 4

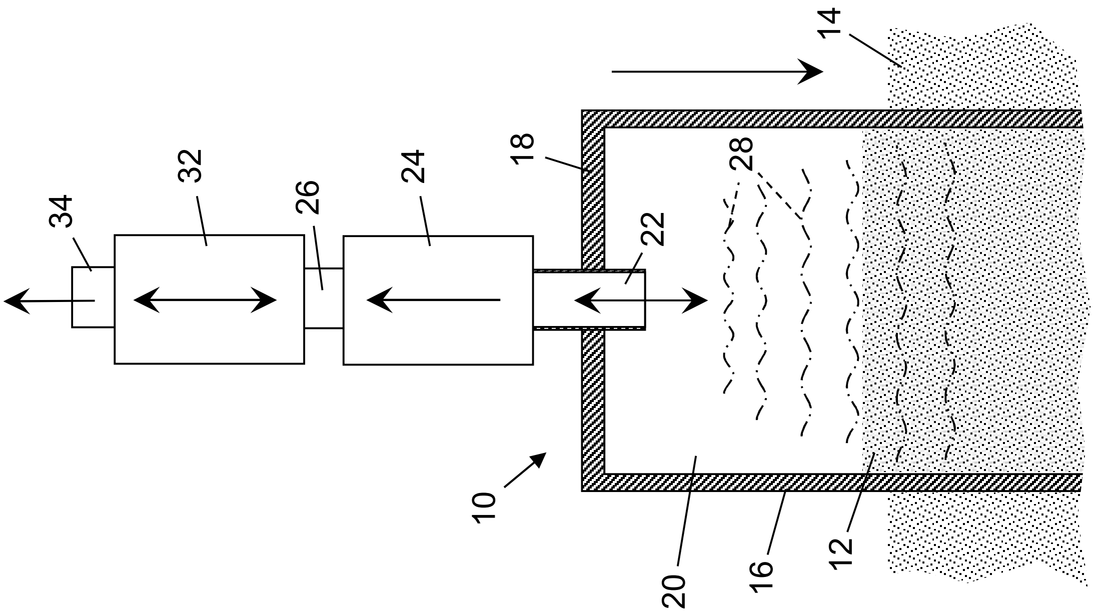


Figure 5

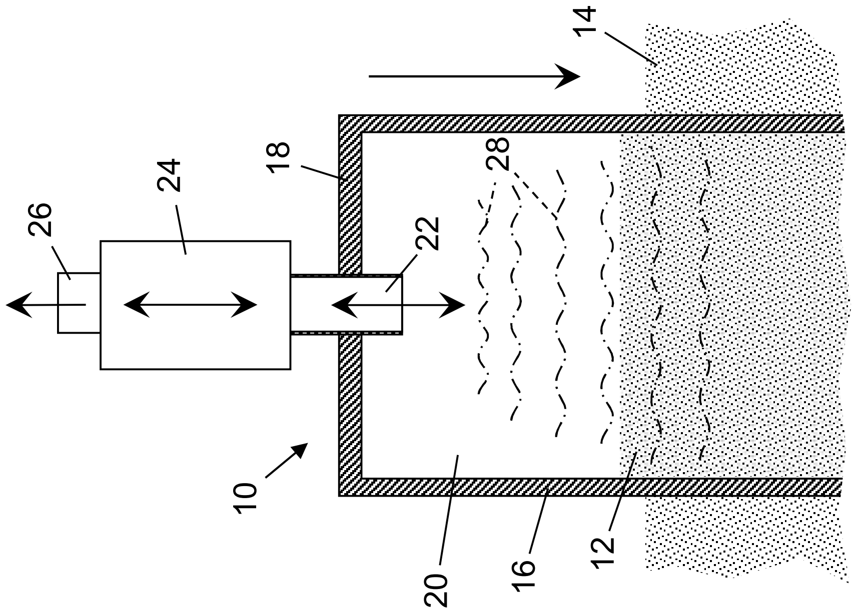


Figure 6

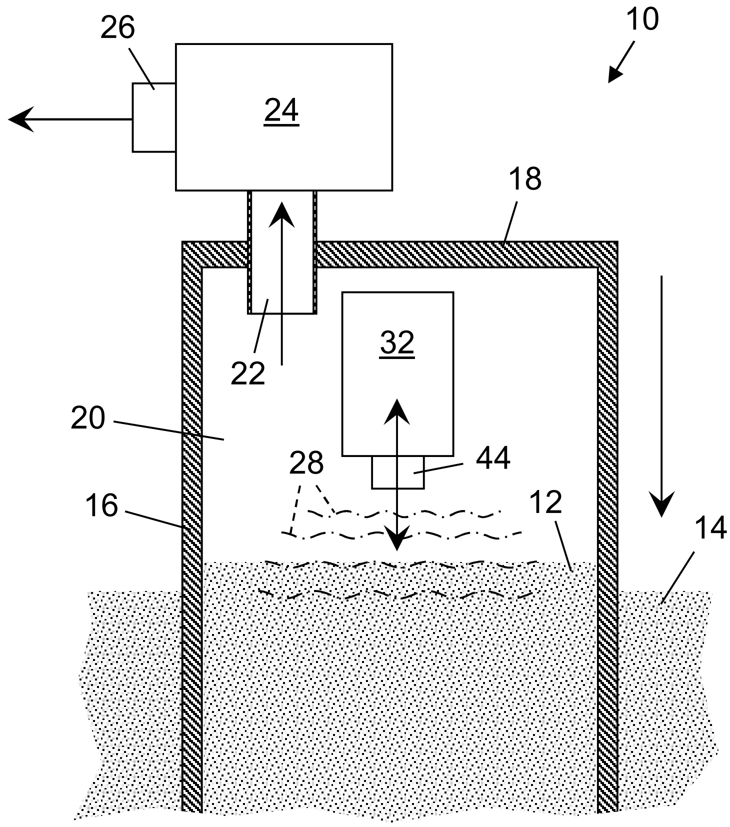


Figure 7

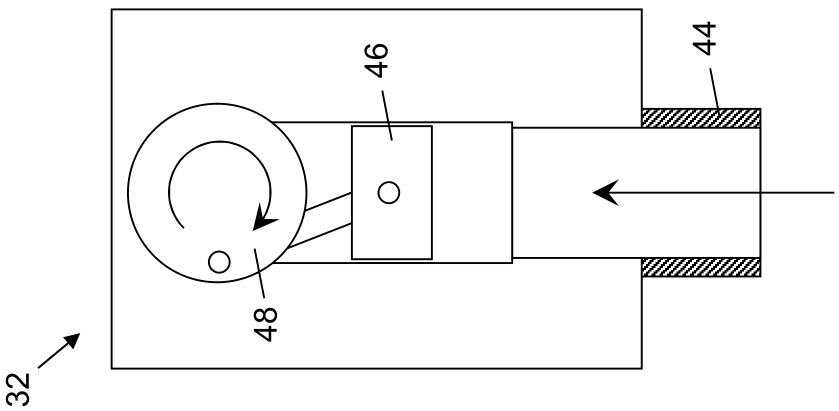


Figure 8a

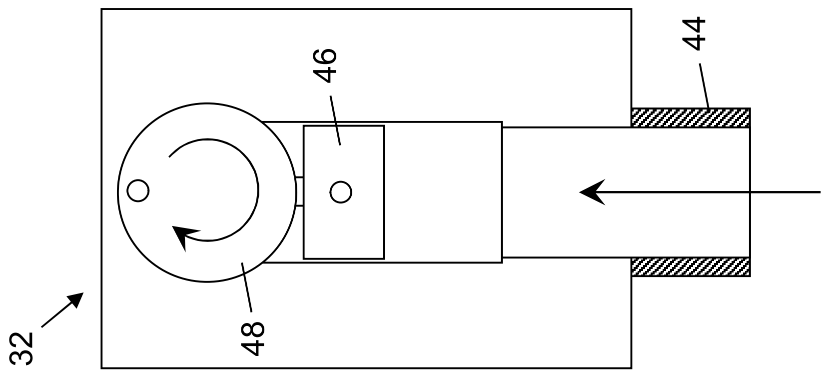


Figure 8b

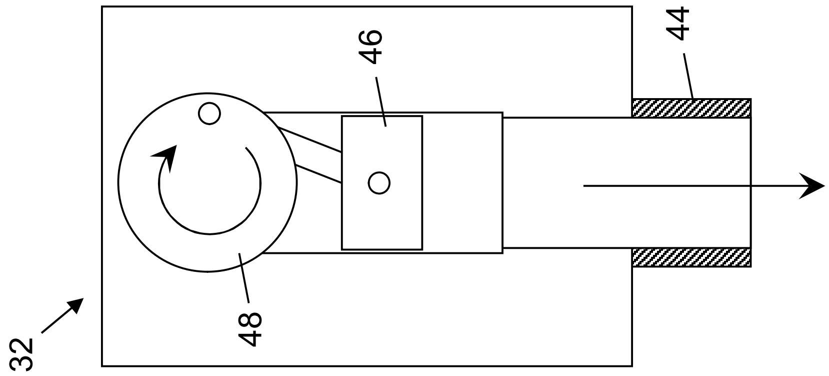


Figure 8c

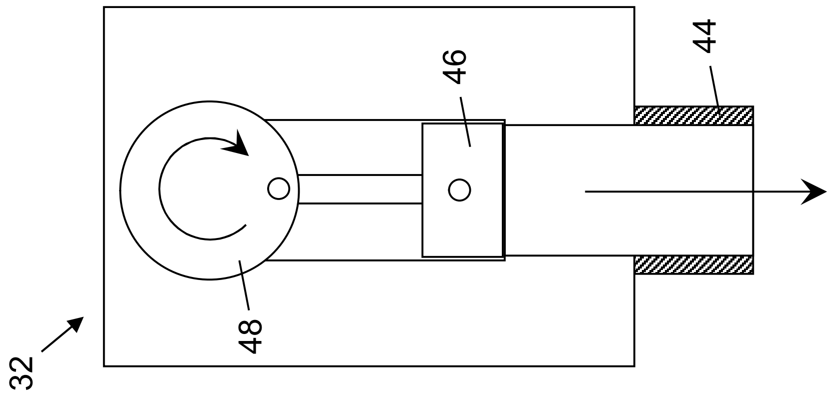


Figure 8d

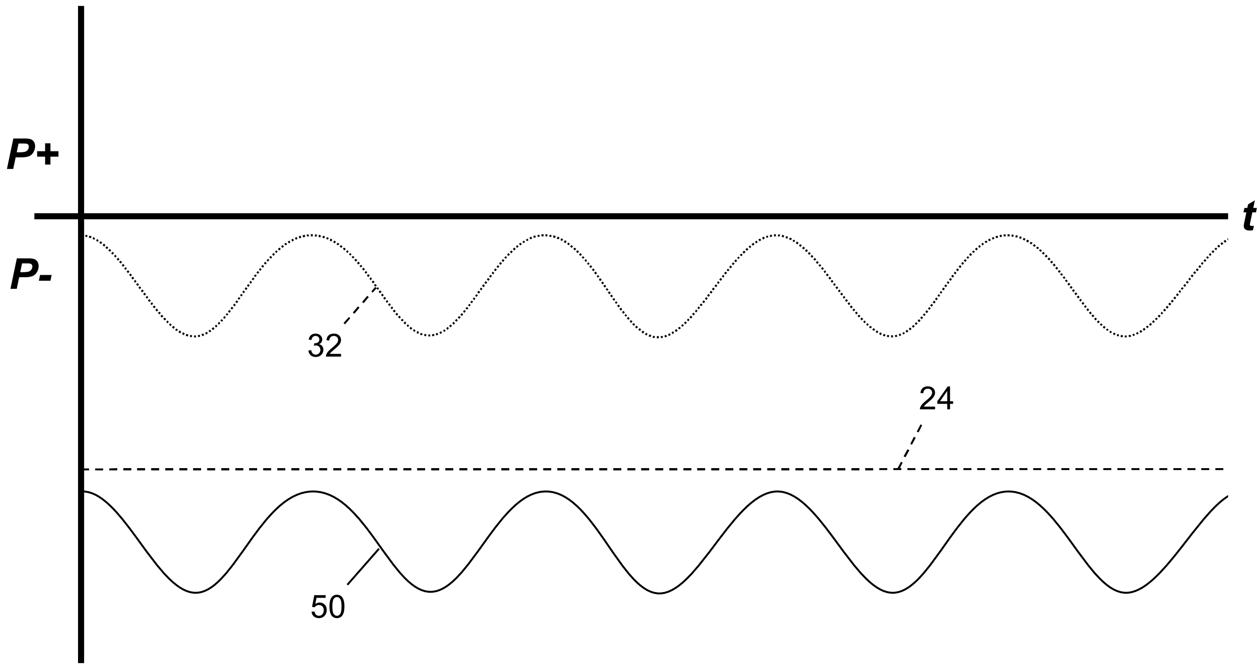


Figure 9

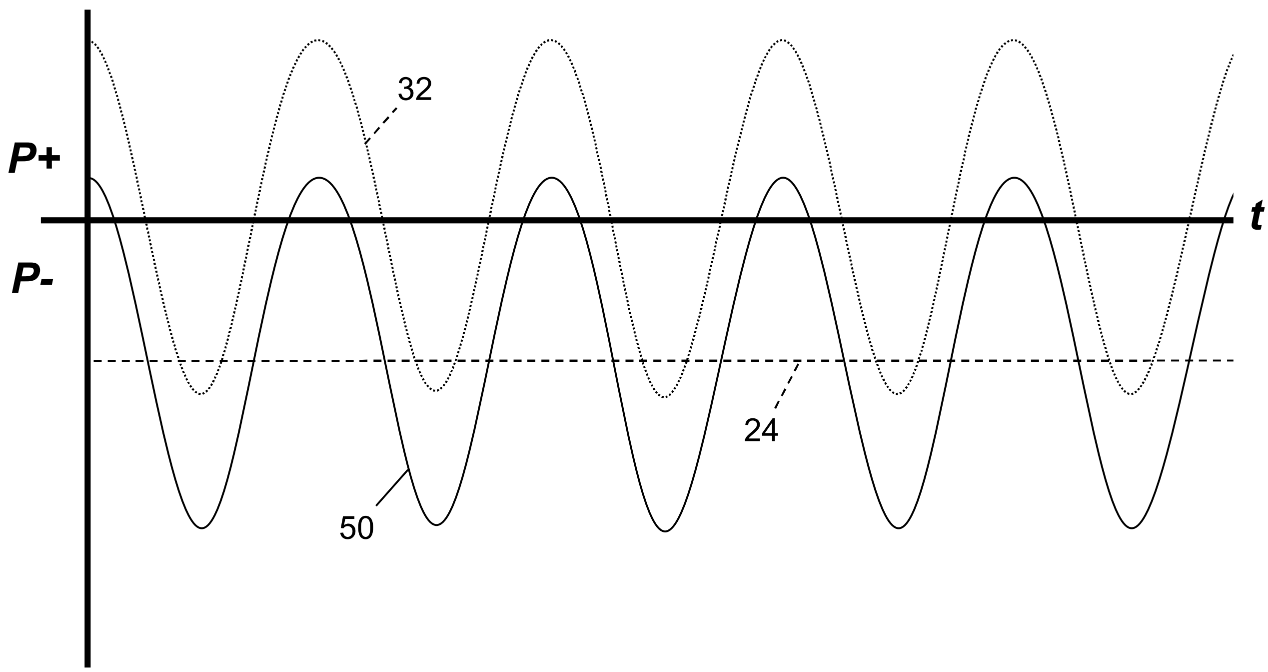


Figure 10

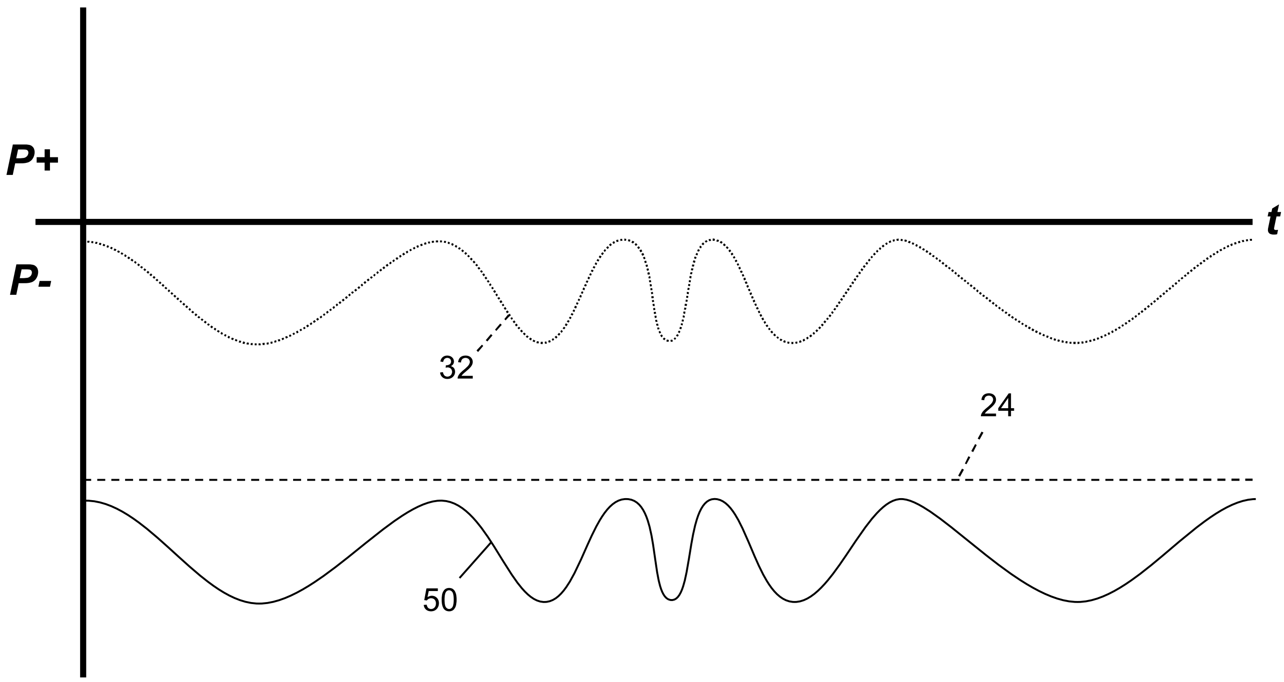


Figure 11

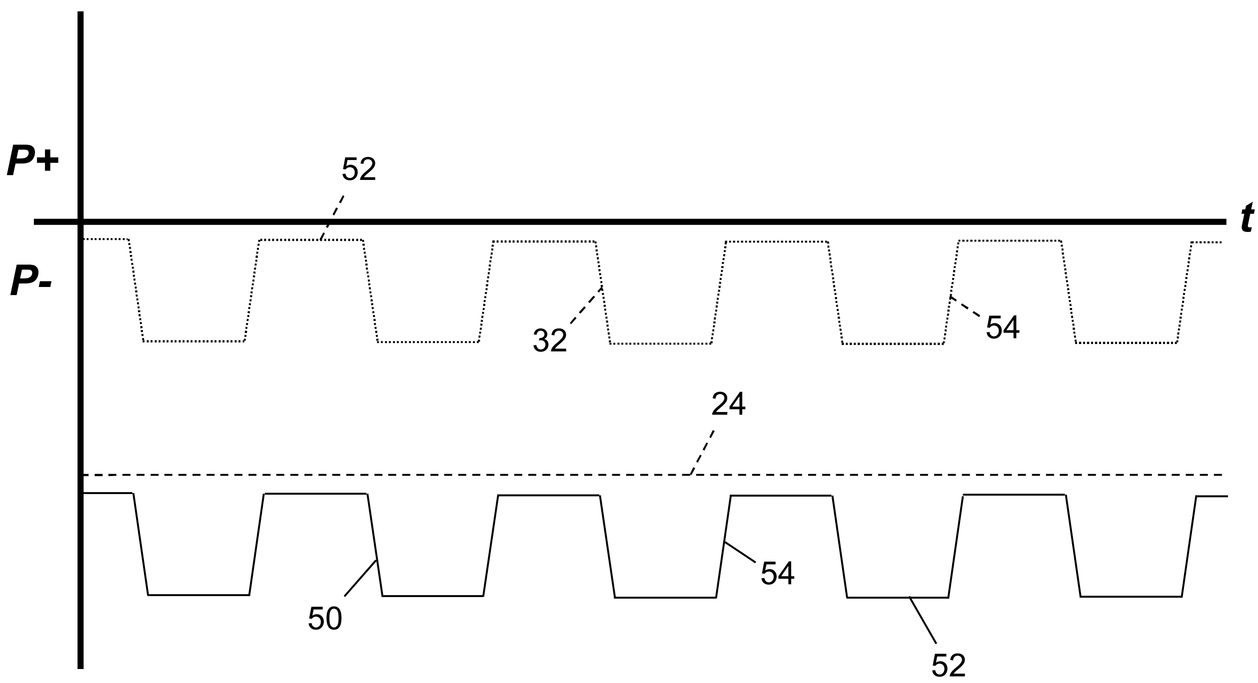


Figure 12

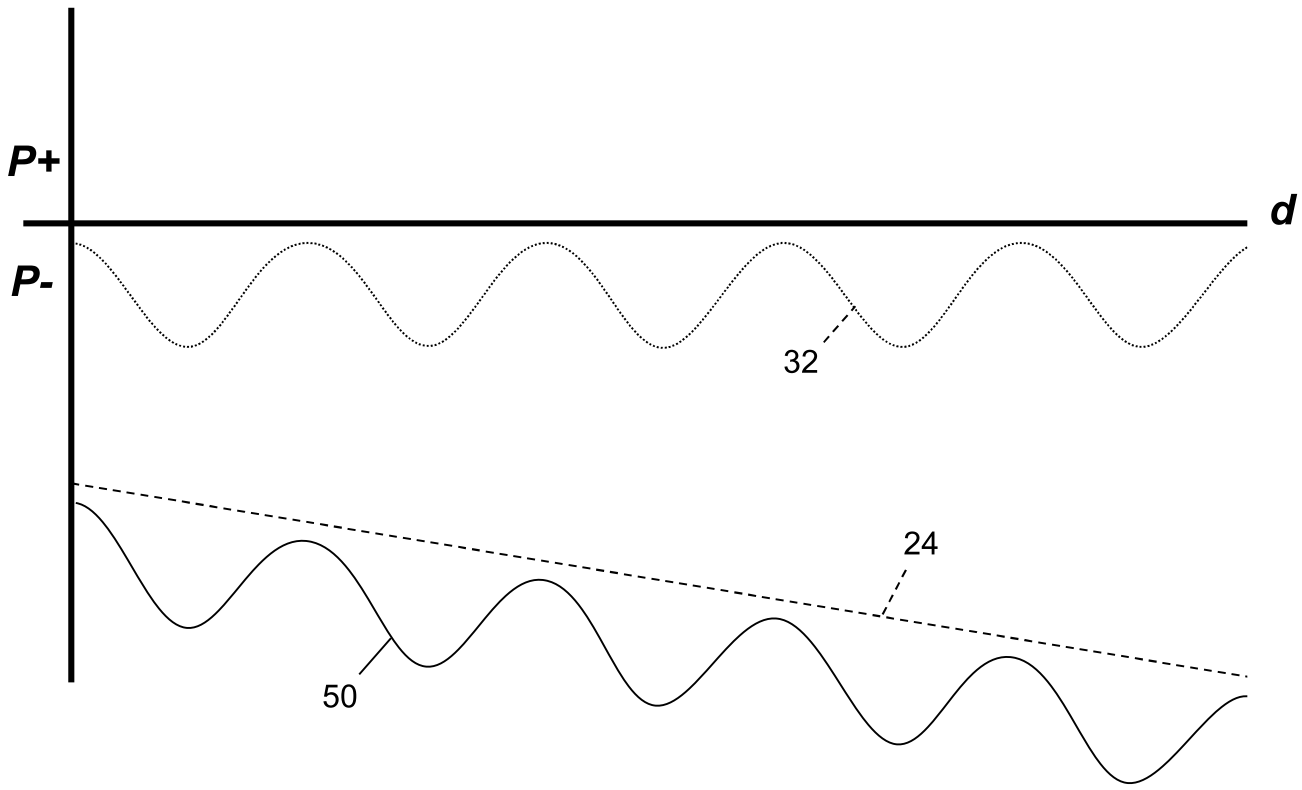


Figure 13

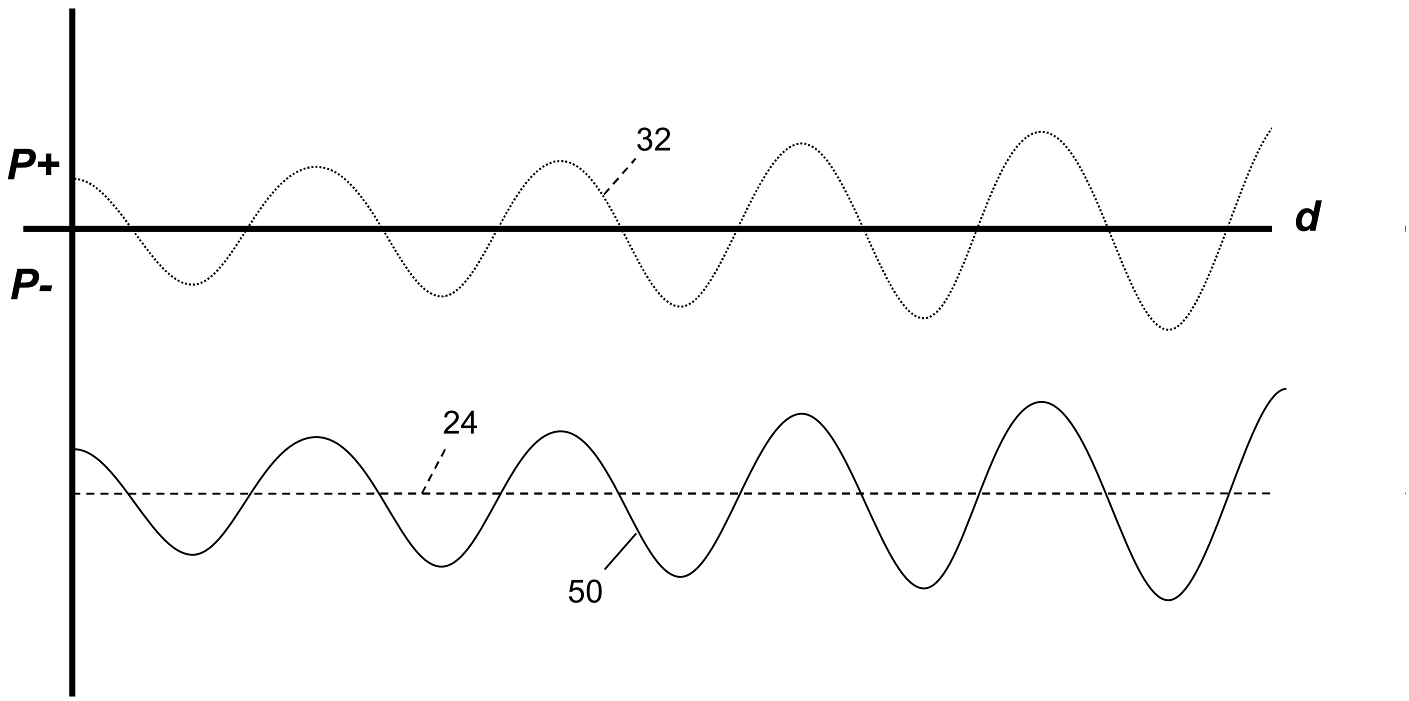


Figure 14